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Roof Material Suitability for IT Mission-Critical Facilities

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ABSTRACT

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Mission-critical facilities house operations that when interrupted, can prove disastrous to an organization's future. Limited market research is available to determine what roof types are best suited to meet the unique demands of these buildings. The purpose of this research was to evaluate different roof materials and to observe trends relative to their lifecycle costs and roof professional's assessment in use with mission-critical facilities. The objectives of the study were to determine the average annual lifecycle costs for the sampled roof materials, to determine the roofing professionals' preferred mission-critical facility roof materials, and to priority rank the sampled roof materials for use with mission-critical facilities

A pilot study was conducted to assess variables in evaluating different roof materials and their use with mission-critical facilities. Additionally, a survey was administered to roofing professionals across the United States to obtain lifecycle cost information for various roof materials as well as ratings for those materials for use with mission-critical facilities.

The research found that single-ply roofs, with the exception of 60 Mil TPO, had lower annual lifecycle costs than built-up roofs due to their having lower install and removal costs, as well as having increasing life expectancies over the years. The metal roof selection was also shown to have a low annual lifecycle cost due to having the longest estimated lifespan. Built-up and metal roofs were rated highest by roofing professionals for their use with mission-critical facilities, suggesting a prioritization of risk reduction versus cost savings. When the lifecycle cost data was applied to the roof material ratings, the data showed that built-up roofs presented themselves as good values for mission-critical facilities; however, 90 Mil EPDM and 24-gauge metal roofs could be considered as viable cost savings alternatives.

Keywords: mission-critical, facility, data center, critical infrastructure, roof system, lifecycle

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1 INTRODUCTION

1.1 Background

As the need for 24/7 operations increases across organizations, the buildings housing those operations have evolved to meet their ongoing and constant demands. In the world of business, these buildings have come to be known as **mission-critical facilities**. Mission-critical facilities can be defined as a facility "…that has an inordinate impact on business operations and/or profitability should key infrastructure systems lose power or other support, such as cooling" (Woodell, 2015). There are many facility types that fall under this definition such as hospitals, airports, hotels, call centers, etc. On a broad basis, all of these facility types are considered critical to the operations of their respective organizations; however, there is a common functionality amongst organizations that has become increasingly critical over time, and that is the functionality of **information technology (IT)**.

Information Technology can be defined as "capabilities offered to organizations by computers, software applications, and telecommunications to deliver data, information, and knowledge to individuals and processes" (Attaran, 2003). As organizations have migrated towards automation of processes, Information Technology can be seen interwoven throughout every aspect of their operations such as email, data collection, access to company systems, transaction execution, payment processing, inventory management, etc. The loss of IT functionality presents a tremendous risk to organizations, as it threatens their ability to do business. The risk is so great in fact, that in 2007 the U.S. National Archives and Records Administration conducted a study that indicated that 25% of companies who experienced an IT outage from 2 to 6 days went bankrupt immediately, and that 93% of companies that lost their data center for 10 or more days filed for bankruptcy within a year (Gold, 2007).

The primary IT equipment for organizations are housed in facilities called **data centers** or network buildings. Data centers are specifically designed and equipped with the infrastructure to meet the demands of the equipment and to ultimately protect the IT operations. Measures are put into place that address power consumption and interruption, cooling, fire detection/protection, remote monitoring, and security (Woodell, 2015). The facilities management operations for data centers are also in line to support the IT operations within the facility through robust janitorial, preventative maintenance, and corrective response programs.

1.2 Statement of the Problem

Many resources are available outlining best practices for designing and maintaining mission-critical facilities. These resources put heavy emphasis on the internal infrastructure of the building, primarily power management and cooling. What appears absent in many of these publications are considerations toward the roof systems of these facilities, both in design and maintenance. This presents a significant risk, as improper roof selection and maintenance can increase the possibility of water entering into the facility. Water when introduced into a network equipment environment, can become catastrophic and increase the likelihood of an outage.

In addition to the operational risks, the lack of guidance around roof considerations for data centers also presents a financial risk to the organization. With all buildings, building owners and managers are tasked with selecting the appropriate roof materials and installation methods for new building construction and roof replacement, along with the appropriate maintenance program. Inadequate knowledge surrounding roof selection for mission-critical facilities can lead to negative impacts to both capital and expense budgets.

1.3 Background and Need

Previous studies looking into roof selection for buildings within the United States are limited. The two largest studies conducted in recent years are the 2005 Roofing Industry Durability and Cost Survey and the 2015-2016 NRCA Market Survey. The studies were published by the Roof Consultants Institute and the National Roofing Contractors Association respectively. The studies surveyed members across their organizations to obtain market data around the lifecycle costs of various roofs, and roof sales across the United States. The RCI study did seek to obtain data from the members of BOMA (Building Owners and Managers Association); however, those requests were denied citing "a lack of interest in the subject" amongst their members. The author of the RCI survey referenced the response as part of their concern regarding communication between the roofing industry and the building owners and managers (Cash, 2006). What is clear from the NRCA Market Survey is that sales figures show increased usage of TPO and PVC roof material in almost every market within the United States (NRCA, 2016). This trend is a change from when those products were new to the market.

1.4 Purpose of the Study

With the limited availability of roof selection market data and accounting for the unique needs of data centers, there is clearly a need to better understand the roof selection considerations for mission-critical facilities. The purpose of this research was to evaluate different roof materials and to observe trends relative to their lifecycle costs and roof professional's assessment in use with mission-critical facilities. The materials were evaluated based on their estimated lifecycle costs and roof professional's assessments in association to different building types. The process of compiling the data necessary for this research involved obtaining survey data from roofing professionals across the United States to measure their estimates for cost and lifespan, as well as the perceived risks of various roof materials.

1.5 Research Objectives

The purpose of this research was to evaluate different roof materials and to observe trends relative to their lifecycle costs and roof professional's assessment in use with mission-critical facilities. The research objectives were to:

1) Determine the average annual lifecycle costs for the sampled roof materials.
2) Determine the roofing professionals' preferred mission-critical facility roof materials.
3) Priority rank the sampled roof materials for use with mission-critical facilities.

To achieve these research objectives, this thesis is separated into the following: Chapter 2 provides a summary of current and relevant literature regarding mission-critical facilities and roof selection. Chapter 3 discusses the research methods used for the research, Chapter 4 contains a presentation and discussion of the results, and Chapter 5 provides conclusions, recommendations, and suggested areas for further research.

1.6 Hypothesis

Because the current market data has shown increases year-over-year in the sales of single-ply roof materials, the research team hypothesized that out of all the roof material selections included in the study, single-ply roofs would have the lowest annual lifecycle costs. The research team also hypothesized that out of all the roof material selections included in the study, single-ply roofs would rate the highest on total value for mission-critical facilities.

1.7 Significance to the Field

Building owners and managers over mission-critical facilities could greatly benefit from this research. They could have lifecycle cost and risk data to use when attempting to select the appropriate roof for their mission-critical facility. Roofing professionals could also benefit from this research as they make roof material recommendations for new construction or replacement projects. This research could potentially be expanded to include additional roof types, additional building types, and different regions globally.

1.8 Definitions

Mission-Critical Facility: (Facility) that has an inordinate impact on business operations and/or profitability should key infrastructure systems lose power or other support, such as cooling.

Information Technology: Capabilities offered to organizations by computers, software applications, and telecommunications to deliver data, information, and knowledge to individuals and processes.

Data Center: Facilities that house Information Technology equipment and provide supporting critical infrastructure to IT operations.

2 LITERATURE REVIEW

2.1 Introduction

As organizations have moved into the Information Age and beyond, there has been an ever-increasing expansion of 24/7 operations. Although 24/7 operations have long existed for key infrastructure organizations such as hospitals, police and fire departments, airline carriers, etc.; advancements in technology have contributed to the addition of these operations within the business world. Functions such as payment processing, online transactions, email, and data processing are required to operate continuously uninterrupted in order to remain competitive in today's business environment. The author Peter Cutis has stated that "Today more than ever, enterprises of all types and sizes are demanding 24-hour system availability…One such example is the banking and financial services industry. Business practices mandate continuous uptime for all computer and network equipment to facilitate round-the-clock trading and banking activities anywhere and everywhere in the world. Banking and financial service firms are completely intolerant of unscheduled downtime, given the guaranteed loss of business that invariably results" (Curtis, 2011).

As functions and even roles within an organization lend themselves to 24/7 support of the organization's mission, it is important to be able to distinguish between what is considered mission-critical and non-mission-critical. The criteria to determine the criticality of a function within an organization can almost always be decided by the immediate impact and scope if that function were to cease, even for a short period of time. The question as to whether the operational interruption affects thousands of individuals for extended periods of time or merely inconveniences a few individuals for a while, will help the organization determine the criticality of the function (Kearn, Galup, Nemiro, 2000). Operations that are deemed to be mission-critical are typically housed in the appropriate mission-critical facilities. Mission-critical facilities can be defined as a facility "that has an inordinate impact on business operations and/or profitability should key infrastructure systems lose power or other support, such as cooling" (Woodell, 2015). As such, mission-critical facilities are designed and built with the operation in mind. Infrastructure is in place to allow the operation to operate efficiently, but more importantly, the infrastructure serves to mitigate potential risks to the operation and keep operational downtime to an absolute minimum.

2.2 Information Technology Mission-Critical Facilities

For the purposes of this study, it is important to further distinguish IT functionality from other 24/7 operations when considering mission-critical facilities. Information Technology can be defined as "capabilities offered to organizations by computers, software applications, and telecommunications to deliver data, information, and knowledge to individuals and processes" (Attaran, 2003). The purpose of focusing on IT mission-critical facilities is to highlight their unique nature, as well as the potential impact an organization can suffer when IT functionality is disrupted. IT mission-critical facilities typically include large and small data centers that house mainframe computers, servers, data storage, and privately and publicly owned telecommunication networks. Typical organizations that have these facilities include governmental agencies, institutions, commercial, telecommunications, and industrial organizations (Uhlman, 2006). The IT functionalities being served by mission-critical facilities can typically be partitioned into the groups of telecommunications systems and data storage/processing centers. Telecommunication systems are defined as "on-line information exchange systems, that is, the system does not store or process customer data but merely transfers the data from one point to another. When a disruption occurs, all information in transit is lost" (Robin, 2000). As its name implies, data storage/processing centers simply house data on servers. A service interruption can result in data that has not yet been permanently saved to become lost and worse, a serious disaster to the data storage/processing equipment can result in the saved data to either become corrupted or lost altogether. Disruptions to IT functionality are often referred to as network outages.

The loss of IT functionality presents a tremendous risk to organizations, as it threatens their ability to do business. Notable examples that showcase the business impact to organizations from losing IT functionality are network outage cases experienced by eBay, E*Trade, and AOL. On June 14, 1999, internet auction site eBay suffered a 22-hour outage resulting in a loss of sales revenue of $200,000 per hour of downtime. The company shareholders experienced a reduction in stock valuation of $4 billion as a result of the outage. E*Trade saw a stock value reduction of $1.5 billion as a result of a 75 minute outage, and AOL lost $4.8 billion after a 19 hour outage (Robin, 2000). Telecommunications companies are levied hefty fines by the Federal Communications Commission (FCC) often in the tens of millions of dollars, for losing extended periods of critical communications functionalities like aviation support and 911 calling. The risk of outage is so great in fact, that in 2007 the U.S. National Archives and Records Administration conducted a study that indicated that 25% of companies who experienced an IT outage from 2 to 6 days went bankrupt immediately, and that 93% of companies that lost their data center for 10 or more days filed for bankruptcy within a year (Gold, 2007).

It is important for organizations to understand the root cause sources of network outages for overall prevention and to minimize their potential impact. Organizations perform risk hazard assessments to identify potential points of failure and address those hazards through optimized equipment selection, development of standards and processes, and the implementation of critical infrastructure protocol to support and protect IT operations. Regulating organizations can also develop standards and classifications for network outages. The FCC is the regulating body that provides guidance to the telecommunications industry so that customers receive essential communications services at a standard level of reliability (Daneshmand and Savolaine, 1993). Telecommunications companies follow the standard outage classifications produced by the American National Standards Institute (ANSI). The standard lists multiple root sources for network outages such as human error, equipment failure, power loss, and environmental conditions such as heating/cooling or water intrusion not conducive to the network equipment environment (ANSI, 2019). The ANSI outage classifications are utilized in reports to the FCC for major network outages that meet the reporting thresholds outlined by the FCC on any facilities provided for a fee to one or more affiliated entities by radio, wire, cable, satellite, and/or lightguide (FCC, 2016).

2.3 Critical Infrastructure Systems

There are typically two approaches an organization can take to ensure the reliability of their IT operations. The first approach is to establish multiple data center locations with equipment and servers that mirror one another's information being stored and processed. This way, if the operations within one facility are interrupted, the remaining can carry on the operational load and maintain constant continuity. This is obviously a very capital intensive strategy as organizations incur high costs related to real estate acquisitions and leases, utilities demand, and the purchasing of redundant IT equipment. In the early 2000's, the approximate cost to construct a new data center was approximately $150 million dollars. Those costs have since multiplied over the years (Kaplan, Forrest, Kindler, 2008). The second approach is for an organization to house their operations in fewer facilities but maintain sufficient redundancy of key critical systems that support the IT functionality within the building and minimizes the possibility of a network outage from occurring (Woodell, 2015). Critical systems for IT facilities commonly fall under the categories of power supply and generation, environmental cooling or HVAC, and fire detection/protection systems.

As stated in the book, Maintaining Mission Critical Systems in a 24/7 Environment, "Continuous, clean, and uninterrupted power is the lifeblood of any data center, especially one that operates 24 hours a day, 7 days a week. Critical enterprise power is the power without which an organization would quickly be unable to achieve its business objectives" (Curtis, 2011). Power reliability is the top priority for any IT mission-critical facility and system redundancies can be found at the commercial power mains entering into the facilities, backup and standby power through the use of generators and automatic transfer switches (ATS), and the use of uninterrupted power supply (UPS) systems to maintain constant and uninterrupted power.

Heating, ventilation, and air conditioning (HVAC) systems fall into the category of critical infrastructure, as they serve to remove heat in the facility created from the IT network equipment. As technology has advanced over the years, IT network equipment has become more compact allowing organizations to leverage their mission-critical facilities to maximize the space utilized by servers, computers, and network switches. Although the equipment has become smaller in size, the power usage and output of each unit has remained similar to that of the larger units of the past, resulting in overall increased heat loads within the facilities. Temperature increases that exceed the specifications of the network equipment, result in the equipment shutting down leading to an outage condition. To combat this, HVAC systems are continuously evaluated to assess their cooling capacity and distribution relative to the current and future heat loads within the facility. Redundant HVAC systems are put into place to prevent a single point of failure in the event that certain systems do not operate in the time of need.

The risk of fire can be devastating to the IT operations of an organizations and its effects can oftentimes be irreversible. The measures organizations put into place to protect against fire are sophisticated fire detections systems utilizing highly sensitive smoke detectors, as well as gaseous agents, such as Halon and more recently FM200, that are released in the event of a fire to smother the flames. Sprinkler systems are commonly present in IT mission-critical facilities; however, they are typically used as the last line of defense due to their conductive nature which would react negatively with the electronic components within the facility (Woodell, 2015).

2.4 Water Hazard

As organizations have identified critical hazards related to power loss, overheating, and fire to their IT mission-critical facilities, they have in turn implemented appropriate system redundancies and have developed disaster recovery plans to address those risks. Water hazard, however, is infrequently identified as a direct risk hazard to IT operations, even though water risks are commonly mentioned in guidance for other critical systems such as HVAC and fire detection/protection. This is unusual, because the introduction of water into an IT network environment can be disastrous. Water is also cited as the root cause to many reported network outages. In a 2017 report, the California Public Utilities Commission (CPUC) reported that during the months of January – February 2017, the state of California experienced the most rainfall recorded in 122 years. This resulted in a 30% increase of communication service interruptions totaling 1,755,644 customers who were without service during that time period, 964,003 of whom were without access to 911 calls. 52,296 businesses were also found to have experienced communication service interruptions. The report further states that “For wireline service, the worst performing service provider reported 78% of its network outages were due to cable failure, as well as its network being especially susceptible to water intrusion” (CPUC, 2018). As water hazard is indeed a risk factor to IT operations, building systems that have the potential to introduce water into the network environment, roof systems especially, should be given similar priority as other critical infrastructure systems.

2.5 Roof Systems

Roof systems are the upper part of the building envelope that provide protection against rain and snow, sunlight, wind, and extreme temperatures. The major components of a roof system are the roof deck (steel or concrete in commercial applications), air/vapor barrier, insulation, and a covering or membrane. The roof membrane is what maintains the roof system in a water tight condition. In this study, references to roof type or roof material refer back to the membrane that exists on the roof. Roofs are typically classified as being either low-sloped or steep-sloped. Low-sloped roofs are characterized as having a slope less than or equal to 3:12 or 25 percent, while steep-sloped roofs are those sloped greater than 3:12 (Smith, 2016). As most IT mission-critical facilities have roofs that are low-sloped, this study will mainly focus on the different low-sloped roof types that exist in the market today.

In the United States and prior to the mid 1970’s, almost all low sloped roofs were either coal-tar or asphalt built-up roofs. In the early 1900’s coal-tar was used with the added effect to cool buildings due to the evaporative properties it had on water that had ponded on top of the buildings. Starting in the 1980’s and continuing today, other low sloped materials have entered the market to compete with built-up roofs, namely modified bitumen, single-ply roofs, and metal panel roofs (Smith, 2016).

2.5.1 Built-Up Roofs (BUR)

Built-up roof membranes are made up of alternating layers of waterproof bitumen (coal-tar or asphalt) and felt sheets (typically fiberglass). Asphalt is the more common built-up roof type of the two. Because asphalt has a tendency to break down overtime from UV exposure, an additional covering such as gravel or a cap sheet is added as a top layer. Although built-up roofs have a long reputation of reliability, there are some potential drawbacks. Asphalt becomes brittle as it ages and can produce cracks with the settling of the building. Built-up roof installation is also among the most complicated as it involves the application of hot asphalt and the use of a flame torch. Because of this, installation often requires installers who have previous experience with built-up roofs which can lead to increased costs due to specialization (DOD, 2019).

2.5.2 Modified Bitumen

Modified bitumen is similar to built-up roofs in that it leverages the water-proof characteristics of asphalt. However, to avoid the bitumen becoming brittle overtime, the asphalt is blended with polymer chemicals to produce polymer modified bitumen (PmB). This asphalt/polymer blend is prefabricated into sheets mixed with reinforcing materials which are then applied either with hot asphalt or by heat torch (McNally, 2011).

2.5.3 Single-Ply

Single-ply membranes are made up of prefabricated sheets of either thermoplastic or thermoset materials that are installed as one layer. The thermoplastic varieties of single-ply membranes are polyvinyl chloride (PVC), thermoplastic polyolefin (TPO), and ketone ethylene ester (KEE). Common thermoset single-plies are ethylene propylene diene monomer (EPDM) and epichlorohydrin (ECH). Single-ply membranes are commonly utilized due to their ease of installation as well as being easy to repair. The main drawback to single-ply roofs is that there exists only one layer of protection. If that layer was to get punctured or fail, water intrusion becomes inevitable. This becomes particularly problematic for roofs with multiple penetrations, or where there is a lot of foot traffic on the roof (Smith, 2016).

2.5.4 Metal Panels

Metal roof panels are utilized for their durability and low rate of repair. Metal roofing products are available in various metals such as steel, aluminum, copper, zinc, stainless steel, and titanium (Cool Metal Roofing Coalition, 2016). The methods used in the installation of a metal roof is very important to maintain a water tight seal. To achieve water tightness, the panel joints should "be soldered or sealed together with sealant tape or sealant, or both. Also, fasteners that penetrate the panel at end-joint splices or flashings must be sealed with gasketed washers" (Smith, 2016). Metal panels contract and expand with the changing seasons, so the seals and fasteners should be checked as part of the preventative maintenance and should be adjusted as needed. Although metal panels are very durable, they are expensive to install and are not optimal for ponding water. It is recommended to increase the slope of the roof to maximize the water tightness of the metal panels.

2.6 Significant Roofing Studies

As part of this research study, the research team contacted the technical division of the National Roofing Contractors Association (NRCA) to inquire about any academic research that had been conducted to evaluate roof materials in use with mission-critical facilities. The research team did not find any other roofing studies pertaining to market factors or mission-critical facilities in standard academic databases. The NRCA representative informed the research team that there had not been any roofing studies specific to mission-critical facilities and that market research relative to individual roof materials was limited. The two largest scale studies conducted in recent years that address market trends in roofing materials are the 2005 Roofing Industry Durability and Cost Survey and the 2015-2016 NRCA Market Survey.

The 2005 Roofing Industry Durability and Cost Survey was conducted by the engineering firm Simpson, Gumpertz, & Heger Inc. with help from the NRCA and the Roof Consultants Institute (RCI). The lead researcher was Professional Engineer (PE) Carl G. Cash. The participants in the study were surveyed to provide durability and lifecycle cost estimates of various roof materials. The results from the study were published in the proceedings of the RCI 21st International Convention held in Phoenix, AZ in 2006. The 2015-2016 NRCA Market Survey is a survey that in the past was conducted biannually amongst its membership to collect current industry market data and to examine roof industry trends within the United States. The study is published and made available by the NRCA. At the time of this study, the most recent survey published was the 2015-2016 edition.

2.6.1 2005 Roofing Industry Durability and Cost Survey

The purpose of the 2005 Roofing Industry Durability and Cost Survey was to provide an unbiased estimate of the mean and minimum durability of properly-designed, installed, and maintained roofing materials, and the estimated lifecycle cost of each system (Cash, 2006). The author of the survey had previously conducted a similar study in 1995. With the help of the National Roofing Contractors Association (NRCA) and the Roof Consultants Institute (RCI), the survey was distributed to 3,729 members of the respective organizations. The response rate was less than 10%, with similar response rate rations across the two organizations. The author did seek to obtain data from the members of BOMA (Building Owners and Managers Association); however, those requests were denied citing “a lack of interest in the subject” amongst their members. The author of the RCI survey referenced the response as part of their concern regarding communication between the roofing industry and the building owners and managers (Cash, 2006). The participants were asked to provide estimates on average and minimum life expectancies of various roof materials, with minimum life expectancies being based on the worst 1% of roofs installed. The results for roof material life expectancies were grouped by low- and high-sloped roofs. The life expectancy was further divided into tiered data series using the average life expectancies to serve as approximate durability values for each series. In addition to life expectancy, the participants were also asked to provide estimated values for installed cost (per square foot), maintenance cost (per square foot), and disposal cost (per square foot) for each roof material. The author then calculated the annual lifecycle cost for each material by adding the installed and disposal costs, dividing by the mean durability, and then adding the annual maintenance costs (Cash, 2006). The results were tabulated and compared to the results from the 1995 study to observe any trends.

For low-sloped roofs, it was observed that the durability ranking of material types in 2005 was similar to the ranking of materials in 1995. Metal and built-up roofs had the longest life expectancies, with approximate mean values of 40 and 25 years respectively. Single-ply roofs such as PVC, EPDM, and TPO were in the tiers with the shortest mean life expectancies of 16 and 14 years. The life expectancies within all tiers had increased in 2005 for both mean and minimum values from the 1995 values. The author noted that the material selections were much more specified within their categories in the 2005 survey than in the 1995 survey. This is highlighted in the durability for metal roofs which had the largest disparity between the surveys. The durability values for metal roofs were 40 years (Mean) and 28 years (Min), compared to 25 years (Mean) and 12 years (Min) recorded in 1995. The 2005 metals specified in Tier 1 were architectural metals versus structural metals in Tier 2 (Cash, 2006). The 1995 survey only specified Metal Panels. The durability results for low-sloped roofs can be found in Table 2-1.

Table 2-1: Ranked Low-Sloped Roofing Durability (2005) and 1995 Survey Data (Cash, 2006)

		2005 Data		1995 Data	
Data Series	Low-Sloped Roofing System	Mean	Min.	Mean	Min
1	Metal Panels - Copper Metal Panels - Stainless Steel Metal Panels - Terne Metal Panels - Zinc	40	28	25	12
2	Metal Panels - Aluminum Metal Panels - Aluminized Steel Metal Panels - Galvalume BUR - Gravel Surfaced Pitch - Tar/Organic Felts Metal Panels - Galvanized Steel BUR - Gravel-Surfaced Pitch - Pitch/Glass Felts	25	14	22	12
3	BUR - Gravel-Surfaced Asphalt Glass Plies SBS Modified Pitch - Multi Ply SBS Modified Asphalt - Multi Ply BUR - Gravel -Surfaced Organic Felts	18	10	17	8
4	APP Modified Asphalt - Multi Ply Evaloy PVC Alloy - Reinforced EPDM Ketone Ethylene Ester (KEE) - Reinforced Poly (Vinyl Chloride) - Reinforced	16	9	14	7
5	Granule-Surfaced APP Modified Pitch BUR - Unsurfaced Asphalt Glass Plies Thermoplastic Polyolefin (TPO) - Reinforced Hypalon (CSPE) and PIB Spray Urethane Foam - Coated	14	7	12	5

For steep-sloped roofs, the durability ranking of materials also remained consistent between the two surveys. From the study, "natural slate had the highest estimated durability, followed by architectural metals and clay tile, followed by metal panels and concrete tile" (Cash, 2006). The life expectancies increased for all roof materials in 2005 from the values in 1995, with the exception of 3-tab strip shingles. The durability results for steep-sloped roofs can be found in Table 2-2.

Table 2-2: Steep-Sloped Roofing Durability (2005) and Previous (1995) Data (Cash, 2006)

		2005 Data		1995 Data	
Data Series	Steep-Sloped Roofing System	Mean	Min.	Mean	Min
1	Natural Slate	70	36	60	35
2	Metal Panels - Copper	51	33	26	14
	Metal Panels - Stainless Steel				
	Metal Panels - Terne				
	Clay Tile			47	25
	Metal Panels - Zinc				
3	Concrete Tile	31	17		
	Metal Panels - Aluminum			26	14
	Metal Panels - Aluminized Steel				
	Metal Panels - Galvalume				
	Metal Panels - Galvanized Steel				
4	SBS Mod. Asphalt - Glass Shingles	25	17		
	Asphalt - Glass Laminated Shingles				
5	Rubber or Plastic Shingles	21	12		
	Cedar Shakes or Shingles				
	Asphalt - Glass Interlocking Shingles				
6	Asphalt - Glass 3-Tab Strips	18	11	18	9
	Asphalt - Organic 3-Tab Strips				

When the lifecycle cost data was calculated, the annual lifecycle cost values for low-sloped roofs ranged from \$0.37/SF to \$1.05/SF. There was little correlation between the material type categories and their annual lifecycle costs. Single-ply materials had annual lifecycle values as low as $0.37/SF, $0.49/SF, and $0.49/SF for Evaloy PVC alloy, EPDM, and PVC respectively and annual lifecycle values as high as $0.80/SF and $0.86/SF for TPO and KEE, respectively. Metal roofs were grouped together among the lower lifecycle cost values with a range of $0.47/SF to $0.51/SF. Built-up roof materials saw a range of annual lifecycle values between $0.41/SF and $0.68/SF as shown in Table 2-3.

Table 2-3: Low-Sloped Roofing Costs - $/Square Foot (Cash, 2006)

		2005 Survey				1995
Data Series	Low-Sloped Roofing System	Installed Cost	Disposal Cost	Maintenance Cost/Year	Life Cycle Cost/Year	
1	Evaloy PVC Alloy - Reinforced	$3.13	$0.81	$0.13	$0.37	
	Granule-Surfaced SBS Multi Ply	$3.70	$1.00	$0.15	$0.41	$0.34
2	Metal Panels - Aluminum	$5.69	$0.91	$0.24	$0.47	
	Metal Panels - Aluminized Steel	$5.37	$1.08	$0.24	$0.48	
	Metal Panels - Galvanized Steel	$5.48	$1.00	$0.21	$0.48	
	EPDM	$3.45	$0.48	$0.24	$0.49	$0.33
	Metal Panels - Copper	$10.46	$0.56	$0.23	$0.49	
	Metal Panels - Galvalume	$5.16	$0.94	$0.25	$0.49	
	Poly Vinyl Chloride, Reinforced	$3.49	$0.92	$0.21	$0.49	
	Metal Panel - Terne	$9.32	$0.96	$0.22	$0.49	$0.36
	Metal Panels - Stainless Steel	$9.38	$1.14	$0.25	$0.51	
	Metal Panels - Zinc	$9.32	$0.88	$0.22	$0.51	
	Gravel-Suf. Pitch/Organic BUR	$5.17	$1.48	$0.27	$0.53	
	Gravel Surf. Pitch/Glass BUR	$5.44	$1.43	$0.23	$0.54	$0.32
	Unsurfaced APP Multi Ply	$2.80	$1.12	$0.22	$0.54	$0.30
3	Gravel-Surf. Asphalt/Glass BUR	$3.83	$1.21	$0.32	$0.57	
	Granule-Surf. APP Pitch, Multi Ply	$3.82	$1.23	$0.25	$0.58	
	Granule-Surf. APP Asphalt, Multi Ply	$3.43	$3.92	$0.18	$0.63	$0.34
	Unsurfaced Asphalt/Glass BUR	$2.94	$1.01	$0.37	$0.64	
	Gravel-Surf. Asphalt/Organic BUR	$3.44	$1.06	$0.39	$0.65	$0.31
	Hypalon (CSPE) or PIB	$3.50	$0.94	$0.31	$0.66	$0.38
4	Granule-Surf. SBS Pitch Multi Ply	$4.48	$1.19	$0.36	$0.68	
	Thermoplastic Polyolefin (TPO)	$3.24	$4.36	$0.24	$0.80	$0.37
	Ketone Ethylene Ester (KEE)	$3.48	$0.98	$0.58	$0.86	
5	Spray Urethane Foam - Coated	$3.12	$1.44	$0.68	$1.05	$0.42

Annual lifecycle values increased for all roof materials in 2005 from 1995. The lifecycle cost increases at the lower values were in line with the decreasing value of the dollar within that time frame. The lifecycle cost increases at the higher values were much more significant and could not be attributed solely to the decreasing value of the dollar during that time period (Cash, 2006).

For steep-sloped roofs, the annual lifecycle costs of the materials ranged from $0.21/SF to $0.82/SF, with SBS modified asphalt-glass shingles, asphalt-glass 3-tab strip shingles, and metal panels – copper being the materials with the lowest annual lifecycle costs. Clay tile and cedar shakes had the highest annual lifecycle costs amongst the steep-sloped materials in the survey (Cash, 2006). The results can be found in Table 2-4.

Table 2-4: Steep-Sloped Roofing Costs - $/Square Foot (Cash, 2006)

	2005 Survey			
Steep-Sloped Roofing System	Installed Cost	Disposal Cost	Maintenance Cost/Year	Life Cycle Cost/Year
SBS Modified Asphalt-Glass Shingles	$3.26	$0.98	$0.04	$0.21
Asphalt-Glass 3-Tab Strip Shingles	$2.13	$0.73	$0.07	$0.23
Metal Panels - Copper	$10.44	$0.66	$0.06	$0.25
Asphalt-Glass Laminated Shingles	$2.74	$0.75	$0.13	$0.27
Asphalt-Glass Interlocking Shingles	$2.06	$0.91	$0.14	$0.29
Asphalt-Organic 3-Tab Strip Shingles	$2.16	$0.74	$0.15	$0.31
Metal Panels - Galvalume	$7.73	$0.63	$0.04	$0.33
Metal Panels - Aluminum	$7.00	$0.76	$0.16	$0.39
Metal Panels - Terne	$11.60	$0.70	$0.15	$0.41
Metal Panels - Aluminized Steel	$6.82	$0.86	$0.20	$0.44
Metal Panels - Zinc	$13.20	$0.68	$0.14	$0.44
Metal Panels - Stainless Steel	$14.05	$0.73	$0.16	$0.44
Natural Slate	$13.91	$1.11	$0.26	$0.48
Concrete Tile	$7.59	$2.60	$0.24	$0.53
Rubber or Plastic Shingles	$9.08	$0.93	$0.10	$0.56
Metal Panels - Galvanize Steel	$8.37	$0.84	$0.21	$0.56
Clay Tile	$9.84	$1.35	$0.35	$0.58
Cedar Shakes or Shingles	$5.80	$1.09	$0.49	$0.82

Although the survey results showed little correlation between cost and the roof material category, what stands out in the study is that in almost every instance, the estimated durability values had increased for every roof material within the 10 years between the two surveys. This can most likely be attributed to improvements in technology within that timeframe, leading to longer lasting roofs. It can be expected that technology improvements have continued from the 2005 survey to today in 2020, which begs the question as to how single-ply materials, which previously ranked lowest in durability, compare to the durability of metal and built-up roofs today and how changes in lifespan can affect their lifecycle costs.

2.6.2 2015-2016 NRCA Market Survey

According to the NRCA, the 2015-2016 NRCA Market Survey "gives contractors an opportunity to provide feedback about the percentage of low- and steep-slope work performed for new construction, reroofing, and repair and maintenance during the year and includes the latest information about overall sales volume trends, roofing experiences, material usage and regional breakdowns" (NRCA, 2016). The data collected from the survey allows contractors to evaluate their own business practices and to serve as a point of comparison for material usage in regions throughout the United States. The survey was distributed to 2,300 NRCA member roofing contractors to which 155 responses were received back (a response rate of 6.7%). The responses received covered the entire United States, broken out into 10 geographic regions: New England, Mid-Atlantic, South Atlantic, East North Central, East South Central, West North Central, West South Central, Mountain, and Pacific.

In the survey, the participants were asked to report their sales volumes for 2015 and projected sales volumes for 2016 by roof material across the categories of new construction work, reroofing, and repair and maintenance work. The data from the responses was further grouped into low-slope and steep-slope roofing categories, with approximately 74% of the sales being for low sloped work and 26% of the sales for steep-sloped work. The results from the survey can be seen in Table 2-5.

Table 2-5: 2015-2016 NRCA Market Survey Results (NRCA, 2016)

2015 and Projected 2016 Low-Slope Sales by Roof System Type				
	2015		2016 (Projected)	
Material Type	New Construction	Reroofing	New Construction	Reroofing
BUR - Asphalt (Hot-Applied)	4.2%	7%	4%	8%
BUR - Coal Tar (Hot-Applied)	0%	0%	0%	0%
BUR - Cold Process	2%	2%	1%	1%
EPDM	22%	26%	23%	25%
PVC	12%	11%	11%	11%
TPO	40%	30%	40%	31%
Spray Polyurethane Foam	2%	5%	3%	5%
Metal Panel - Structural	1%	1%	1%	1%
Metal Panel - Architectural	3.4%	2%	3%	2%
APP Polymer-Modified Bitumen	3.2%	3%	3%	3%
SBS Polymer-Modified Bitumen	7.2%	9%	7%	9%
Self-Adhering Polymer-Modified Bitumen	2%	2%	2%	2%
Liquid Applied	1%	2%	1%	2%
Vegetative	0%	0%	1%	0%
2015 and Projected 2016 Steep-Slope Sales by Roof System Type				
	2015		**2016 (Projected)**	
Roof System Type	**New Construction**	**Reroofing**	**New Construction**	**Reroofing**
Asphalt Shingles	47%	59%	47%	59%
Clay Tile	4.3%	4.5%	3%	4.4%
Concrete Tile	3%	2.3%	4%	2.3%
Wood Shakes and Shingles	2.1%	2%	2%	2%
Slate	3.3%	5%	4%	5.1%
Metal Panel - Architectual	37.1%	23.2%	36%	23.2%
Metal Shingles	0%	0%	1%	1%
Spray Polyurethane Foam	2.2%	3%	2%	2%
Fiber-Cement/Synthetic	1%	1%	1%	1%
Vegetative	0%	0%	0%	0%

The results from the survey showed that for low-sloped roofs, single-ply roofing material made up the vast majority of roof sales with thermoplastic olefin (TPO) roofs leading at 40% of new construction work and 30% of reroof work in 2015. Ethylene propylene diene monomer (EPDM) roofs were second in sales at 22% for new construction and 26% for reroofing in 2015.

Polyvinyl chloride roofs were third at 12% for new construction and 11% for reroofing in 2015. The combined sales for built-up roofs (BUR) accounted for less than 12% of the total sales volume, which has shown a significant decrease from years past. The results for steep-sloped roofs showed asphalt shingles was the predominant material used with 47% of sales for new construction and 59% of sales for reroofing. Architectural metal followed with 37% for new construction and 23% for reroofing (NRCA, 2016).

The survey results for the geographic regions remained consistent with the national results with only a few deviations. The West South-Central Region, made up of the states of Arkansas, Louisiana, Oklahoma, and Texas, saw very little EPDM usage but instead had high sales of modified bitumen at 40% for new construction and 24.9% for reroofing. TPO was still a dominant material in this region making up 34% of sales for new construction and 43% of sales for reroofing. The Mountain and Pacific Regions saw higher sales for spray polyurethane foam, but still saw the highest sales volumes in single-ply roof materials. The geographic regions saw similar consistency with the steep-sloped roof results with asphalt shingles leading sales. The exception that stood out were the West North-Central region, consisting of Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, and South Dakota. The West North-Central region favored metal panel – architectural overall, with sales for new construction and reroofing at 89% and 41%, respectively (NRCA, 2016).

The results of the 2015-2016 NRCA Market Survey show an increasing trend in the use of single-ply roof materials for low-sloped roofs, especially the use of TPO materials. The results also indicate a decrease in the use of built-up roofs. This is most likely due to the lower cost of single-ply roofs in comparison to built-up roofs. Single-ply roofs require much less labor for installation, and they do not require installers to have experience working with torches or hot asphalt as is common with built-up roofs. The trend towards single-ply materials also suggests an increase in confidence in the durability of those materials. As technology improves over time, it can be expected that single-ply materials will become less prone to failure and experience longer lifespans. As it is common for mission-critical facilities to have low sloped roofs, the research team expects the trends from the NRCA survey to extend to mission-critical facilities.

2.7 Summary

Organizations have evolved to require functions that operate continuously 24/7 to be competitive in today's business environment. Interruptions to these operations have proven to be disastrous over the years, impacting the financial futures of the organizations who experience them. Organizations have responded by implementing infrastructure to support these critical operations and minimize the probability and impact of outages. The buildings housing these operations and infrastructure have come to be known as mission-critical facilities.

IT operations in particular carry with them a tremendous amount of risk relative to service interruption. In addition to selecting the appropriate network equipment and developing standards and processes to mitigate these risks, organizations have also identified the building infrastructure systems that are critical to sustaining IT operations. Power generation, HVAC, and fire life safety systems commonly fall under the critical infrastructure criteria for IT operations, and are addressed through disaster recovery plans, repair and maintenance programs, and the use of redundant systems in design and construction.

Roof systems, however, have not been assigned the same priority as other critical systems. This is unfortunate, as the intrusion of water into the network environment has proven to be the root cause for many network related outages. A limited amount of market studies have been conducted within the United States to evaluate various roof materials across all industry. The author of one such study suggested the notion of whether all roofing systems were perceived as equal – differing only in minor details (Cash, 2006).

Because little to no research has been conducted regarding roofs for mission-critical facilities, an evaluation of various roof types and their suitability for use with mission-critical facilities could be helpful to building owners and roofing professionals in selecting the most appropriate roofs for their projects in regard to both risk reduction and the maximizing of value.

3 METHODOLOGY

3.1 Introduction

This research evaluates various roof materials for use with different mission-critical facilities within the United States. The primary research objectives were to:

1) Determine the average annual lifecycle costs for the sampled roof materials.
2) Determine the roofing professionals' preferred mission-critical facility roof materials.
3) Priority rank the sampled roof materials for use with mission-critical facilities.

Of particular interest is to determine whether single-ply roof materials have advanced in technology to where their use with mission-critical facilities provide more value than the use of multi-layer built-up roofs.

In an attempt to address the research objectives as stated above, a mixed method methodology using both qualitative and quantitative approaches was selected for the data collection portion of the research (Creswell, 2017).

3.2 Setting

The research performed for this study took place across the United States. The location choice was suitable for various reasons including: Access to participants, variance in responses due to geographic market factors, as well as representation of responses from local, regional, and national industry professionals. This research was conducted through Brigham Young University located in Provo, Utah.

The methodology was staged in two parts. The first stage was a pilot study to test the effectiveness of a prototype survey amongst 3 industry subject matter experts. The subject matter experts evaluated the survey and provided feedback of changes to implement prior to the study being conducted with the larger population. After the pilot study was completed, the second stage of the methodology was a survey of roofing professionals across the United States. The survey compared different roofing materials against various mission-critical facility types to determine a weighting system and priority ranking of those materials for each building type.

3.3 Subjects & Participants

Three subject matter experts were selected for the pilot study to test the effectiveness of the prototype survey. Two of the experts worked for national roofing firms as a Director of Global Accounts and a Senior Project Manager, respectively. The third expert was the owner of a Utah based roofing company. All three of the subject matter experts had over 20 years of experience in the roofing industry.

For the survey stage of the research, the participants selected were employees of roofing contractor and roofing consultant companies across the United States. The professionals were selected based on their performing a mission-critical facility reroofing project for a leading information technology company, within the previous 10 years. The company selected has a real estate footprint of tens of millions of square feet over thousands of owned and leased properties across the United States. In order to bid on these projects, the roofing professionals had to meet stringent qualifications including history of past roofing projects, history of successful projects working with mission-critical facilities, minimum insurance requirements, adherence to the company's roof design standards, etc. The participant sample was not held to any geographic constraints within the United States; however, as part of the study, the roofing professionals would indicate which state(s) they service and/or whether they worked for a national provider. The participants were made up of company owners, administrators, project managers, and estimators with varying years of experience in the roofing industry.

3.4 Measurement Instruments

3.4.1 Pilot Study

To study the feasibility of obtaining lifecycle cost information and total value preference for various roof materials for use with mission-critical facilities, a pilot study was conducted to test the effectiveness of a prototype survey that would ultimately be distributed to roofing professionals across the United States. The three subject matter experts selected were chosen due to their experience and expertise in the roofing industry.

The roofing subject matter experts were invited to evaluate the prototype survey and provide their feedback for suggested changes prior to the survey being distributed to the sample population. The researcher contacted each participant by phone to obtain their commitment to participate in the pilot study. After each subject matter expert affirmed their participation in the positive, the researcher then sent a copy of the survey along with evaluation instructions via email. The participants were asked to respond back with their feedback within two weeks' time and were encouraged to complete the survey as an optional step. At the end of the two-week period, the researcher held a call with each subject matter expert individually and recorded their feedback remarks. The feedback collected from the pilot study was then used to modify the survey to be administered to the sample population.

3.4.2 The Survey

To study and evaluate various roof materials for use with mission-critical facilities, a survey was administered to roofing professionals across the United States. The survey asked for specific data points related to the lifecycle costs of roofing membrane materials, as well as a rating of those materials for suitability of use with various mission-critical facilities.

Survey participants consisted of current employees from active roofing contractor and roofing consultant companies. Survey respondents held various titles and responsibilities within their respective organizations. Each respondent was first contacted by phone where they were briefed on the study and asked to participate in completing the survey. Upon their acceptance, the participants were emailed the survey with completion instructions. Each participant was given two weeks to complete the survey from when the time they received it, after which they would email back the completed survey to the research team.

3.4.2.1 The Survey Instrument

The survey compared different roofing materials against various mission-critical facility types to determine a weighting system and priority ranking of those materials for each building type. The roof materials selected represented the most common low-sloped roof types being built-up roofs, modified bitumen, single-ply, and metal roofs. The roof materials were also similar to those evaluated in both the 2005 Roofing Industry Durability and Cost Survey and the 2015-2016 NRCA Market Survey, as described in the literature review. The roof materials being evaluated were as follows:

1) 4-Ply Built-Up Roof with Gravel
2) 2-Ply Modified Bitumen Hybrid with Single-Ply Cap Sheet
3) 3-Ply Built-Up Roof with Modified Cap Sheet

4) 2-Ply Modified Bitumen

5) 60 Mil EPDM Fully Adhered

6) 90 Mil EPDM Fully Adhered

7) 60 Mil TPO Fully Adhered

8) 80 Mil TPO Fully Adhered

9) 50 Mil XT KEE Fully Adhered

10) 60 Mil KEE PVC Fully Adhered

11) 80 Mil PVC Fully Adhered

12) Metal 24-Gauge Minimum

The building types used for the evaluation were as follows:

1) Administrative Buildings – Administrative buildings support office work of an administrative nature. They contain finished interiors with constructed walled interior rooms or open workstation-style seating. Administrative buildings are finished with carpet or tile, finished or drop ceilings, lighting, minimal power/HVAC load, and office automation located throughout.

2) Central Office – Central offices are buildings of any size which contain network switching equipment that connect end users to each other, both locally and via long distance carriers. Central offices contain the inside plant elements required for these functions, such as distribution frames and interoffice facility termination points. These buildings may have a combination of industrial concrete or tiled floors with other finished areas and potential high-demand for power/HVAC.

3) Data Center/Data Processing Facility – Data Centers are large facilities containing the equipment required to manage Internet Hosting/Network Services of external

customers. Data Processing facilities are buildings whose primary function is to contain data processing equipment to provide critical services to internal and external customers. Both are extremely high-demand power/HVAC and mission-critical.

4) Equipment Building – An equipment building is generally an un-staffed structure, which contains telephone equipment but excludes a switch (i.e., repeater huts, radio equipment, fiber terminals, SLC 96 huts, ROW). Equipment buildings will generally have industrial flooring with moderate power/HVAC requirements.
5) Storage Building- Storage buildings are buildings or sheds in which the majority of space is used for equipment and supply storage. These buildings have industrial furnishings throughout, concrete or tile flooring, and unfinished walls and/or ceilings. Storage buildings are secured and monitored to prevent pilferage. They have minimal power/HVAC requirements.
6) Warehouse – Warehouses are buildings whose primary use is storage and handling of inventory and supplies. These buildings are built specifically for that purpose, and may include such things as high shelving, conveyor systems, and loading docks. They may also contain office space. Warehouses typically have industrial furnishings throughout, concrete flooring, unfinished walls and/or ceilings. Warehouses have moderate power/HVAC requirements to keep contents climate controlled.
7) Garage – Garages are buildings which house repair, installation, maintenance, and/or engineering crews and/or their vehicles, tools, supplies and other storage as may be required. These properties also may include crew rooms and some administrative space. They typically contain industrial furnishings throughout with concrete floors. Garages have minimal power/HVAC requirements.

Central office, data center/data processing facilities, and equipment buildings were identified to be the mission-critical building types for this study, as these facilities house mission-critical IT operations. Administrative buildings, storage buildings, warehouses, and garages were identified to be non-mission-critical for this study. The comparison would help distinguish between vendor roofing preferences for mission-critical facilities versus standard commercial applications.

The survey was divided into two parts. The first part measured the annual lifecycle cost of each standalone roofing material. The variables measured for each material included:

1) Lifespan of roof materials in years
2) Installation cost per SQFT
3) Removal cost per SQFT
4) Annual maintenance cost per SQFT

The participants were asked to populate each data field with current market estimates.

The second part of the survey asked the roofing professionals to rate the various roofing materials, taking into account total value (cost, lifespan, and risk), for use with each building type. The ratings selections were as follows:

1) Best
2) Good
3) Acceptable
4) Minimally Acceptable
5) Not Recommended

The complete survey can be found in Appendix B.

4 FINDINGS

4.1 Research Overview

This chapter presents the findings from the research which was staged in two parts; a pilot study followed by a survey. The pilot study was conducted from October 2018 through March 2019. The pilot study involved sending three industry subject matter experts a sample of the survey instrument for their evaluation and feedback. The feedback received was then used to modify the survey instrument for use in the main portion of the study.

Following the pilot study, the survey was administered to roofing professionals across the United States. The researcher contacted the participants by phone and then sent the survey by email to 46 roofing firms. 17 responses were delivered back to the research team. The content of the responses was analyzed and categorized for this research.

4.2 Pilot Study Results

The three subject matter experts were emailed the draft sample survey in Excel format (Appendix A) on October 19, 2018. They were asked to review the sample survey and provide any feedback or suggested changes prior to the survey being administered to the sample population. The subject matter experts were informed that a follow up interview would be scheduled with each one of them to review the feedback that had been recorded for the survey. The sample survey format can be seen in Figure 4-1.

Facility Type	4-Ply BUR w/gravel		
Administrative *Building that supports office work of an administrative nature. Finished interiors with constructed walled interior rooms or open workstation-style seating. Finished with carpet or tile, finished or drop ceilings, lighting, minimal power/HVAC load, office automation located throughout.*	RANKING	LIFESPAN/YRS	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	RATE OF INCIDENCE (#/LIFESPAN)

Figure 4-1: Sample Survey Format Used in Pilot Study

The following interviews were conducted either in person or by phone in the researcher's office. The feedback from the interviews was recorded and was later analyzed and compared to modify the sample survey prior to it being distributed to the sample population. The subject matter experts were given the same version of the sample survey, and no modifications were made to the survey until all three interviews had taken place.

4.2.1 Interview 1

The first subject matter expert was interviewed by phone on November 12, 2018. The purpose of the interview was to receive feedback on the effectiveness of the draft survey prior to it being distributed to the main population of the study. Throughout the interview, the researcher also requested suggestions for modifications to the survey. The feedback and modification suggestions were recorded to later be compared with the responses of the other subject matter experts participating in the pilot study. The interview lasted approximately 60 minutes. The main points the subject matter expert provided as feedback were as follows:

1) Reduce the number of data entry fields – The subject matter expert commented that the survey contained too many data fields to fill out which would be overly time consuming and a burden for those completing the survey. Upon review, the researcher and subject matter expert counted 576 data fields within the draft survey, not including the participant self-identify information fields. The subject matter expert suggested splitting the survey up into two parts to consolidate answers where they would remain consistent across categories (i.e. Cost data would remain relatively consistent regardless of the building type applied).
2) Ranking portion of the survey ineffective – The sample survey asked the participants to rank each roof material selection by suitability for use with each building type. The subject matter expert explained that with 13 roofing materials to evaluate, the ranking portion of the study would be difficult to assess accurately and would ultimately be ineffective. Choosing to rank one material over another at times would simply be a guess from the participant as the materials in question would perform in a similar fashion for the specified application. The subject matter expert did see value in the participants providing their opinion regarding total value of the materials selected, but they did not suggest an alternative method to the ranking field.
3) Remove "Rate of Incidence" field – The sample survey included a field where the participants were asked to estimate the number of roof leak/failure incidences throughout the lifespan of the roof material selection. The subject matter expert commented that it would be nearly impossible to estimate the occurrence of roof incidences for each roof material. Roof incidences could be attributed to external factors outside of the selected roof material such as the roof design, the installation of

the roof, and regular maintenance. The subject matter expert suggested removing the "Rate of Incidence" field as most participants would simply be submitting a guess for their response.

4) Adjust thicknesses of single-ply membranes – The subject matter expert noted that the survey contained various thicknesses of single-ply membranes. They explained that the industry norm was to select either a 60 mil or 90 mil thickness for EPDM membranes and to select either a 60 mil or 80 mil thickness for TPO and PVC membranes. The 72 mil thickness for single-ply membranes that was included in the sample survey, was no longer commonly used in the industry. The exception to this was the KEE XT material which was commonly used at a 50 mil thickness. The subject matter expert suggesting changing the thicknesses of the single-ply membranes to match the industry norms and to remove the 72 mm option.
5) Remove ballasted options for single-ply membranes – The subject matter expert noted that there were ballasted options for two of the roofing materials. They suggested removing the ballasted options for several reasons: It was inconsistent with the other selected materials on the survey, it would skew the costs higher for the materials with that option, and the expert generally recommended against choosing ballasted roofs for any application as they are difficult to maintain and repair.
6) Remove "4-Ply BUR w/ gravel" selection – The subject matter expert stated that the "4-Plu BUR w /gravel" selection was too similar to the "3-Ply BUR w/ Modified Cap" selection, as the modified cap sheet served as a fourth layer to the membrane. They also reiterated their previous comments in regard to ballasted roofs and explained that roofs with gravel are subject to all of the same disadvantages as ballasted roofs. Their

suggestion was to remove the “4-Ply BUR w/ gravel” selection and to keep the “3-Ply BUR w/ Modified” selection.

7) Provide an alternative KEE containing material – The subject matter expert noted the “50 Mil XT KEE” selection in the sample survey and explained that the XT KEE material was a very good product but was proprietary to one roofing manufacturer. They further explained that other KEE materials were not proprietary. The subject matter expert suggested keeping the “50 Mil XT KEE” selection but also adding a KEE PVC material to the list of selections as a comparison.
8) Remove high slope roof material selections – The subject matter expert noted that all of the roof material selections with the exception of “Fiberglass Asphalt or Concrete Shingle/Tile” were common to low slope roof applications. The latter was common to high slope roof applications. To keep the study consistent and focused, the subject matter expert suggested removing the “Fiberglass Asphalt or Concrete Shingle/Tile” selection from the survey.
9) Provide basic assumptions/conditions for install, removal, and annual maintenance – To reduce the variance in lifecycle cost responses, the subject matter expert suggested providing basic assumptions for the install of the roof. Specifically, they recommended the following basic assumptions: Assume normal roof access, 2 inches of insulation on an existing concrete deck, and a normal amount of roof penetrations.

4.2.2 Interview 2

The second subject matter expert was interviewed in person on December 13, 2018. The purpose of the interview was to receive feedback on the effectiveness of the draft survey prior to it being distributed to the main population of the study. Throughout the interview, the researcher also requested suggestions for modifications to the survey. The feedback and modification suggestions were recorded to later be compared with the responses of the other subject matter experts participating in the pilot study. The interview lasted approximately 60 minutes. The main points the subject matter expert provided as feedback were as follows:

1) Reduce the number of data entry fields – Similar to the first interview, the subject matter expert noted that the survey contained too many data fields to fill out and would be overly time consuming and a burden for those completing the survey. The subject matter expert suggested grouping the roof materials into smaller groups per applicable building type.
2) 4-ply and 3-ply built-up roofs are similar – The subject matter expert commented that the "4-Ply BUR w/ gravel" and "3-Ply BUR w/ Modified Cap" selections were very similar due to the fact that the modified cap sheet on the 3-Ply built-up roof acts as a fourth layer. They did comment that the "4-Ply BUR w/ gravel" was the most resilient roof on the selection list.
3) Adjust thicknesses of single-ply membranes – The subject matter expert had similar comments to that of the first interview in regard to the varying thicknesses of the single-ply membrane selections. They suggested that the EPDM selections should have thicknesses of 60 mil and 90 mil, the TPO and PVC selections should have thicknesses of 60 mil and 80 mil, and the XT KEE selection should remain at 50 mil.
4) Specify whether EPDM selections are fully adhered or mechanically fastened – The subject matter expert indicated that the installation method for EPDM would significantly alter the lifecycle cost responses. For the purposes of this study, they recommended evaluating the EPDM roofs as fully adhered only.

5) Utilize KEE in PVC selections – The subject matter noted the XT KEE material and explained that it was a proprietary roofing material exclusive to one manufacturer. They further explained that KEE was a material used in PVC roofs to add pliability to the PVC membrane. Although they had a high opinion of the XT KEE material, they recommended adding a KEE option to the 60 mil PVC selection for comparison and for good practice in selecting that PVC at that thickness.
6) Remove ballasted options for single-ply membranes – The subject matter expert recommended against using ballasted roofs in practice, as they are high in cost to install due to the labor and transport required to add the rocks to the roof surface. The expert also mentioned the difficulty in locating and repairing leaks on ballasted roofs.
7) Provide basic assumptions/conditions for install, removal – The subject matter expert stated the importance of providing basic assumptions to reduce the variance in lifecycle cost responses associated with the roof installation and removal. The subject matter expert recommended the following assumptions for the roof installation field: Good roof access, two layers of insulation (R25), basic sheet metal, and normal quantity of roof penetrations. They recommended the following assumptions for the roof removal field: Good roof access, two layers of insulation (R25), and no modifications to deck.
8) Remove “Annual Maintenance” data field – The subject matter expert stated that the maintenance costs would not vary from material to material and would especially not vary amongst material sections applied to different building types. They recommend removing the “Annual Maintenance” data field from the survey.
9) Have participants rank the top six roof materials for each building type – The subject matter expert found little value in ranking 13 different roof materials against each

building type. They commented that it would be difficult at times to rank one roof material over another for a given building, as many of the roof selections available would perform similarly. The subject matter expert suggested having the participants list and rank their top 6 roof materials per building type.

4.2.3 Interview 3

The third subject matter expert was interviewed by phone on March 5, 2019. The purpose of the interview was to receive feedback on the effectiveness of the draft survey prior to it being distributed to the main population of the study. Throughout the interview, the researcher also requested suggestions for modifications to the survey. The feedback and modification suggestions were recorded to later be compared with the responses of the other subject matter experts participating in the pilot study. The interview lasted approximately 45 minutes. The main points the subject matter expert provided as feedback were as follows:

1) Apply a Freeze Frame to the Survey Instrument – The subject matter expert suggested adding a freeze frame to the electronic survey instrument. With the large number of data fields requesting information, this would make it easier for the participants to navigate the survey instrument while adding their responses.
2) Remove Ballasted Selections – The subject matter expert questioned the inclusion of ballasted roof selections in the survey. They emphasized the cost premiums associated with installing a ballasted roof and the negative aspects of maintaining and repairing those roofs. The subject matter expert suggesting removing all ballasted selections from the survey including the "4-Ply BUR w/ gravel" selection.
3) Adjust Thicknesses of Single-Ply Membranes – The subject matter expert noted the inconsistent thicknesses between the single-ply membrane selections. They suggested

removing the 75 mil option as it was no longer commonly used and defaulting all the single-ply selections to 60 mil and 90 mil options.

4) EPDM Fully Adhered – Following the recommendation of removing all ballasted options, the subject matter expert recommended specifying that the EPDM roof selection would maintain itself as fully adhered.

5) Adjust 4-Ply Roof Selection – The subject matter expert suggested modifying the 4-ply selection to a "4-Ply BUR w/ Modified Cap". This selection would differentiate itself from the "3-Ply BUR w/ Modified Cap" as the most robust selection on the survey.

4.2.4 Pilot Study Implementation

After analyzing and comparing the feedback received from the three pilot study interviews, the research team implemented the following modifications to the survey prior to it being administered to the sample population:

1) Survey Divided into Two Parts – Unanimous feedback from the pilot study indicated that there were too many data fields to complete in the sample survey. This would cause the survey instrument to be burdensome and overly time consuming to the participants, leading to the possibility of a low response rate. The research team also received feedback from the subject matter experts that the lifecycle cost data for the roofing materials would not vary widely among the different building types. Taking the pilot study feedback into consideration, the research team decided to split the survey into two parts. The first part of the survey would obtain the lifecycle cost information for each roof material selection regardless of building types. The following fields were used to capture the lifecycle cost data for each roof material selection: "Lifespan/Yrs", "Costs/SF Install", "Costs/SF Removal", and "Costs/SF Annual Maint".

The second part of the survey was focused on evaluating the participant's preference of the roofing material selections for use with different building types by perceived total value. Each roof material selection was plotted against the different building types with a field to select a rating for each application. The five ratings to choose from were as follows: Best, Good, Acceptable, Minimally Acceptable, and Not Recommended. By splitting the survey into two focused parts, the research team was able to reduce the number of data fields from 576 fields from the sample survey to 132 fields in the final survey, not including the participant self-identify information fields.

2) Basic Assumptions Added to Instructions – Two of the subject matter experts had suggested adding basic assumptions to the survey to minimize the variance of lifecycle cost responses. The research team added the basic assumptions to the Instructions tab of the survey for "Costs/SF Install", "Costs/SF Removal", and "Costs/SF Annual Maint". The assumptions provided for the respective fields were as follows: "Costs/SF Install" – Assume the following: 1) Good roof access, 2) Two layers of insulation (R25), 3) Basic sheet metal, 4) Normal quantity of roof penetrations.

   "Costs/SF Removal" – Assume the following: 1) Good roof access, 2) Two layers of roof insulation (R25), 3) No modifications to deck.

   "Costs/SF Annual Maint" – Assume the following: 1) Good roof access, 2) Two layers of insulation (R25), 3) Basic sheet metal, 4) Normal quantity of roof penetrations.

3) Ranking of Materials Replaced with Rating – The research team reviewed the feedback from the pilot study to alter the ranking method within the survey. The pilot study interviews indicated that it would be difficult to rank 13 different roof material selections for use with a given building type, as some roof material selections would

perform similarly when applied to the same building type. The research team modified the survey to change the ranking field to a rating field with five different rating choices. The five ratings to choose from were as follows: Best, Good, Acceptable, Minimally Acceptable, and Not Recommended.

4) "Rate of Incidence" Field Removed – The feedback received from two of the subject matter experts indicated that the responses received for the "Rate of Incidence" field would be unreliable as different external factors (Design, install, maintenance, etc.) could significantly affect the rate at which a roof could experience leaks or failures. The research team removed the "Rate of Incidence" field from the survey.
5) Ballasted Single-Ply Selections Removed – All three subject matter experts suggested removing any ballasted options for single-ply membrane roof selections. This would help to establish consistency across responses, especially in terms of lifecycle cost. The research team removed ballasted single-ply selections from the survey.
6) Single-Ply Thicknesses Adjusted – The feedback from the survey suggested a need to standardize the thicknesses of the single-ply roof selections to current industry standards. The research team modified the survey to include a 60 and 90 mil options for EPDM selections, and 60 and 80 mil options for TPO and PVC selections. The 50 mil option was kept for the XT KEE roof selection. All 75 mil options for single-ply roofs were removed from the survey.
7) KEE PVC Material Added – Two of the subject matter experts suggested adding an alternate KEE material to the existing XT KEE selection. One suggestion in particular was to modify the lower thickness PVC roof to include KEE within it. The research team removed the "75 Mil PVC" selection and added a "60 Mil KEE PVC" selection

8) High Slope Roof Materials Removed – The “Fiberglass Asphalt or Concrete Shingle, Tile” selection was removed from the survey, as that material is primarily used for high slope roof applications, and all of the other roof selections on the survey were for low slope applications.
9) Freeze Frame Applied – A freeze frame was added to the electronic survey instrument to increase ease of use for the participants.
10) Self-Identify Information Fields Added to Instructions Tab – Self-Identify Information fields were added to the Instructions tab of the survey so that the research team could better track the responses received by the participants. The added fields were as follows: Name, Company Name, Phone, Supplier Type, States or Regions Served (Enter NATIONWIDE if applicable), and Comments.

The Sample Survey and Final Survey drafts from the pilot study can be found in Appendix A and Appendix B, respectively.

4.3 Survey Participants

The research team contacted each organization by phone to explain the study and to obtain a verbal commitment from the roofing professionals to participate in the survey. The research team obtained 46 verbal commitments. The research team drafted an email containing an attachment of the survey in Excel file format as well as basic instructions on how to complete the survey. The participants were to return the completed survey within two weeks from receipt of the email. The final survey format can be seen in Figure 4-2.

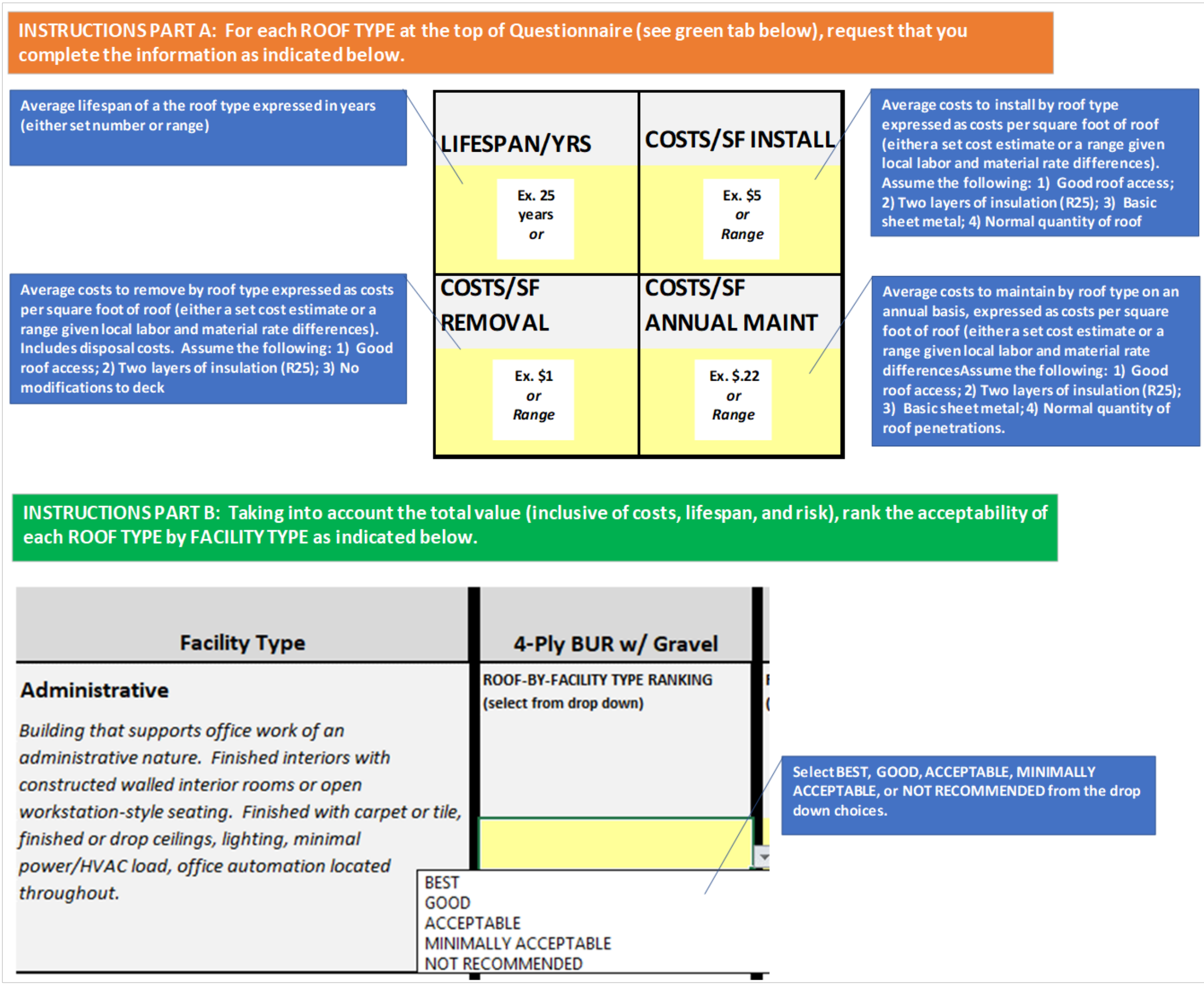

Figure 4-2: Final Survey Format Used in Data Collection

The emails were sent out to the participants on June 21, 2019. The research team reached out to the participants to encourage completion and return of the survey. Throughout the sampling period, 17 responses were received in total, with the last response being received on July 22, 2019. The research team concluded the sampling period August 23, 2019. The respondent population had good representation across the United States. In addition to the state/region specific providers, there were 4 nationwide providers who responded to the survey. The geographic coverage of the respondents can be found in Table 4-1.

Table 4-1: Geographic Coverage of Respondents

Respondent	Geographic Service Area
1	No Response
2	CO
3	US Central, US West, US Midatlantic
4	No Response
5	WI, MN, IA
6	Nationwide
7	UT, WY, ID
8	No Response
9	Nationwide
10	WA
11	Nationwide
12	AR, AZ, CO, CT, DC, GA, IA, IN, KS, KY, MD, MI, MO, NC, NE, NJ, NY, OH, OK, PA, TN, TX, UT, VA, VT, WA, WI, WY
13	US Central, US Midwest
14	AZ, NV, NM
15	No Response
16	Nationwide
17	US West, US Midatlantic

The research team also contacted five US roofing manufacturers to obtain lifespan estimates of the sampled roof materials. The manufacturers did not provide specific lifespan estimates for the roof materials; however, they communicated that 20- and 30-year warranties were available for all of the sampled materials as long as the warranty requirements were met throughout the life of the roof. By meeting the design, installation, and maintenance requirements, the manufacturers estimated that the roofing material lifespans should exceed the specified warranty periods. Upon conclusion of the study, the research team noted that several roof material selections were estimated by the roofing professionals to have lifespans less than what is available for warranty by the roofing manufacturers.

4.4 Survey Results

The research team compiled all of the surveys received into one spreadsheet tool. A program was embedded into the spreadsheet tool to take the responses from each survey and average them together. The survey results were divided into two parts. Part A contained the average annual lifecycle cost data for each roof material selection. Part B measured the ratings assigned by the roofing professionals to each roof material selection for use with the different building types. The survey results from Part A and Part B were first analyzed independently. Following that, the research team then combined the two data sets to record any trends observed. A sensitivity test was applied by assigning a score to the lifecycle cost values of each roof material selection. The lifecycle cost scores and roof rating scores were then weighted at different intervals to observe their effects on the suitability of each material for use with mission-critical facilities. The averaged survey results can be found in Appendix C.

4.4.1 Part A: Lifecycle Cost Analysis

Part A of the survey results measured the lifecycle cost data for each roof material selection. The data fields captured in Part A were: “Lifespan/Years”, “Costs/SqFt Install”, “Costs/SqFt Removal”, and “Costs/SqFt Annual Maintenance”. The averages for each data field were tabulated and combined to determine the total lifecycle cost for each roof material selection. The total lifecycle cost was determined by multiplying the annual maintenance costs of each roof material selection by its estimated lifespan in years, and then adding it to its install and removal costs. The total lifecycle costs were then divided by the estimated lifespan in years to determine the annual lifecycle cycle costs as shown in Table 4-2.

Table 4-2: Annual Lifecycle Costs of Roof Materials

Roof Material	Lifespan (Yrs)	Costs/SF				
		Install	Removal	Annual Maintenance	Life Cycle	Annual Life Cycle Cost
50 Mil XT KEE	19.9	$12.04	$3.09	$0.14	$17.89	$0.899
80 Mil PVC	22.8	$13.47	$3.05	$0.20	$20.97	$0.919
Metal 24 Ga Minimun	31.6	$17.95	$3.95	$0.23	$29.07	$0.920
60 Mil KEE PVC	20.6	$12.80	$2.89	$0.19	$19.59	$0.949
90 Mil EPDM	22.9	$14.15	$2.94	$0.20	$21.77	$0.952
80 Mil TPO	21.0	$13.25	$3.14	$0.17	$20.02	$0.954
60 Mil EPDM	18.8	$11.66	$2.97	$0.20	$18.30	$0.974
4-Ply BUR w/Gravel	25.7	$16.36	$3.77	$0.20	$25.27	$0.982
2-Ply Mod Bit w/Cap	23.2	$15.60	$3.29	$0.18	$23.04	$0.992
3-Ply BUR w/Cap	24.4	$16.89	$3.57	$0.16	$24.35	$1.000
60 Mil TPO	17.2	$11.70	$3.00	$0.19	$18.01	$1.047
2-Ply Mod Bitumen	20.3	$14.75	$3.42	$0.20	$22.15	$1.090

The roof material selections were divided into three categories: Built-up roofs, single-ply roofs, and a metal roof. The metal roof selection was used as a control to compare against the other two roof types. The roof material selections were grouped into each category as follows:

Built-Up Roofs

- 4-Ply Built-Up Roof with Gravel
- 2-Ply Modified Bitumen Hybrid with Single-Ply Cap Sheet
- 3-Ply Built-Up Roof with Modified Cap Sheet
- 2-Ply Modified Bitumen

Single-Ply Roofs

- 60 Mil EPDM Fully Adhered
- 90 Mil EPDM Fully Adhered
- 60 Mil TPO Fully Adhered
- 80 Mil TPO Fully Adhered

- 50 Mil XT KEE Fully Adhered
- 60 Mil KEE PVC Fully Adhered
- 80 Mil PVC Fully Adhered

Metal Roof

- Metal 24-Gauge Minimum

The annual lifecycle cost data followed a normal distribution and ranged from $0.899/SF to $1.090/SF. The mean value was $0.973/SF, and the median value was $0.964/SF. The range of values was $0.191/SF. The research team observed that the single-ply roof materials were lower overall in annual lifecycle cost in comparison to the built-up roof options with 50 Mil XT KEE as the lowest annual lifecycle cost of $0.899/SF. The exception to this was 60 Mil TPO, which ranked as the second highest annual lifecycle cost at $1.090/SF. This can be attributed to 60 Mil TPO having the shortest estimated lifespan at 17.2 years. Although the built-up roofs had estimated lifespans slightly exceeding their single-ply counterparts, the high cost of install for built-up roofs negated the efficiency provided by their durability. The selection with the lowest annual lifecycle cost was 2-Ply Modified Bitumen at $1.090/SF. The metal roof had the third lowest annual lifecycle cost of $0.920 despite having the highest install, removal, and total lifecycle cost which were outliers in the dataset. The metal roof's total lifecycle cost of $29.07/SF was offset by its estimated lifespan of 31.6 years which was also an outlier. The research team noted the range of $0.191/SF represented a relatively small range at only a 21.2% cost increase impact when selecting between the selection with the highest annual cost vs the selection with the lowest annual cost. This can be contrasted with the total lifecycle cost range of $11.18/SF, representing itself as a 62.5% cost increase from the lowest to highest cost roof selection. The range for total lifecycle costs was much more dramatic, with the potential of leading project stakeholders to only focus on the upfront costs of a roof material, as opposed to recognizing the costs of the roof material throughout its useful life. This example emphasizes the importance of factoring in the estimated lifespan into the lifecycle cost analysis to gain better insight when selecting the appropriate roof material for a project.

4.4.2 Part B: Roof Material Rating by Building Type

Part B of the survey asked the participants to provide a rating for each roof material selection for use with both mission-critical and non-mission-critical buildings. The participants were instructed to rate the acceptability of each roof type by facility type, taking into consideration total value inclusive of costs, lifespan, and risk. The participants could choose one of 5 ratings for each roof material application. The ratings to choose from in the survey were: "Excellent", "Good", "Acceptable", "Minimally Acceptable", and "Not Recommended". The facilities assessed in this study were grouped into mission-critical facilities and non-mission critical facilities as follows:

Mission-Critical Facilities

- Central Offices
- Data Center/Data Processing Facilities
- Equipment Buildings

Non-Mission-Critical Facilities

- Administrative Buildings
- Storage Buildings
- Warehouses
- Garages

4.4.3 Roof Ratings for Mission-Critical Facilities

The research team first analyzed the results of Part B by facility group, starting with the mission-critical facilities. Each rating was assigned a numerical value from 1-5: 1 – Not Recommended, 2 – Minimally Acceptable, 3 – Acceptable, 4 – Good, 5 – Excellent. The roof material ratings were tabulated and sorted by the average rating across the three building types as shown in Table 4-3.

Table 4-3: Roof Rating by Mission-Critical Facility Type

Roof Material	Central Office	Data Center	Equip	Mission-Critical
3-Ply BUR w/Cap	4.4	4.2	4.3	**4.3**
4-Ply BUR w/Gravel	3.9	3.7	3.8	**3.8**
2-Ply Mod Bit w/Cap	3.1	3.1	3.2	**3.1**
Metal 24 Ga Minimun	3.1	2.8	3.0	**2.9**
90 Mil EPDM	2.9	2.9	2.9	**2.9**
2-Ply Mod Bitumen	2.8	2.6	2.9	**2.8**
80 Mil PVC	2.6	2.4	2.3	**2.5**
60 Mil KEE PVC	2.5	2.1	2.5	**2.4**
80 Mil TPO	2.1	2.2	2.3	**2.2**
60 Mil EPDM	2.1	2.1	2.4	**2.2**
50 Mil XT KEE	2.1	2.0	2.1	**2.0**
60 Mil TPO	1.6	1.5	1.9	**1.7**

The roof ratings data for mission-critical facilities followed a normal distribution and ranged from a rating of 1.7, between Not Recommended and Minimally Acceptable, to a rating of 4.3, between Excellent and Good. The range and distribution of the ratings suggests that the roofing professionals were able to differentiate the roofing material selections by total value and provide a preference of the material selections for use with mission-critical facilities. The mean rating value was 2.7, between Acceptable and Minimally Acceptable, and the median value was 2.6, between Acceptable and Minimally Acceptable. The results can be seen in Figure 4-3.

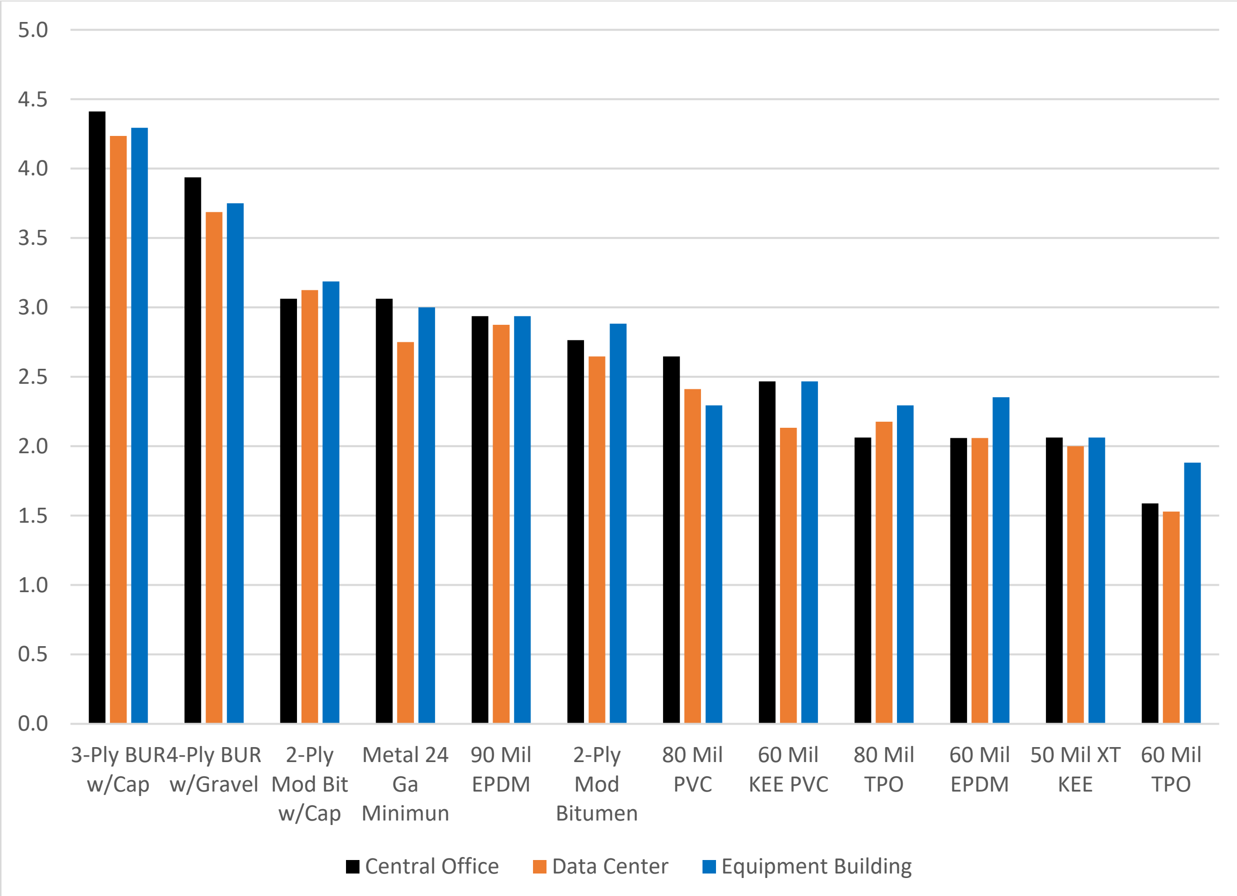

Figure 4-3: Roof Rating Comparison by Mission-Critical Facility Type

The research team observed that for the mission-critical facilities, the participants rated the built-up and metal roofs higher overall than the single-ply selections. The sole exception to this was the 90 Mil EPDM Fully Adhered selection which rated higher than the 2-Ply Modified Bitumen selection. The 3-Ply Built-Up Roof with Modified Cap Sheet rated the highest among the built-up roofs, with an average score of 4.3 or between the ratings of Excellent and Good. The 2-Ply Modified Bitumen selection rated the lowest among the built-up roofs, with an average score of 2.8 or between Acceptable and Minimally Acceptable. The 90 Mil EPDM Fully Adhered selection rated the highest among the single-ply roofs, with an average rating of 2.9 or between Acceptable and Minimally Acceptable. The 60 Mil TPO Fully Adhered selection rated the lowest overall with an average score of 1.7 or between Minimally Acceptable and Not Recommended. The Metal 24-Gauge Minimum selection rated fourth overall, with an average score of 2.9 or between Acceptable and Minimally Acceptable. The research team further examined the results across each individual mission-critical building type to validate consistency across the mission-critical building group. The results were consistent between the building types of central office, data center, and equipment building, with the roofing professionals rating the built-up, metal and the 90 Mil EPDM roofs highest, and the remaining single-ply roofs receiving the lowest ratings across the three building types.

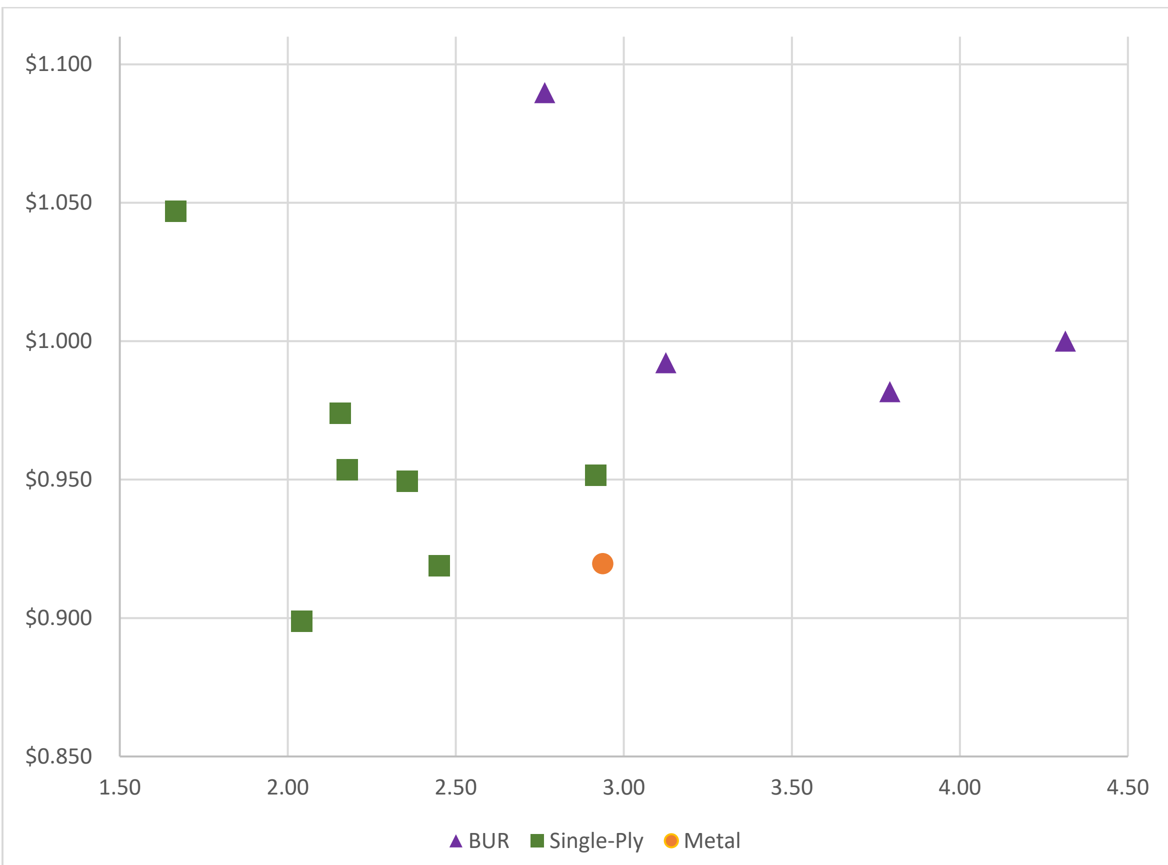

Figure 4-4: Rating and Cost for Mission-Critical Facilities

The research team plotted the annual lifecycle costs of each roof material selection against the average Roof-by-Facility Type ratings for mission-critical facilities as shown in Figure 4-4. For mission-critical facilities, the research team did not observe a correlation between the ratings scores and the annual lifecycle costs. The results showed similar ratings among low and high cost roof material selections. The ratings were much closer aligned to which roof material group (built-up roof (BUR), single-ply, and metal) the material selection belonged to, with the built-up roofs being rated higher than single-ply roofs and the metal roof rating in the middle for mission-critical facilities. This can be observed by the separation of the material types in Figure 4-4, with the different materials of the same type clustering together in rating, independent of cost.

The research team observed that for mission-critical facilities, the participants weighted risk higher than costs and lifespan while assigning their total value ratings to the various roofing materials. This is supported by the results found in Part A where the single-ply roofs were found to be consistently lower in cost than the built-up and metal selections. The research team attributed the overweighting of risk to the participants' understanding of the critical nature of the operations occurring within those facilities. Each participant had experience performing projects for mission-critical facilities and understood that a failure as a result of the roofing project could carry an impact far greater than savings achieved from the project. The overweighting of risk in consideration of mission-critical facilities produced results with the most robust roofing options rating as the highest. The EPDM selection was the only single-ply option that rated higher than a built-up option, however it was the thickest selection within the single-ply group. The Metal 24-Gauge Minimum and 90 Mil EPDM roofs which rated fourth and fifth respectively for mission-critical facilities were among the lower cost options from the lifecycle analysis results, with lower annual lifecycle costs than any of the built-up roof selections.

4.4.4 Roof Ratings for Non-Mission-Critical Facilities

The research team analyzed the ratings from the non-mission critical facilities using the same numerical scores (1-5) assigned to each rating. The roof material ratings for the non-mission critical facilities were tabulated and sorted by the average rating across the four building types as shown in Table 4-4.

Table 4-4: Roof Rating by Non-Mission-Critical Facility Type

Roof Material	Admin	Storage	Warehouse	Garage	Non-Mission-Critical
60 Mil KEE PVC	3.7	3.9	3.9	3.9	**3.9**
Metal 24 Ga Minimun	3.6	4.3	3.8	3.9	**3.9**
80 Mil PVC	3.6	3.6	3.6	3.6	**3.6**
80 Mil TPO	3.4	3.4	3.5	3.6	**3.5**
90 Mil EPDM	3.5	3.3	3.5	3.4	**3.4**
60 Mil EPDM	3.2	3.4	3.5	3.2	**3.4**
60 Mil TPO	2.9	3.4	3.4	3.4	**3.3**
50 Mil XT KEE	3.0	3.1	3.3	3.2	**3.1**
2-Ply Mod Bitumen	3.1	3.1	2.9	2.9	**3.0**
3-Ply BUR w/Cap	3.6	2.4	2.4	2.6	**2.8**
4-Ply BUR w/Gravel	3.1	2.4	2.3	2.4	**2.5**
2-Ply Mod Bit w/Cap	2.8	2.4	2.1	2.3	**2.4**

The roof ratings data for non-mission-critical facilities followed a normal distribution and ranged from a rating of 2.4, between Minimally Acceptable and Acceptable, to a rating of 3.9, between Good and Acceptable. The mean value was 3.2, between Good and Acceptable, and the median value was 3.3, between Good and Acceptable. The range of ratings for non-mission-critical facilities was smaller than the range for mission-critical facilities. This highlights a shift in the roofing professionals' prioritization away from risk for non-mission-critical facilities, as more of the roof selections could be interchanged. This is further highlighted as none of the roof material selections received a rating between 4 and 5 (Good to Best) or between 2 and 1

(Minimally Acceptable to Not Recommended) suggesting that more roof material selections would be appropriate for use with non-mission-critical facilities than with mission-critical facilities. This suggests that the roofing professionals surveyed view the operations housed in non-mission-critical facilities as more tolerant in the event of a roof failure. The research team observed that for non-mission-critical facilities, the participants rated the single-ply and metal roofs higher overall than the built-up roof selections. The 60 Mil KEE PVC Fully Adhered rated the highest among the single-ply roofs, with an average score of 3.9 or between the ratings of Good and Acceptable. The 50 Mil XT KEE Fully Adhered selection rated the lowest among the single-ply roofs, with an average score of 3.1 or between Good and Acceptable. The 2-Ply Modified Bitumen selection rated the highest among the built-up roofs, with an average rating of 3.0 or a rating of Acceptable. The 2-Ply Modified Bitumen Hybrid with Single-Ply Cap Sheet selection rated the lowest overall with an average score of 2.4 or between Acceptable and Minimally Acceptable. The Metal 24-Gauge Minimum selection rated second overall, with an average score of 3.9 or between Good and Acceptable.

The research team observed that for the non-mission-critical facilities, the participants did not apply the same weighting of risk as they did with the mission-critical facilities while assigning total value ratings to the roof material selections. The results showed that the opposite effect occurred. As the impact from risk was greatly reduced for the non-mission-critical facilities, the ratings results for the non-mission-critical facilities aligned much closer with the annual lifecycle cost results from Part A, with the lower cost roofs trending towards higher total value ratings. This effect of assigning higher priority to cost, resulted in the lower cost single-ply roofs receiving higher ratings than the built-up roofs. The comparison of roof material ratings for mission-critical and non-mission-critical facilities can be seen in Table 4-5. The research team observed that the highest rated materials for mission-critical facilities were rated the lowest for use with non-mission critical facilities, an inverse in ratings distribution.

Table 4-5: Ratings for Mission-Critical and Non-Mission-Critical Facilities

Roof Material	Mission-Critical	Non-Mission-Critical
3-Ply BUR w/Cap	4.3	2.8
4-Ply BUR w/Gravel	3.8	2.5
2-Ply Mod Bit w/Cap	3.1	2.4
Metal 24 Ga Minimun	2.9	3.9
90 Mil EPDM	2.9	3.4
2-Ply Mod Bitumen	2.8	3.0
80 Mil PVC	2.5	3.6
60 Mil KEE PVC	2.4	3.9
80 Mil TPO	2.2	3.5
60 Mil EPDM	2.2	3.4
50 Mil XT KEE	2.0	3.1
60 Mil TPO	1.7	3.3

The annual lifecycle costs and total value ratings were plotted together and can be seen in Figure 4-5. The roof material selections were separated by material type, and the ratings were again aligned to which roof material group (built-up roof (BUR), single-ply, and metal) the material selection belonged to, this time with the single-ply roofs being rated higher than built-up roofs and the metal roof receiving the second highest rating for non-mission-critical facilities. This time, however, there was an observable trend of higher ratings being assigned to lower cost materials. The research team did note that cost was not the sole factor in the assignment of ratings for non-mission-critical facilities, as the lowest cost selection, 50 Mil XT KEE, and the highest cost selection, 2-Ply Modified Bitumen, both received ratings below the mean and median values.

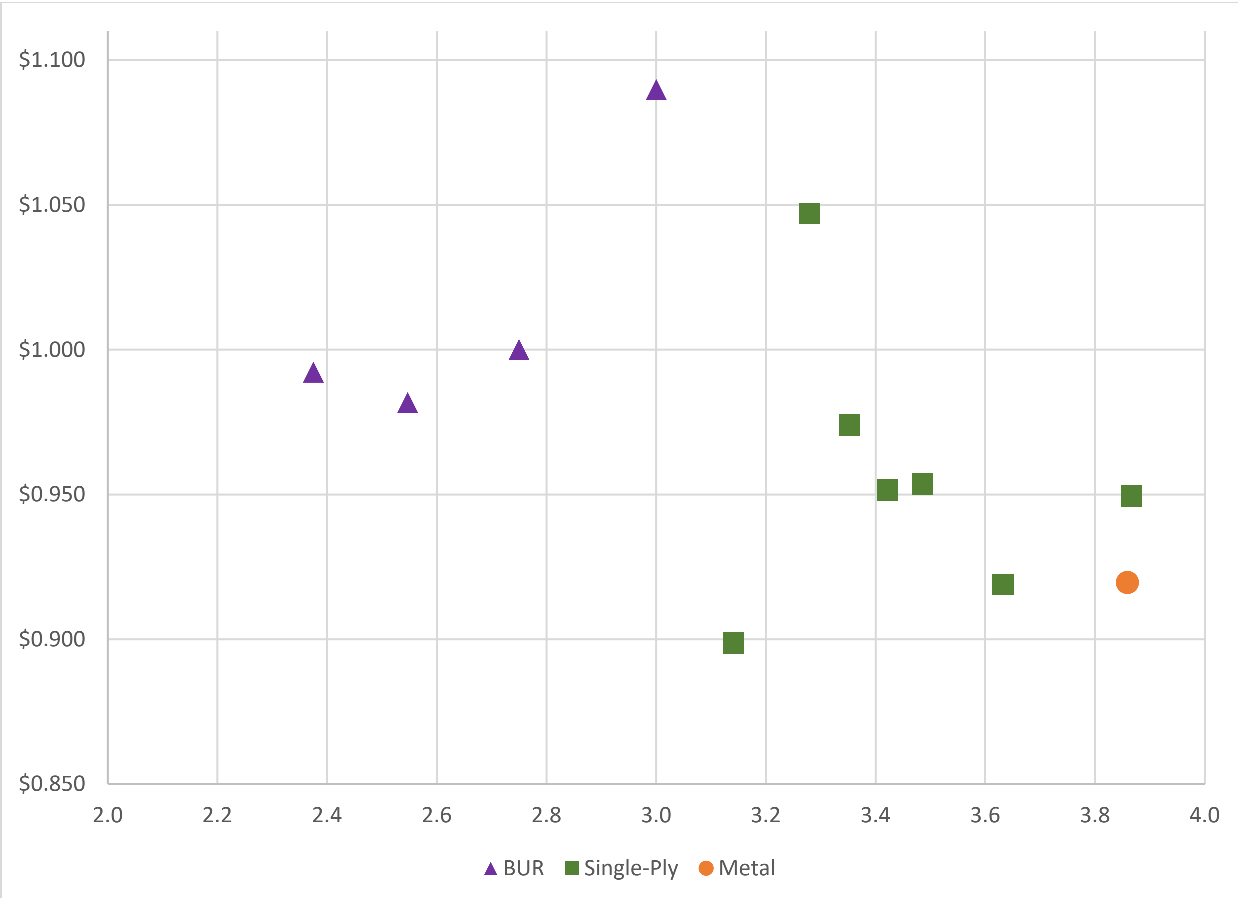

Figure 4-5: Rating and Cost for Non-Mission-Critical Facilities

There was some variance observed in the ratings upon analyzing the individual non-mission-critical facility types. While the ratings results were consistent between the Storage, Warehouse, and Garage facility types; the ratings for built-up roofs were significantly higher for Administrative buildings as shown in Figure 4-6. The research team attributed the higher ratings to Administrative buildings being more likely to house mission-critical operations than Storage, Warehouse, and Garage facilities. Although this study classified Administrative buildings as non-mission-critical due to their primary operation not being IT, Administrative buildings often house operations that require 24/7 reliability such as call centers, and some Administrative buildings house IT operations mingled together with the office environment.

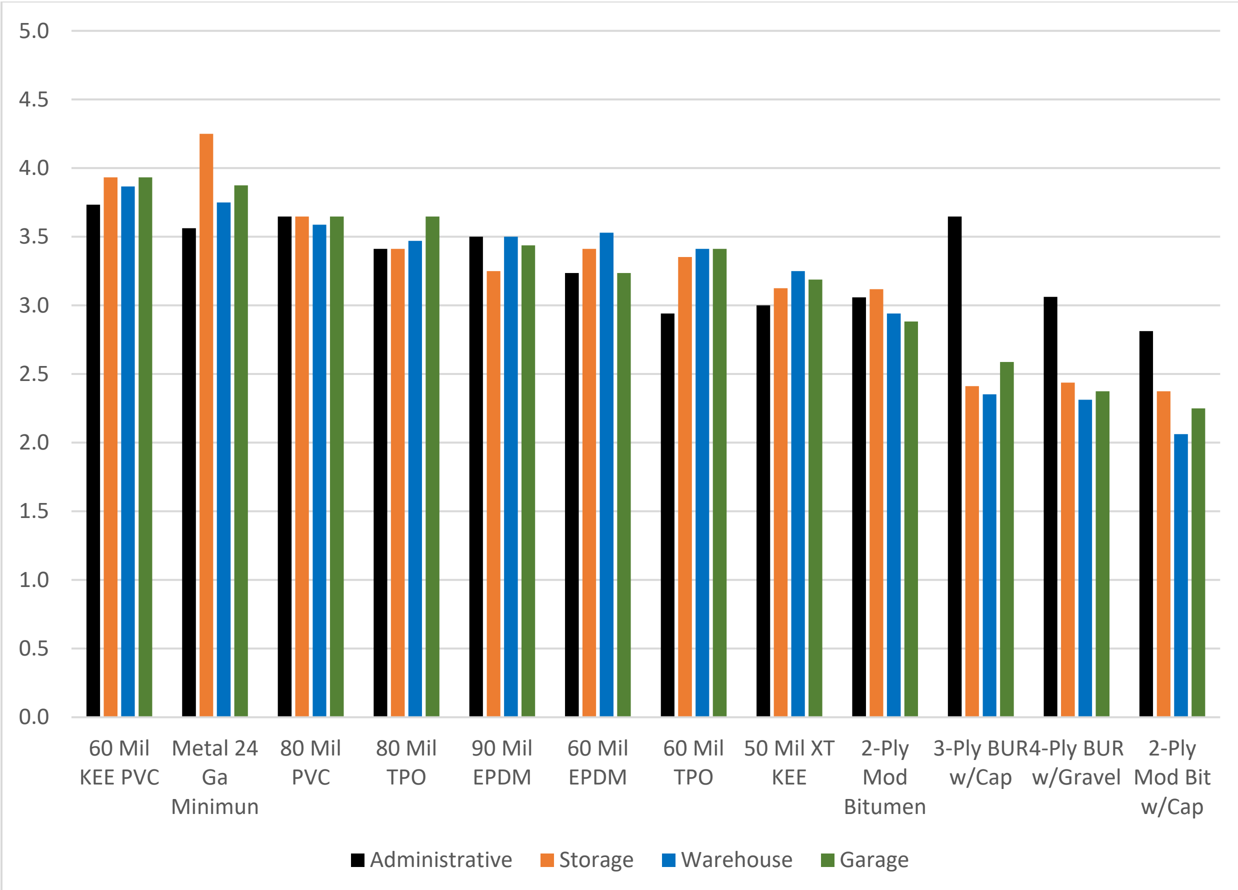

Figure 4-6: Roof Rating Comparison by Non-Mission-Critical Facility Type

4.4.5 Cost Applied to Rating

To conclude the analysis of results, the research team combined the responses from Part A and Part B of the survey to observe any trends or patterns as a result of applying the lifecycle cost data to the Roof-by-Facility Type ratings for mission-critical facilities. The research team desired to observe the effect of weighting the lifecycle costs and ratings on the suitability of each roof material selection for use with mission-critical facilities. The team began by first designating the average mission-critical rating as the base score for each roof material selection. The research team then calculated the mean and standard deviation of the annual lifecycle cost data. The mean observed was $0.973 and the standard deviation was $0.052. Each annual lifecycle cost value was then converted to a score from 1-5 based off of where each value fell within standard deviations from the mean: 1 – Within positive two and positive three standard deviations from the mean, 2 – Within positive one and positive two standard deviations from the mean, 3 – Within positive one standard deviations from the mean, 4 – Within negative one standard deviations from the mean, 5 – Between negative two and negative one standard deviations from the mean. The mission-critical rating and annual lifecycle cost scores were then weighted and combined to develop a suitability score for each roof material selection with 5 being most suitable, and 1 being least suitable. A sensitivity test was performed where the suitability scores were captured at various 10% weighting intervals from a 100% mission-critical rating score, to a 50% mission-critical rating score / 50% annual lifecycle cost score as shown in Table 4-6. The purpose of this was to test the sensitivity of the rating to lifecycle cost suitability score, as to not overweight either the rating or cost factors.

Table 4-6: Roof Suitability Scores for Mission-Critical Facilities

	Mission-Critical Rating	Annual Life Cycle Cost	Standard Deviation Score	100	90/10	80/20	70/30	60/40	50/50
3-Ply BUR w/Cap	4.3	$1.000	3	4.3	4.2	4.1	3.9	3.8	3.7
4-Ply BUR w/Gravel	3.8	$0.982	3	3.8	3.7	3.6	3.6	3.5	3.4
2-Ply Mod Bit w/Cap	3.1	$0.992	3	3.1	3.1	3.1	3.1	3.1	3.1
Metal 24 Ga Minimun	2.9	$0.920	5	2.9	3.1	3.4	3.6	3.8	4.0
90 Mil EPDM	2.9	$0.952	4	2.9	3.0	3.1	3.2	3.4	3.5
2-Ply Mod Bitumen	2.8	$1.090	1	2.8	2.6	2.4	2.2	2.1	1.9
80 Mil PVC	2.5	$0.919	5	2.5	2.7	3.0	3.2	3.5	3.7
60 Mil KEE PVC	2.4	$0.949	4	2.4	2.5	2.7	2.8	3.0	3.2
80 Mil TPO	2.2	$0.954	4	2.2	2.4	2.5	2.7	2.9	3.1
60 Mil EPDM	2.2	$0.974	3	2.2	2.2	2.3	2.4	2.5	2.6
50 Mil XT KEE	2.0	$0.899	5	2.0	2.3	2.6	2.9	3.2	3.5
60 Mil TPO	1.7	$1.047	2	1.7	1.7	1.7	1.8	1.8	1.8

The suitability scores were then ranked 1-12, with 12 being the most suitable and 1 being the least suitable. The suitability rankings were plotted together at each weight per roof material selection as shown in Figure 4-7.

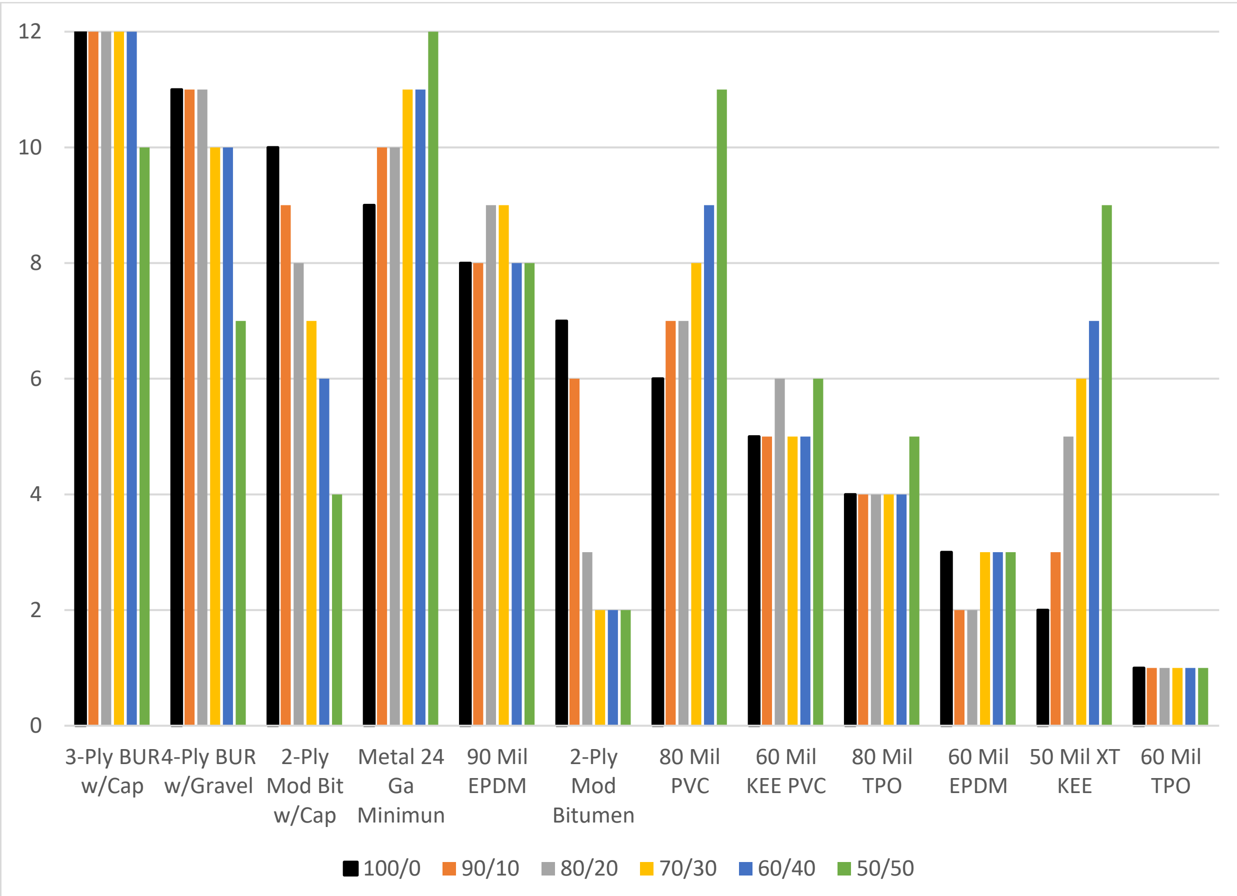

Figure 4-7: Weighted Roof Suitability Rankings for Mission-Critical Facilities

Using the original ratings as the basis for comparison, the research team made the following observations when cost was applied to the Roof-by-Facility Type ratings:

1) 60 Mil TPO Fully Adhered consistently ranked lowest in suitability for mission-critical facilities due to it having the lowest overall rating as well as the second highest annual lifecycle cost.

2) 3-Ply Built-Up Roof with Modified Cap Sheet consistently ranked highest in suitability with the exception at the 50% rating / 50% cost weighting where the Metal 24-Gauge Minimum selection ranked the highest. The metal roof was able to rise in suitability due to it having the second lowest annual lifecycle cost.
3) As cost was applied to the ratings, the 2-Ply Modified Bitumen Hybrid with Single-Ply Cap Sheet selection saw the most dramatic decrease in suitability at each weight interval. This is due to it being the selection with the highest annual lifecycle cost.
4) The 80 Mil PVC Fully Adhered and 50 Mil XT KEE Fully Adhered selections saw the most dramatic increases to their suitability ranking when cost was applied to their ratings. At the 50% rating / 50% cost weighting, the two materials ranked amongst the most suitable at 11 and 9 respectively. This can be attributed to those material selections having the two lowest annual lifecycle costs overall.
5) Metal 24-Gauge Minimum and 90 Mil EPDM Fully Adhered were the only material selections in the top half of rankings for mission-critical facilities that saw their rankings increase when the cost weighting also increased. They also had costs below the mean annual lifecycle cost. This suggests that those two materials present themselves as good value both in risk and cost and could be considered as viable alternatives to the top-rated built-up roof selections.

The application of different weightings levels between annual lifecycle costs and mission-critical ratings serve as a sensitivity test to illustrate that as lifecycle costs receive a higher weight towards suitability for mission-critical facilities, the ranking of roof materials that otherwise have lower roof professional ratings begin to increase. As mentioned previously, this can be seen in the 80 Mil PVC Fully Adhered and 50 Mil XT KEE Fully Adhered selections that were rated 2.5, between Acceptable and Minimally Acceptable, and 2.0, Acceptable, respectively. At the 90% rating / 10% cost weighting, 80 Mil PVC Fully Adhered begins to rank in the top half of suitability for use with mission-critical facilities. 50 Mil XT KEE Fully Adhered which rated second to last at 2.0, Minimally Acceptable, received a suitability ranking in the top half of materials at the 60% rating / 40% cost weighting. Both materials were ranked in the top 4 for use with mission-critical facilities at the 50% rating / 50% cost weighting. The sensitivity test provides a caution against overweighting annual lifecycle cost, as it introduces an increased amount of risk to the operation from the perspective of the roofing professionals.

4.5 Summary of Results

Upon analysis of the results, the research team found that single-ply roofs, with the exception of 60 Mil TPO, had lower annual lifecycle costs than built-up roofs. This was due to single-ply roofs having lower install and removal costs as well as competitive lifespans to that of built-up roofs. Built-up roofs, however, rated higher than single-ply roofs for use with mission-critical facilities. The ratings results indicated that the roofing professionals prioritized risk over cost when assigning total value ratings. The metal roof option presented itself as a good value as it carried the 4th lowest annual lifecycle cost as well as being rated amongst the top 4 suitable roofs for mission-critical facilities.

When the lifecycle cost data was combined with the ratings results, the research team weighted the cost data and ratings at different intervals and observed that the single-ply roof materials increased in ranking as the cost weighting also increased. This was especially true for the two materials with the lowest annual lifecycle costs, 50 Mil XT KEE Fully Adhered and 80 Mil PVC Fully Adhered, that were ranked amongst the top 4 suitable material selections for mission-critical facilities at a 50% rating / 50% cost weighting despite having ratings approaching minimally acceptable. Metal 24-Gauge Minimum and 90 Mil EPDM Fully Adhered were the only material selections in the top half of rankings for mission-critical facilities that saw their rankings increase when the cost weighting also increased, suggesting that they could be considered as viable alternatives to the top-rated built-up roof selections.

5 CONCLUSIONS

5.1 Conclusion

As organizations become increasingly dependent on mission-critical facilities to support their 24/7 operations, there exists a greater need for strategic roof material selection to address the reliability of operations as a result of the roof system's performance, as well as being able to meet financial demands by optimizing building lifecycle costs. The purpose of this research was to evaluate different roof materials and to observe trends relative to their lifecycle costs and roof professional's assessment in use with mission-critical facilities. The research objectives were to:

1) Determine the average annual lifecycle costs for the sampled roof materials.
2) Determine the roofing professionals' preferred mission-critical facility roof materials.
3) Priority rank the sampled roof materials for use with mission-critical facilities.

The lifecycle cost information was obtained by surveying roofing professionals across the United States and asking them to provide estimates for "Lifespan/Years", "Costs/SqFt Install", "Costs/SqFt Removal", and "Costs/SqFt Annual Maintenance" for each roof material selection. The average responses for each data field were tabulated and combined to determine the total lifecycle costs. The total lifecycle costs were divided by the estimated lifespan in years of the respective roof materials to determine the average annual lifecycle cycle costs of each selection.

The roofing professionals' preference of roofing materials for use with mission-critical facilities was also obtained by surveying roofing professionals across the United States. Each participant was asked to rate the acceptability of each roof type by facility type, taking into consideration total value inclusive of costs, lifespan, and risk. The participants could choose one of 5 ratings for each roof material application: “Excellent”, “Good”, “Acceptable”, “Minimally Acceptable”, and “Not Recommended”. Each rating was assigned a numerical value from 1-5: 1 – Not Recommended, 2 – Minimally Acceptable, 3 – Acceptable, 4 – Good, 5 – Excellent. The average roof material ratings were then tabulated and grouped by building type.

A definitive priority rank list of the roof materials for use with mission-critical facilities was not established due to the variances created by applying different levels of the lifecycle cost results to the roof material ratings. The research team did develop a sensitivity test to observe how the suitability rankings of the roof materials change as the lifecycle cost and ratings results are combined at different weighting levels.

The research supported the hypothesis that single-ply roof selections would have the lowest annual lifecycle costs. The single-ply roof selections overall carried lower install and removal costs and although the singly-ply roofs had slightly shorter lifespans than the built-up roof selections, the lifespans of the single-ply roofs were competitive enough to equate to lower annual lifecycle costs overall. The exception to this was the 60 Mil TPO Fully Adhered selection which. Although it measured among the lowest in install and removal costs, it had the lowest estimated lifespan at only 17.2 years which greatly affected its annual lifecycle costs. The research team did observe the total lifecycle cost range of \$11.18/SF; a 62.5% cost increase from the lowest to highest cost roof selection. When factoring in the estimated lifespans to the lifecycle analysis, the range between the lowest and highest annual lifecycle costs was much less dramatic at only \$0.191/SF per year, a cost increase impact of 21.3%. The results suggest that organizations can gain greater insight into the lifecycle costs of their roofing by approaching costs on an annual basis in addition to merely calculating total cost over the lifetime of the asset.

The research did not support the hypothesis that single-ply roof selections would rate the highest in total value for mission-critical facilities. The built-up roofs consistently rated highest in total value for their use with mission-critical facilities. Although recent market studies have shown year-over-year increases in the sale of single-ply roof materials and the lifespan of those materials have become much more competitive with built-up roofs, the roofing professionals placed great emphasis on risk when considering the total value rating of roof materials for mission-critical facilities. This prioritization of risk can be attributed to the experience the roofing professionals who participated in this study had working on mission-critical projects. The potential for savings on a mission-critical project can easily be overshadowed by the potential impact of a roofing failure.

The trends observed when combining the cost data with the ratings shed light on the potential risks of overweighting the annual lifecycle costs for suitability rankings. 80 Mil PVC Fully Adhered and 50 Mil XT KEE Fully Adhered increased to top material selections for mission-critical facilities as the lifecycle cost weighting increased, despite having mediocre to low roof professional ratings.

5.2 Use in the Field

Because roof selection market data remains limited, especially when taking into consideration mission-critical facilities, building owners and roofing professional could greatly benefit from this research by having current lifecycle cost data as well as roofing professional's assessments of various roof types to utilize when selecting the appropriate roof for future mission-critical facility projects. The project stakeholders could also study the trends observed when the cost data was applied to the rating data to utilize in their own risk assessments when considering tradeoffs between single-ply, metal, and built-up roofs. Project stakeholders who place emphasis on cost minimization, could use this research for value engineered project solutions that involve roof materials that still rate high amongst roofing professionals for total value inclusive of risk, but also have lower annual lifecycle costs than the most conservative choices. For example, building owners looking for cost savings may opt to select 90 Mil EPDM Fully Adhered or Metal 24-Gauge Minimum as alternatives to the higher rated built-up roof options. They both carry annual lifecycle costs ($0.952/SF and $0.920/SF) less than the mean annual lifecycle cost ($0.973) while still maintaining a roof professional rating of 2.9, or near Acceptable. Project stakeholders that place utmost emphasis on risk reduction can gain insight by observing the trends in lifespan of the roofing materials in the study. Although the probability of roof incidences by roof material is fairly unpredictable due to a multitude of external factors, the estimated lifespan of each roof material could be an indication of the durability and resilience of the roof material selection. That data, along with the roof professionals' ratings could help risk adverse project stakeholders select more robust options such as Metal 24-Gauge Minimum, 4-Ply Built-Up Roof with Gravel, 3-Ply Built-Up Roof with Modified Cap Sheet, and 2-Ply Modified Bitumen Hybrid with Single-Ply Cap Sheet, being the materials with the longest estimated lifespans as well as having the highest ratings for use with mission-critical facilities. The sensitivity test in this study is especially helpful for stakeholders to avoid placing too much priority on cost when considering the suitability of roofing materials. As observed from the results, overweighting the cost factors could lead to the selection of roof materials that received mediocre to poor ratings from roofing professionals.

5.3 Limitations

Limitations with this study were associated with the survey responses. Although the research team obtained 46 verbal commitments out of the original sample of 62 roofing professionals (74%), the actual response rate was lower at 17 responses or 27.4% of those who were sent the survey. The responses from the survey were valuable in obtaining current material lifecycle costs and observing trends relative to vendor assessments of roof materials for mission-critical facilities; however, the study could have benefited from a larger sample size to reinforce the conclusions obtained from the results. With a larger sample size, the research team could also assess whether geographic location influenced the individual responses to add another variable to the results. The sample chosen for this study was also a potential limitation, as all of the participants had performed mission-critical facility work for the same information technology company. By broadening the sample population, the research team could obtain results even more representative of the roofing industry in the United States.

5.4 Opportunities for Further Research

There exist numerous opportunities to expand on research relative to roofs and mission-critical facilities. As this study focused on facilities supporting IT functionality, further research could seek to identify roof selection trends for non-IT mission-critical facilities across various industries. The research could also be expanded to observe the global effect on roof selection for mission-critical facilities. The participants selected for this study were exclusively roofing professionals. Future studies could include the perspective of building owners and managers to gain insight from additional stakeholders.

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APPENDIX A. SAMPLE SURVEY USED IN PILOT STUDY

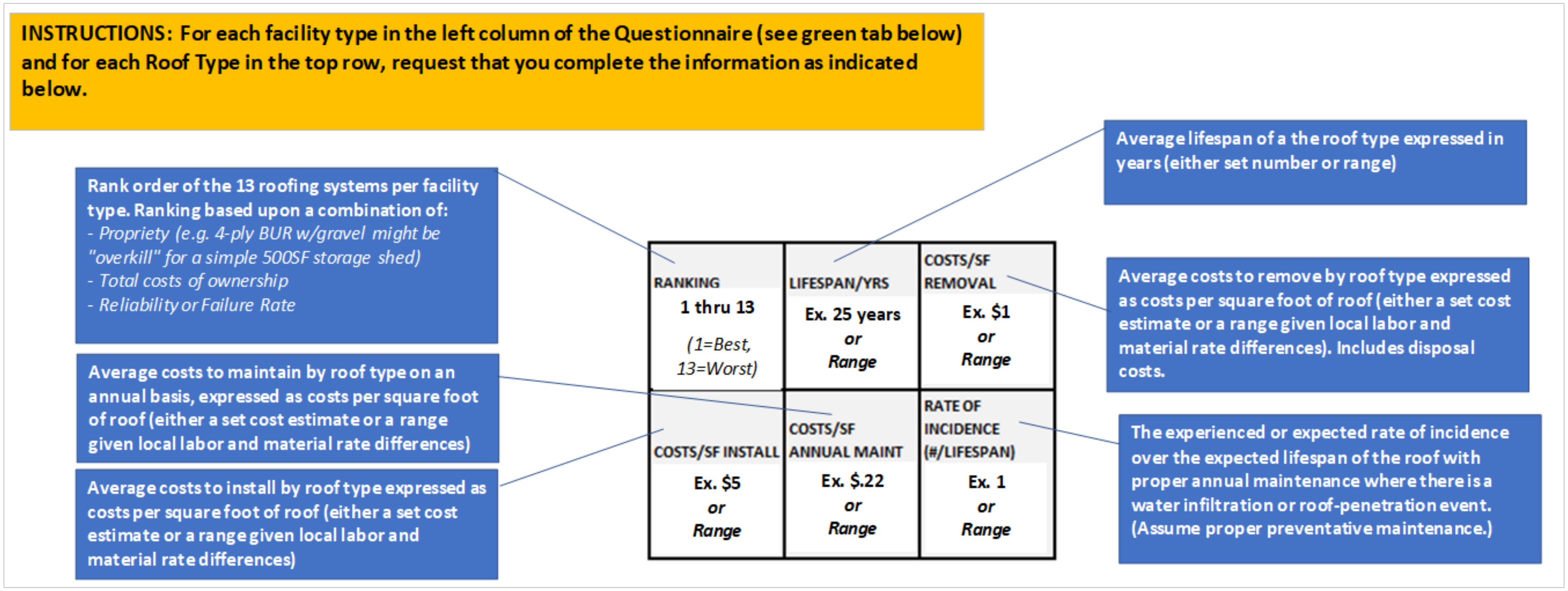

Figure A-1: Sample Survey Instructions

Facility Type	Roof Material (13 Selections outlined in text)		
Administrative *Building that supports office work of an administrative nature. Finished interiors with constructed walled interior rooms or open workstation-style seating. Finished with carpet or tile, finished or drop ceilings, lighting, minimal power/HVAC load, office automation located throughout.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	RATE OF INCIDENCE (#/LIFESPAN)
Central Office *Building of any size which contains network switching equipment that connects end users to each other, both locally and via long distance carriers. Contains the inside plant elements required for this function, such as distribution frames and interoffice facility termination points. May be a combination of industrial concrete or tiled floors with other finished areas and potential high-demand for power/HVAC.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	INCIDENCE (#/LIFESPAN)
Data Center/Data Processing Facility *Data Centers are large facilities containing the equipment required to manage Internet Hosting/Network Services of external customers. Data Processing facilities are buildings whose primary function is to contain data processing equipment to provide critical services to internal and external CenturyLink customers. Both facilities are extremely high-demand power/HVAC and mission-critical.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	INCIDENCE (#/LIFESPAN)

Figure A-2: Sample Survey Part 1

Facility Type	Roof Material (13 Selections outlined in text)		
Equipment *Generally an un-staffed structure, which contains telephone equipment and excludes a switch (i.e., repeater huts, radio equipment, fiber terminals, SLC 96 huts, ROW). Generally industrial flooring with moderate power/HVAC requirements.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	INCIDENCE (#/LIFESPAN)
Storage *Buildings or sheds in which the majority of space is used for equipment and supply storage. Industrial furnishings throughout, concrete or tile flooring, unfinished walls and/or ceilings. Secured and monitored to prevent pilferage. Minimal power/HVAC requirements.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	INCIDENCE (#/LIFESPAN)
Warehouse *Buildings whose primary use is storage and handling of inventory and supplies. These buildings are built specifically for that purpose, and may include such things as high shelving, conveyor systems, and loading docks. May also contain office space. Typically have industrial furnishings throughout, concrete flooring, unfinished walls and/or ceilings. Moderate power/HVAC requirements to keep contents climate controlled.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	INCIDENCE (#/LIFESPAN)
Garage *Buildings which house repair, installation, maintenance, and/or engineering crews and/or their vehicles, tools, supplies and other storage as may be required. These properties also may include crew rooms and some administrative space. Typically contain industrial furnishings throughout with concrete floors. Minimal power/HVAC requirements.*	RANKING	LIFESPAN	COSTS/SF REMOVAL
	COSTS/SF INSTALL	COSTS/SF ANNUAL MAINT	INCIDENCE (#/LIFESPAN)

Figure A-3: Sample Survey Part 2

APPENDIX B. FINAL SURVEY USED IN STUDY

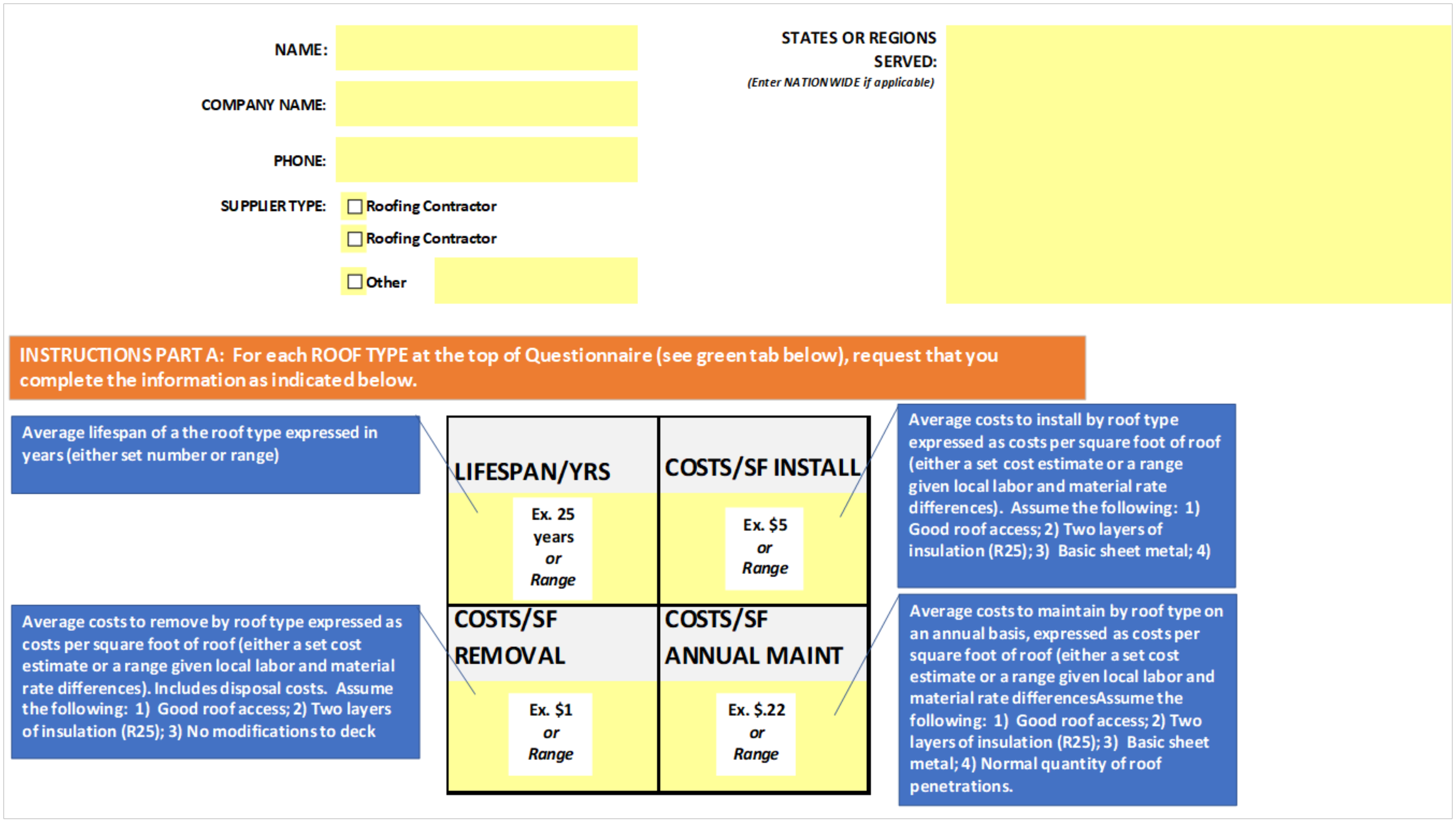

Figure B-1: Final Survey Instructions Part 1

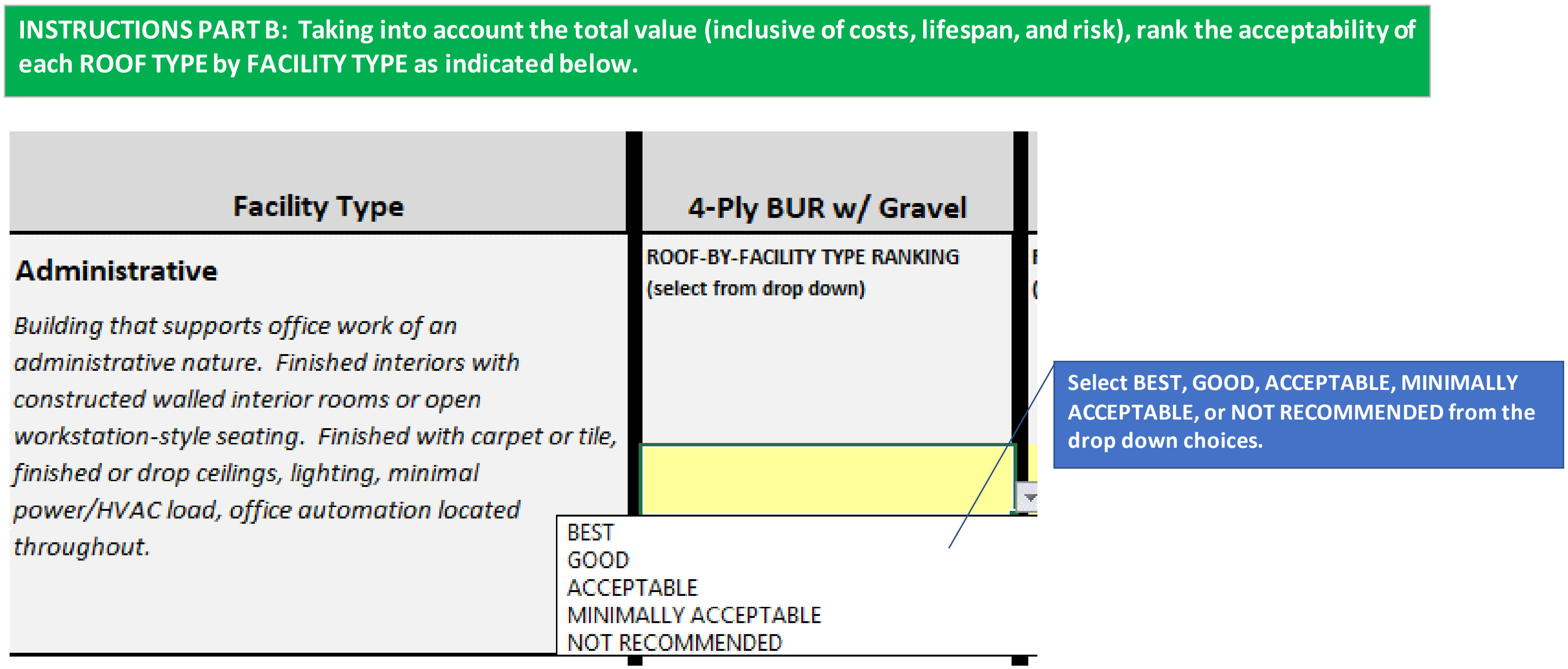

Figure B-2: Final Survey Instructions Part 2

PART A

	4-Ply BUR w/ Gravel		2-Ply Modified Bitumen Hybrid w/ Single-Ply Cap	
	LIFESPAN/YRS	COSTS/SF INSTALL	LIFESPAN/YRS	COSTS/SF INSTALL
	COSTS/SF REMOVAL	COSTS/SF ANNUAL MAINT	COSTS/SF REMOVAL	COSTS/SF ANNUAL MAINT

PART B

Facility Type	4-Ply BUR w/ Gravel	2-Ply Modified Bitumen Hybrid w/ Single-Ply Cap
Administrative *Building that supports office work of an administrative nature. Finished interiors with constructed walled interior rooms or open workstation-style seating. Finished with carpet or tile, finished or drop ceilings, lighting, minimal power/HVAC load, office automation located throughout.*	ROOF-BY-FACILITY TYPE RANKING (select from drop down)	ROOF-BY-FACILITY TYPE RANKING (select from drop down)
Central Office *Building of any size which contains network switching equipment that connects end users to each other, both locally and via long distance carriers. Contains the inside plant elements required for this function, such as distribution frames and interoffice facility termination points. May be a combination of industrial concrete or tiled floors with other finished areas and potential high-demand for power/HVAC.*	ROOF-BY-FACILITY TYPE RANKING (select from drop down)	ROOF-BY-FACILITY TYPE RANKING (select from drop down)

Figure B-3: Final Survey Part 1

Facility Type	Roof Material (12 Selections outlined in text)
Data Center/Data Processing Facility *Data Centers are large facilities containing the equipment required to manage Internet Hosting/Network Services of external customers. Data Processing facilities are buildings whose primary function is to contain data processing equipment to provide critical services to internal and external CenturyLink customers. Both facilities are extremely high-demand power/HVAC and mission-critical.*	ROOF-BY-FACILITY TYPE RANKING (select from drop down)
Equipment *Generally an un-staffed structure, which contains telephone equipment and excludes a switch (i.e., repeater huts, radio equipment, fiber terminals, SLC 96 huts, ROW). Generally industrial flooring with moderate power/HVAC requirements.*	ROOF-BY-FACILITY TYPE RANKING (select from drop down)
Storage *Buildings or sheds in which the majority of space is used for equipment and supply storage. Industrial furnishings throughout, concrete or tile flooring, unfinished walls and/or ceilings. Secured and monitored to prevent pilferage. Minimal power/HVAC requirements.*	ROOF-BY-FACILITY TYPE RANKING (select from drop down)

Figure B-4: Final Survey Part 2

Facility Type	Roof Material (12 Selections outlined in text)
Warehouse *Buildings whose primary use is storage and handling of inventory and supplies. These buildings are built specifically for that purpose, and may include such things as high shelving, conveyor systems, and loading docks. May also contain office space. Typically have industrial furnishings throughout, concrete flooring, unfinished walls and/or ceilings. Moderate power/HVAC requirements to keep contents climate controlled.*	**ROOF-BY-FACILITY TYPE RANKING (select from drop down)**
Garage *Buildings which house repair, installation, maintenance, and/or engineering crews and/or their vehicles, tools, supplies and other storage as may be required. These properties also may include crew rooms and some administrative space. Typically contain industrial furnishings throughout with concrete floors. Minimal power/HVAC requirements.*	**ROOF-BY-FACILITY TYPE RANKING (select from drop down)**

Figure B-5: Final Survey Part 3

APPENDIX C. SURVEY RESULTS

Table C-1: Survey Results Part 1

ROOFING SURVEY RESULTS							
PART A							
4-Ply BUR w/Gravel		2-Ply Modified Bitumen Hybrid w/Single-Ply Cap		3-Ply BUR w/Modified Cap		2-Ply Modified Bitumen	
LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL
26	$16.36	23	$15.60	24	$16.89	20	$14.75
COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT
$3.77	$0.20	$3.29	$0.18	$3.57	$0.16	$3.42	$0.20
60 Mil EPDM Fully Adhered		90 Mil EPDM Fully Adhered		60 Mil TPO		80 Mil TPO	
LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL
19	$11.66	23	$14.15	17	$11.70	21	$13.25
COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT
$2.97	$0.20	$2.94	$0.20	$3.00	$0.19	$3.14	$0.17
50 Mil XT KEE		60 Mil KEE PVC		80 Mil PVC		Metal 24 Gauge Minimum	
LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL	LIFESPAN/YEARS	COSTS/SqFt INSTALL
20	$12.04	21	$12.80	23	$13.47	32	$17.95
COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT	COSTS/SqFt REMOVAL	COSTS/SqFt ANNUAL MAINT
$3.09	$0.14	$2.89	$0.19	$3.05	$0.20	$3.95	$0.23

Table C-2: Survey Results Part 2

PART B								
Facility Type	**4-Ply BUR w/Gravel**		**2-Ply Modified Bitumen Hybrid w/Single-Ply Cap**		**3-Ply BUR w/Modified Cap**		**2-Ply Modified Bitumen**	
Administration	Score =	3.1	Score =	2.8	Score =	3.6	Score =	3.1
Central Office	Score =	3.9	Score =	3.1	Score =	4.4	Score =	2.8
Data Center	Score =	3.7	Score =	3.1	Score =	4.2	Score =	2.6
Equipment	Score =	3.8	Score =	3.2	Score =	4.3	Score =	2.9
Storage	Score =	2.4	Score =	2.4	Score =	2.4	Score =	3.1
Warehouse	Score =	2.3	Score =	2.1	Score =	2.4	Score =	2.9
Garage	Score =	2.4	Score =	2.3	Score =	2.6	Score =	2.9
Facility Type	**60 Mil EPDM Fully Adhered**		**90 Mil EPDM Fully Adhered**		**60 Mil TPO**		**80 Mil TPO**	
Administration	Score =	3.2	Score =	3.5	Score =	2.9	Score =	3.4
Central Office	Score =	2.1	Score =	2.9	Score =	1.6	Score =	2.1
Data Center	Score =	2.1	Score =	2.9	Score =	1.5	Score =	2.2
Equipment	Score =	2.4	Score =	2.9	Score =	1.9	Score =	2.3
Storage	Score =	3.4	Score =	3.3	Score =	3.4	Score =	3.4
Warehouse	Score =	3.5	Score =	3.5	Score =	3.4	Score =	3.5
Garage	Score =	3.2	Score =	3.4	Score =	3.4	Score =	3.6
Facility Type	**50 Mil XT KEE**		**60 Mil KEE PVC**		**80 Mil PVC**		**Metal 24 Gauge Minimum**	
Administration	Score =	3.0	Score =	3.7	Score =	3.6	Score =	3.6
Central Office	Score =	2.1	Score =	2.5	Score =	2.6	Score =	3.1
Data Center	Score =	2.0	Score =	2.1	Score =	2.4	Score =	2.8
Equipment	Score =	2.1	Score =	2.5	Score =	2.3	Score =	3.0
Storage	Score =	3.1	Score =	3.9	Score =	3.6	Score =	4.3
Warehouse	Score =	3.3	Score =	3.9	Score =	3.6	Score =	3.8
Garage	Score =	3.2	Score =	3.9	Score =	3.6	Score =	3.9