Research Article

Roof System Suitability for IT Mission-Critical Facilities

Charles A. Petrinovich[1], Clifton B. Farnsworth Ph.D., P.E.[2], Justin E. Weidman Ph.D.[3], James P. Smith Ph.D.[4], and Evan D. Bingham Ph.D.[5]

[1]MS Student, Construction and Facilities Management, Brigham Young University, Provo, Utah; PH (801) 422-2021; FAX (801) 422-0653; email: cpdelta45@gmail.com
[2]Associate Professor, Construction and Facilities Management, Brigham Young University, Provo, Utah; PH (801) 422-6494; FAX (801) 422-0653; email: cfarnsworth@byu.edu
[3]Associate Teaching Professor, Construction and Facilities Management, Brigham Young University, Provo, Utah; PH (801) 422-5358; FAX (801) 422-0653; email: justinweidman@byu.edu
[4]Assistant Professor, Construction and Facilities Management, Brigham Young University, Provo, Utah; PH (801) 422-2023; FAX (801) 422-0653; email: jamessmith@byu.edu
[5]Associate Professor, Construction and Facilities Management, Brigham Young University, Provo, Utah; PH (801) 422-9320; FAX (801) 422-0653; email: evan.bingham@byu.edu

ABSTRACT

Information technology (IT) mission-critical facilities house operations that, when interrupted, can prove disastrous to an organization's operations. Limited market research is available to determine what roof system types are best suited to meet the unique demands of these buildings. The purpose of this research was to rate the suitability of commonly used roofing systems for IT mission-critical facilities and determine their associated lifecycle costs. This research was performed with a leading US based telecommunications company to help evaluate roofing system options used in their IT mission-critical facilities. A survey was administered to roofing professionals across the US to obtain lifecycle cost information and ratings for various roofing systems. The research found that single-ply roofs generally had lower annual lifecycle costs than built-up roofs, due to lower installation and removal costs and increasing life expectancies. Metal roofs also had a low annual lifecycle cost due to the longer estimated lifespan. On the other hand, lowest installation cost was not the governing factor for recommended selection of roof systems for IT mission-critical structures. Rather, built-up and metal roofs were rated highest by roofing professionals, for their value in mission-critical facilities, ultimately indicating a necessary prioritization for risk reduction versus cost savings.

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

Introduction

As the need for nonstop operations increases across organizations, the facilities that house those operations have evolved to meet these ever growing and constant demands. These buildings are known as mission-critical facilities, because they have an inordinate impact on business operations and/or profitability should key infrastructure systems lose power or other support (Woodell, 2015). Examples of facilities that fall under this definition include hospitals, airports, hotels, data centers, etc. One common functionality amongst any of these types of organizations that has become increasingly critical over time is the functionality of information technology (IT). IT can be defined as the digital communication capabilities of an organization (Attaran, 2003). As organizations have migrated towards automation of processes, IT has become interwoven throughout every aspect of the organization's operations. The loss of IT functionality presents a tremendous risk to an organization because it threatens their ability to do business. One study indicated that 25% of companies who experienced an IT outage from 2 to 6 days went bankrupt immediately, and 93% of companies that lost their data center for 10 or more days filed for bankruptcy within a year (Gold, 2007).

Mission-critical IT facilities (also commonly called data centers) are specifically designed and equipped with the infrastructure to meet the equipment demands and ultimately protect IT operations. Safety and security measures are commonly put into place that address power consumption and interruption, cooling, fire detection/protection, remote monitoring, and security (Woodell, 2015). Significant emphasis is placed on designing, constructing, and maintaining mission-critical facilities to ensure safe, secure, and continuous IT operations, especially for the internal infrastructure of the building, including power management and cooling. The roof system for IT mission-critical facilities presents a significant risk to the organization, because water finding its way into the facility and the network equipment environment increases the likelihood of an outage and can become catastrophic. Unfortunately, there is limited availability of roof selection market data accounting for the unique needs of data centers. This problem was recently acknowledged by a leading US based IT telecommunications company, with a real estate footprint of tens of millions of square feet spread over thousands of properties across the entire US. This paper summarizes a research project performed in conjunction with that telecommunications company, ultimately enabling the company to make effective decisions regarding the design, construction, and maintenance of the roofing systems selected for their mission critical facilities. This company was motivated to make more informed cost-effective decisions for their facility needs, based on the lifecycle costs of the various roofing system options commonly found amongst their facilities, coupled with maximum protection of the underlying IT infrastructure. Due to the potential risks of roof leaks catastrophically affecting the operations of the company, effective solutions could not simply be made on cost-effectiveness of the roofing systems alone. Although still inherent in the decision-making process, roofing system selection was also contingent upon overall effectiveness in providing a lower risk roofing system. Supporting details from the full study can be found in Petrinovich (2020). This research included the following three objectives: 1) determining the average annual lifecycle costs for commonly used roof systems, 2) rating the effectiveness of roof systems used for mission-critical facilities, and 3) generating a priority ranking of roof systems for mission-critical facilities. This study can be used by facility owners and managers, as well as general contractors and roofing professionals, for making roofing system decisions for both new construction or roof replacement projects for IT mission-critical structures.

Background

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 (e.g., hospitals, police and fire departments, and airline carriers), advancements in technology have contributed to additional necessary functionality of operations. Functions such as payment processing, online transactions, email, and data processing are required to continuously operate uninterrupted in order to remain competitive in today's business environment (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 determine functions that are considered 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 (Kearn et al., 2000). Structures housing mission-critical operations are built with that operational functionality in mind. The supporting infrastructure must allow the operation to operate efficiently; but more importantly, the infrastructure serves to mitigate potential risks to the operation and keep operational downtime minimal (Kaplan et al., 2008).

For the purposes of this study, it is important to further distinguish IT functionality from other 24/7 operations. IT mission-critical facilities typically include large and small data centers that house mainframe computers, servers, data storage, and both privately and publicly owned telecommunication networks. Examples of organizations that commonly have these facilities include governmental agencies, institutions, commercial, telecommunications, and industrial organizations (Uhlman, 2006). A service interruption (also called a network outage) can result in data that has not yet been transferred or permanently saved to become lost (ANSI, 2019). A more serious problem would occur if the equipment malfunctioned or became damaged and all the stored data became corrupted or lost altogether (Robin, 2000). Losing IT functionality can result in significant economic losses for the company, with extended outages commonly leading to bankruptcy (Robin, 2000; Gold, 2007). 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 (FCC, 2016; Daneshmand and Savolaine, 1993). Therefore, it is important for these organizations to understand all of the sources of risk for potential network outages within their IT mission-critical facilities.

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 developed disaster recovery plans to address those risks. Water hazard, however, is infrequently identified as a direct risk 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 has been cited as the root cause of many reported network outages. For example, during the months of January – February 2017, the state of California experienced the most rainfall recorded in 122 years. The California Public Utilities Commission (CPUC) reported that this resulted in a 30% increase of communication service interruptions totaling more than 1.7 million customers who were without service during that time period, more than half of whom were without access to 911 calls (CPUC, 2018). This also disrupted communication to more than fifty-thousand businesses. The report further indicated that the worst performing wireline service provider reported 78% of its network outages were due to cable failure, because its network was especially susceptible to water intrusion (CPUC, 2018). Since water hazard is a serious risk factor to IT operations, building systems that have the potential to introduce water into the network environment (i.e., roof systems) should be given similar priority as other critical IT infrastructure systems.

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 (typically steel or concrete in commercial applications), air/vapor barrier, insulation, and a covering or membrane. The roof membrane is what maintains a water tight condition in the roof system, and is the central component of this study. Roofs are typically classified as being either low-sloped (having a slope less than or equal to 3:12, or 25%) or steep-sloped (slopes greater than 3:12) (Smith, 2016). Since most IT mission-critical facilities have low-sloped roofs, this study focuses on the different low-sloped roof systems available in the market today. Prior to the mid 1970's, almost all low-sloped roofs in the US were either coal-tar or asphalt built-up roofs (Smith, 2016). Beginning in the 1980's, however, other low sloped materials began to enter the market to compete with built-up roofs, namely modified bitumen, single-ply roofs, and metal panel roofs (Smith, 2016).

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 (DOD, 2019). Because asphalt tends to break down over time 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). Modified bitumen is similar to built-up roofs, in that it leverages the waterproof characteristics of asphalt. However, to avoid the bitumen becoming brittle over time, 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 with either hot asphalt or by heat torch (McNally, 2011).

Single-ply membranes are made up of prefabricated sheets of either thermoplastic or thermoset materials that are installed as a single layer (Smith, 2016). 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. Water intrusion is inevitable if that layer gets punctured or fails. This becomes particularly problematic for roofs with a lot of foot traffic (Smith, 2016).

Metal roof panels are utilized for their durability and low rate of repair. Metal roofing products are available in various metals such as steel, stainless steel, aluminum, copper, zinc, and titanium (Bush et al., 2016). The methods used in the installation of a metal roof are 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 low-sloped applications with water ponding potential.

Literature Review

The literature review associated with this research identified four principal types of literature related to mission-critical and other types of commercial roofing systems; first, establishing the importance of mission-critical roofing systems, second, roofing systems associated with commercial facilities, third, environmental trends associated with commercial roofing systems, and finally, lifecycle cost analysis and cost comparison studies for commercial roofing systems.

The principal goal of a mission-critical facility is to establish, support, maintain, and protect the infrastructure and operations that are absolutely necessary for the organization to carry out its mission (Liotine, 2003). The critical IT infrastructure, network continuity is key. In other words, maintaining the ability to continue operations of the network in light of a disruption. In this case, continuity stresses an avoidance approach and avoiding disaster recovery in the first place. A roof failure for a mission-critical IT facility would put the organization in disaster recovery mode. Therefore, the principal goal is building survivable network infrastructure (Liotine, 2003), implying that the facility protecting that infrastructure is equally essential. Cabellero (2013) indicated that threats to IT facilities can include forces of nature. Accordingly, any threat agent (water in this research) gives rise to a threat (a roof failure in this research) which in turn exploits a vulnerability. The vulnerability then can lead to a security risk that can damage the company's assets (the security of the IT infrastructure in this research). However, this can be counter measured by a safeguard that directly protects against the threat agent. In short, roofing systems are an essential security measure to physically safeguard the IT infrastructure and ultimately protect the organization from damaging consequences (Cabellero, 2013).

Guyer (2018) identified considerations for selecting an appropriate roofing system. For low slope roofing systems, especially common for IT and other similar types of commercial facilities, membrane systems that are completely sealed at the laps and flashing are common. For these types of roofs, it is essential that the roofing system can withstand temporary standing water conditions. Guyer (2018) further indicated that approximately 75% of the roofing activity includes tasks associated with reroofing, as opposed to building the new roof. Baskaran et al. (2007)

concluded that roofing systems are expected to provide water tightness and near continuous protection from various damaging effects, especially water. Baskaran et al. (2007) further indicated that the average market share for commercial roofs in the US included 46% single ply, 19% built-up roofs, and 18% modified bitumen. Roofing contractors are especially interested in implementing cost reduction strategies including prefabrication, mechanization, using lighter and less energy intrusive components, and utilizing less labor-intensive systems and designs (Baskaran et al., 2007). Although not specific to IT facilities, this research indicates that most commercial facilities in the US utilize simpler and correspondingly cheaper roofing options.

One area of roofing system research that seems to be quite extensive is specifically related to energy efficient roofing materials and systems. For example, there are multiple studies that have indicated that heating and cooling of the structure can be influenced by the reflectivity and color of the roofing system (Testa and Krarti, 2017; Hosseini et al., 2018). Other recent studies have identified potential environmental metal loading from the built environment due to the effects of the corrosion of metallic roofing systems (McIntyre et al., 2019). Although, perhaps not nearly as important as the ability to withstand water intrusion in an IT mission-critical facility, these other factors are certainly affecting the roofing industry. More related to this research is the literature associated with weathering affects on commercial roofing systems. Berdahl et al. (2008) identified how roofing materials degrade over time due to exposure from the elements, namely wind, sunlight, moisture, atmospheric pollution, and temperature variations. Jordan et al. (2018) further elaborated how condensation trapped beneath the roofing membranes is another potential source of roofing system degradation and damage. Although, this research didn't specifically focus on the causes of roofing failures, the decision to select specific types of IT mission-critical facility roofing systems is inherently linked to this commercial roofing failure related literature.

Most relevant to this research study is the literature specifically associated with lifecycle analysis of roofing systems and corresponding cost comparison studies. Sproul et al. (2014) compared the lifecycle costs of white, green, and black commercial roofing systems, indicating that white roofing systems were the most economical over a 50-year life. However, Blackhurst et al. (2010) further indicated that lifecycle costs of green roofing systems compared with traditional roofing systems were difficult to assess without detailed designs, specifications, and pricing details. Taylor (2019) built upon the earlier reflectivity studies, but coupled this research with lifecycle cost comparisons, ultimately concluding that increased levels of reflectivity increase the amount of annual savings. As for assessment and decision making, the Building Envelope Lifecycle Asset Management Project focused on helping identify when and how to repair roofing stock. The focus of this project was on optimizing the results of the maintenance expenditures, while maximizing the value of the asset over the lifecycle (Vanier, 1998). In the end, this research developed a roofing maintenance model that considered condition assessment, risk analysis, energy analysis, and other types of maintenance information (Vanier, 1998). As for selecting roofing materials, more recently Contarini and Meijer (2015) compared materials for roof construction from an environmental point of view and to quantify the damage to the environment in terms of production, installation, maintenance, and operation. They determined that PVC roofing systems have less damaging effects than do EPDM and white bitumen products. Finally, Coffelt explored the occupant related costs associated with roofing system failure. Current roof management system cost models focus almost exclusively on the optimization of maintenance solutions (Coffelt and Hendrickson, 2010). Surprisingly, there is a lack of strong correlation between physical inspection ratings, leaks, and projected annual costs (Coffelt et al., 2010; Coffelt, 2008). This may suggest that the inspection may not be definitive in identifying the least cost points for roof replacements. This is partially due to the lengthy period of time required to move from a very poor condition to a failed state. In other words, a roof can stay in a very poor condition for a lengthy period of time, so long as regular maintenance is performed (Coffelt et al. 2010). Coffelt et al. (2010) also explored the likelihood of failure and the associated user cost. Nuisance leaks have an 82.4% change of occurring but only a $137 average occupant cost. On the other hand, serious leaks and catastrophic leaks come with a 16.2% and 0.04% chance of failure and $4,185 and $447,000 in associated user costs, respectively. Although the probability is low, for IT mission-critical facilities, the associated user costs could be exponentially larger; not because of damage to the infrastructure, but because of loss of mission-critical operation. It is these latter threats that IT mission critical facilities seek to avoid, and therefore illustrates the importance of balancing both cost-effective and protective roofing solutions.

Significant Roofing Studies

The most pertinent literature related to this research included two market research studies; the 2005 Roofing Industry Durability and Cost Survey (Cash, 2006) and the 2015-2016 NRCA Market Survey (NRCA, 2016). It should be noted, that of the literature identified in the review, these latter two studies were the only two reports that included a thorough cost comparison of different roofing system types. Unfortunately, there were not any roofing studies specific to mission-critical facilities identified. Because of this, an evaluation of various roof types and their suitability for use with IT mission-critical facilities is useful for building owners and roofing professionals in selecting the most appropriate roof systems for their projects, in regard to both risk reduction and maximizing value.

The purpose of the 2005 Roofing Industry Durability and Cost Survey was to provide an unbiased estimate of the durability of properly-designed, installed, and maintained roofing materials, and the estimated lifecycle cost of each system (Cash, 2006). Survey participants were asked to provide estimates on average and minimum life expectancies and values for installed, maintenance, and disposal costs for various roof systems. 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, had the shortest mean life expectancies of 16 and 14 years. Annual lifecycle costs for single-ply roof systems varied between $0.37/SF to $0.86/SF. Metal roof and built-up roof annual lifecycle costs ranged from $0.47/SF to $0.51/SF and $0.41/SF to $0.68/SF, respectively (Cash, 2006). Although the results showed little correlation between cost and the roof material category, this study did indicate that technology improvements had increased the estimated durability over the previous ten years. Since this study was conducted fifteen years ago, the current research project is needed to compare the durability of metal and built-up roofs today and how changes in lifespan have affected their lifecycle costs.

The purpose of the 2015-2016 NRCA Market Survey was to provide data for contractors to evaluate their business practices and compare material usage in regions throughout the United States. The survey asked roofing contractors from around the nation to indicate the breakdown of low- and steep-slope work performed for new construction, reroofing, and repair and maintenance during the year, and ultimately provided overall sales volume trends, roofing experiences, material usage and regional breakdowns (NRCA, 2016). This survey was at one time completed annually, but this study was the most recent data available. The survey indicated that 74% of sales were for low-sloped work, the majority of that associated with single-ply roof systems. The survey results for the geographic regions remained consistent with the national results with very few deviations. The results of this study showed an increasing trend in the use of single-ply roof materials for low-sloped roofs (NRCA, 2016). 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 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 continues to improve, it can be expected that single-ply materials will become less prone to failure and experience longer lifespans. This research further explores this trend relative to IT mission-critical facilities.

Methodology

This research evaluated various roof systems used with IT mission-critical facilities within the United States. Of particular interest was comparing the overall value and preference of single-ply roof systems, multi-layer built-up roofs, and metal roof systems for being used with IT mission-critical facilities. The telecommunications company that initiated this research maintains and operates properties that include all of the various roofing systems evaluated in this research. In an attempt to address the research objectives, a predominantly quantitative approach was selected for the data collection and analysis portion of the research (Creswell, 2017).

The research was staged in two parts: first, the effectiveness of the research instrument was tested amongst three industry subject matter experts; and second, the research instrument was sent to additional roofing professionals across the United States. The three subject matter experts selected to test the instrument worked for large national roofing firms, and included titles of director of global accounts, senior project manager, and owner, respectively. Each had over 20 years of experience in the roofing industry. Working with the telecommunications company, 62 different roofing companies were identified as playing a significant role in the company's roof construction and reconstruction efforts. These companies were selected because of the experience performing mission-critical facility roofing and reroofing projects for the telecommunications company. Although 46 (or 74%) initially indicated that they would be willing to participate in the survey, the actual response rate was only 17 (or 27%). In order to bid on projects for this company, 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, and adherence to the company's roof design standards. The participant sample was not held to any geographic constraints within the United States; however, the participating professionals were distributed fairly equally across the US, and included many regional and nationwide roofing providers. Four respondents indicated working nationwide, three respondents covering multiple regions of the country (including US West, Midwest, Central, and Midatlantic), with the remaining respondents spread across 32 identified states (most covering multiple states) including AR, AZ, CO, CT, DC, GA, IA, ID, IN, KS, KY, MD, MI, MN, MO, NC, NE, NJ, NM, NV, NY, OH, OK, PA, TN, TX, UT, VA, VT, WA, WI, WY. The participants were made up of company owners, administrators, project managers, and estimators with significant experience in the roofing industry. The authors acknowledge that there may be differences in preference and costs across the nation. However, since the purpose of this research was to establish relative trends between different roof systems, it was assumed that these differences would generally average out.

Five leading US roofing manufacturers were also contacted to obtain lifespan estimates of the roof systems targeted in this research. However, the manufacturers did not provide specific lifespan estimates for the roof materials; rather, they communicated that 20- and 30-year warranties were available for all of the sampled systems as long as the warranty requirements were met throughout the life of the roof. By meeting the design, installation, and

TABLE 1.—Roof Systems Studied

Category	Roof System
Built Up	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	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	Metal 24-Gauge Minimum

maintenance requirements, the manufacturers estimated that the roofing material lifespans should exceed the specified warranty periods.

Survey Instrument

To study and evaluate various roof systems and materials for use with mission-critical facilities, a survey was administered to determine the lifecycle costs of roofing membrane systems, as well as rating those systems for suitability of use with various mission-critical facilities. Part A asked survey participants to provide an estimate for the following four items: average lifespan of the roof type expressed in years, average costs to install by roof top expressed as costs per square foot of roof, average costs to remove (including disposal costs) by roof types expressed as costs per square foot of roof, and the average costs to maintain by roof type on an annual basis expressed as costs per square foot of roof. Part B asked survey participants to include a rating for each roof system relative to different facility types, accounting for total value (cost, lifespan, and risk) and rated from 1 – 5 (not recommended, minimally acceptable, acceptable, good, and best, respectively). The data analysis of the survey results was performed by simply averaging the survey participants responses for each of the different survey questions. The roof systems selected for this study represented the most common low-sloped roof types currently used by the telecommunications company. The twelve different roof systems evaluated in this study are shown in Table 1. The telecommunications company used in this research builds and maintains seven different types of facilities, and each was evaluated in conjunction with the different roof systems. The building types used for the evaluation are shown in Table 2. This breakdown helps distinguish between preferences for mission-critical facilities versus standard commercial facility applications.

Findings

There were two principal elements of analysis performed for this research. The lifecycle cost analysis explored the relative costs of the roof systems studied and the roof rating analysis explored the relative suitability of each.

TABLE 2.—Structure Types Studied

Category	Roof System
Mission-Critical	Central Offices
	Data Center / Data Processing Facilities
	Equipment Buildings
Non-Mission-Critical	Administrative Buildings
	Storage Buildings
	Warehouses
	Garages

Lifecycle Cost Analysis

Part A of the survey results measured the lifecycle cost data for each roof type. 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 installation and removal costs. The total lifecycle costs were then divided by the estimated lifespan in years to determine the annual lifecycle costs. A summary of this information is shown in Table 3. The annual lifecycle cost data spanned from a minimum of $0.899/SF to a maximum of $1.090/SF, a range of $0.191/SF, with a mean and median cost of $0.973/SF and $0.964/SF, respectively.

The data indicated 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. The exception to this was 60 Mil TPO, which ranked as the second highest annual lifecycle cost, but can be attributed to 60 Mil TPO having the shortest estimated lifespan. Although the built-up roofs had estimated lifespans slightly exceeding their single-ply counterparts, the high cost of installation for built-up roofs negated the efficiency provided by their durability. The selection with the lowest annual lifecycle cost was 2-Ply Modified Bitumen. The metal roof had the third lowest annual lifecycle cost, despite having the highest install, removal, and total lifecycle costs, which were outliers in the dataset. The total lifecycle cost of the metal roof was offset by its longer estimated lifespan. The annual lifecycle cost range of $0.191/SF represents a relatively small range, with only a 21.2% cost increase impact when selecting between the highest and lowest annual cost options. On the other hand, this can be contrasted with the total lifecycle cost range of $11.18/SF, representing 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 cost of the roof material spread 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 roofing materials for a project.

TABLE 3.—Annual Lifecycle Costs of Roof Systems

		Costs/SF				
Roof System	Lifespan (years)	Install	Removal	Annual Maint.	Lifecycle	Annual Lifecycle
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 Minimum	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	\$24.34	\$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

Roof Ratings Analysis

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. Table 4 shows the results of the roof ratings for both the mission-critical and non-mission-critical structures.

The roof ratings data for mission-critical facilities ranged from a rating of 1.7 (between Not Recommended and Minimally Acceptable) to a rating of 4.3 (between Good and Best). The range and distribution of the ratings suggests that the roofing professionals were able to differentiate the roofing system selections by total value and provide a preference of the roof system selections for use with mission-critical facilities. For 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 which rated just higher than the 2-Ply Modified Bitumen selection. The data indicates that built-up roofs provide better overall value than single-ply roofs, although they vary in value amongst each other. It should further be noted that most of the roof systems rated below an acceptable rating for mission-critical structures. This indicates an overall preference towards built-up roofing systems, when considering the combined effects of minimized risk, cost effectiveness, and increased lifespan. However, the best single-ply roof systems rated essentially equivalent to the metal and lowest built-up roof systems. There were not any significant differences noted between different mission-critical structure types (i.e., central office, data center, and equipment buildings). Ultimately, these results indicate a preference to avoid single-ply roofing systems for mission-critical structures.

Table 4 also shows the results for non-mission critical facilities using the same numerical rating scale. The roof ratings data for non-mission-critical facilities ranged from a rating of 2.4 (between Minimally Acceptable and Acceptable) to a rating of 3.9 (between Acceptable and Good). 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 1 and 2 or between 4 and 5, suggesting that more roof material selections would be appropriate for use with non-mission-critical facilities than with mission-critical facilities. This also suggests that the roofing professionals surveyed view

TABLE 4.—Roof Ratings

	Mission-Critical Structures				Non-Mission-Critical Structures				
Roof System	Central Office	Data Center	Equipment	Average	Admin	Storage	Warehouse	Garage	Average
3-Ply BUR w/Cap	4.4	4.2	4.3	4.3	3.6	2.4	2.4	2.6	2.8
4-Ply BUR w/Gravel	3.9	3.7	3.8	3.8	3.1	2.4	2.3	2.4	2.5
2-Ply Mod Bit w/Cap	3.1	3.1	3.2	3.1	2.8	2.4	2.1	2.3	2.4
Metal 24 Ga Minimum	3.1	2.8	3.0	2.9	3.6	4.3	3.8	3.9	3.9
90 Mil EPDM	2.9	2.9	2.9	2.9	3.5	3.3	3.5	3.4	3.4
2-Ply Mod Bitumen	2.8	2.6	2.9	2.8	3.1	3.1	2.9	2.9	3.0
80 Mil PVC	2.6	2.4	2.3	2.5	3.6	3.6	3.6	3.6	3.6
60 Mil KEE PVC	2.5	2.1	2.5	2.4	3.7	3.9	3.9	3.9	3.9
80 Mil TPO	2.1	2.2	2.3	2.2	3.4	3.4	3.5	3.6	3.5
60 Mil EPDM	2.1	2.1	2.4	2.2	3.2	3.4	3.5	3.2	3.4
50 Mil XT KEE	2.1	2.0	2.1	2.0	3.0	3.1	3.3	3.2	3.1
60 Mil TPO	1.6	1.5	1.9	1.7	2.9	3.4	3.4	3.4	3.3

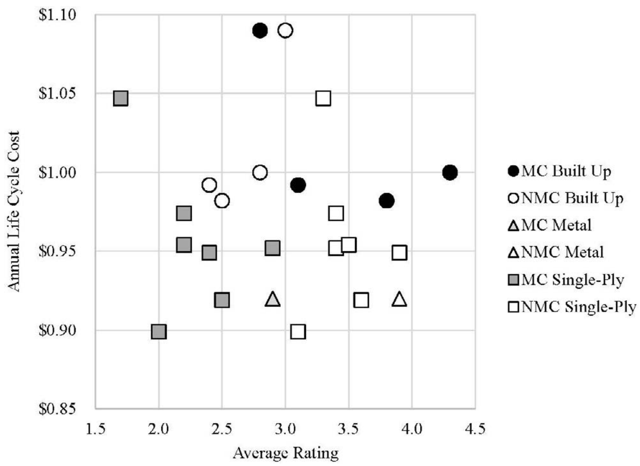

FIGURE 1.—

the operations housed in non-mission-critical facilities as more tolerant in the event of a roof failure. The participants rated the single-ply and metal roofs higher overall than the built-up roof selections for non-mission-critical facilities. It should also be noted that while the ratings 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 Table 4). This can most likely be attributed to administrative structures being more likely to house mission-critical operations than the other three non-mission-critical facility types. 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.

Since the value rating was based on the combined effects of risk, cost, and lifespan, the only real variable differential between mission-critical and non-mission-critical structures was the risk itself. The results indicate 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, when assigning the total value ratings to the roof systems. Rather, the results showed that the opposite effect occurred. When the impact from risk was reduced for the non-mission-critical facilities, the ratings results aligned much closer with the annual lifecycle costs from Part A. In essence, without significant risk the lower cost roofs trend 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 for non-mission-critical structures. This higher risk rating for mission-critical structures illustrates the research participants' understanding of the critical nature of the operations occurring within those facilities. These results indicate that the critical nature of a roofing failure could carry an impact far greater than savings achieved from the project. The higher weighting of risk in consideration of mission-critical facilities produced results with the most robust roofing options rating as the highest. In short, the results between mission-critical and non-mission-critical structures have an inverse rating distribution due to the element of higher risk associated with mission-critical structures.

Figure 1 shows a comparison of the average rating plotted against the annual life cycle cost for mission-critical (MC) and non-mission-critical (NMC) structures and the different roofing types (built-up, metal, and single-ply roof systems). These results show similar ratings among low and high cost roof material selections, for both mission-critical and non-mission-critical structures, respectively. The ratings are also much closer aligned to which roof system group (built-up roof, single-ply, and metal) the roof systems belonged to. This can be seen by the different roof systems of the same type generally clustering together in rating, independent of cost. This suggests that the type of roof system matters more in the selection process than the specific roof system.

Cost Applied to Rating

The final objective of this research was to generate a priority ranking of roof systems for mission-critical facilities. This was done by combining the results from Part A and Part B of the survey instrument, to observe trends in the combined effects of lifecycle cost data with the roof-by-facility type ratings for mission-critical facilities. The average mission-critical rating was first designated as the base score for each roof material selection. The average and standard deviation of the annual lifecycle cost data were then determined to be $0.973 and $0.052, respectively. Each annual lifecycle cost value was then converted to a relative standard deviation score based on how close it was to the average cost value. Annual lifecycle cost values lower than the average scored higher than those that cost more. 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 the least. Because it was not known how much weight the roof rating score should carry in the combined suitability score, 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 (see Table 5). The previous results greatly implied that the risk should be a significant consideration for mission-critical facilities. However, cost is still an essential part of the selection process. The purpose of this exercise was to provide a relative ranking comparison of the different roofing systems. So, rather than focus on the scores themselves, the suitability scores for each weighted category were ranked from 1 to 12, with 12 being the most suitable roofing system. The suitability rankings were then plotted against each other based on the weighted sensitivity results, as shown in Figure 2. This sensitivity analysis was used to identify individual roofing systems that were more susceptible to be ranked higher based on cost over risk. Using the original ratings as the basis for comparison, the

TABLE 5.—Roof Suitability Scores for Mission-Critical Facilities

Roof System	Roof Rating	Annual Lifecycle Cost	Standard Deviation Score	Sensitivity to Risk (Roof Rating / Standard Deviation Score)					
				100/0	90/10	80/20	70/30	60/40	50/50
3-Ply BUR w/Cap	4.3	$1.000	2.5	4.30	4.12	3.94	3.76	3.58	3.40
4-Ply BUR w/Gravel	3.8	$0.982	2.8	3.80	3.70	3.60	3.50	3.40	3.30
2-Ply Mod Bit w/Cap	3.1	$0.992	2.6	3.10	3.05	3.00	2.95	2.90	2.85
Metal 24 Ga Minimum	2.9	$0.920	4.0	2.90	3.01	3.12	3.23	3.34	3.45
90 Mil EPDM	2.9	$0.952	3.4	2.90	2.95	3.00	3.05	3.10	3.15
2-Ply Mod Bitumen	2.8	$1.090	0.7	2.80	2.59	2.38	2.17	1.96	1.75
80 Mil PVC	2.5	$0.919	4.0	2.50	2.65	2.80	2.95	3.10	3.25
60 Mil KEE PVC	2.4	$0.949	3.5	2.40	2.51	2.62	2.73	2.84	2.95
80 Mil TPO	2.2	$0.954	3.4	2.20	2.32	2.44	2.56	2.68	2.80
60 Mil EPDM	2.2	$0.974	3.0	2.20	2.28	2.36	2.44	2.52	2.60
50 Mil XT KEE	2.0	$0.899	4.4	2.00	2.24	2.48	2.72	2.96	3.20
60 Mil TPO	1.7	$1.047	1.6	1.70	1.69	1.68	1.67	1.66	1.65

following observations for this part of the analysis were made:

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 having the highest annual lifecycle cost. Although considered a good option for risk, as cost becomes more critical its suitability decreases.
4) The Metal 24-Gauge Minimum, 80 Mil PVC Fully Adhered, and 50 Mil XT KEE Fully Adhered selections saw the most dramatic increases in their suitability ranking, when cost becomes a more significant factor. At the 50% / 50% weighting, the three systems ranked amongst the most suitable at 12, 9 and 8, respectively. This can be attributed to the metal roof system having the longest lifecycle and the other two roof selections having the two lowest annual lifecycle costs overall.
5) 3-Ply Built-Up Roof with Modified Cap and 4-Ply Built-Up Roof with Gravel consistently ranked the highest when considering both value and cost. Metal 24-Gauge Minimum is also consistently among the best options when considering both value and cost. One single-ply roof system, the 90 Mil EPDM Fully Adhered option, ranked just below these three consistently for the various value and cost considerations. This indicates that thicker single-ply systems are relatively comparable to the built-up roof systems.

The application of different weightings levels between annual lifecycle costs and mission-critical ratings illustrate that as lifecycle costs receive a higher weight towards suitability for mission-critical facilities, the ranking of roof systems that otherwise have lower roof professional ratings generally begin to increase. The results of this exercise provides a caution against overweighting annual lifecycle cost. This is because it introduces an increased amount of

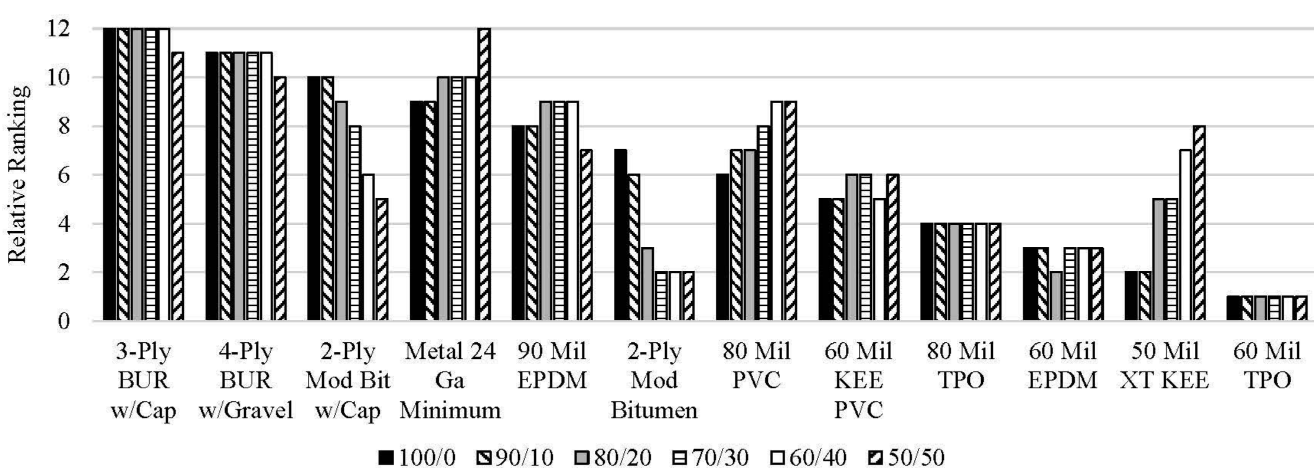

FIGURE 2.—

risk to the operation, from the perspective of the roofing professionals.

Conclusions

As organizations become increasingly dependent on mission-critical facilities to support their 24/7 operations, there exists a greater need for strategic selection of roof systems that perform reliably and meet financial demands of optimized building lifecycle costs. The purpose of this research was to evaluate different roof systems with regard to their lifecycle costs and roof professional's assessment in use with mission-critical facilities. The first research objective was to determine the average annual lifecycle costs for the commonly used low-pitch roof systems. The single-ply roof selections overall carried lower installation and removal costs. 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 total lifecycle cost stretched from $17.89/SF to $29.07/SF, a range of $11.18/SF. This equates to a 62.5% cost increase from the lowest to highest cost roof selection. However, when factoring in the estimated lifespans into the lifecycle analysis, the range between the lowest and highest annual lifecycle costs was much less dramatic at only $0.191/SF per year, or a cost increase impact of 21.3%. These results suggest that organizations can gain greater insight into the lifecycle costs of their roofing by approaching costs on an annual basis, rather than merely calculating total cost over the lifetime of the asset.

The second research objective played a significantly more important role in this research project, because this objective was to determine roofing professionals' preferred roof systems for use in mission-critical facilities. This portion of the research accounted for overall roof system value, including an element of risk. Ultimately the roofing professionals indicated that built-up roof systems were better suited for mission-critical structures. 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 greater 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 third objective was to provide a priority ranking of the various roofing systems that could be used for mission-critical facilities. A definitive priority rank list of the roof systems for use with mission-critical facilities was not established due to the variances created by applying different levels of the lifecycle costs to the roof material ratings. However, this research did perform a sensitivity study to observe how the suitability rankings of the roof materials change as the lifecycle cost and ratings results were combined at different weighting levels. Although built-up and metal roof systems generally scored the highest with regard to value, the single-ply roof systems increased in relative ranking as the cost considerations increased. This was especially true for the two systems 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 system selections for mission-critical facilities at a 50% rating / 50% cost weighting, despite having value ratings approaching minimally acceptable. Metal 24-Gauge Minimum and 90 Mil EPDM Fully Adhered were the only material selections in the top half of value 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. Ultimately, 3-Ply Built-Up Roof with Modified Cap Sheet and 4-Ply Built-Up Roof with Gravel were the preferred choices for roof systems in mission-critical facilities.

Implementation

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. This research provides an estimate of current lifecycle cost data, but more importantly 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 benefit from the combined relative 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/SF) while still maintaining an acceptable roof rating.

Project stakeholders that place utmost emphasis on risk reduction can utilize this data to select the roof systems that roofing professionals rank the highest for mission-critical facilities. Although the probability of roof incidences by roof system is fairly unpredictable due to a multitude of external factors, the estimated lifespan of each roof system 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 systems with the longest estimated lifespans as well as having the highest ratings for use with mission-critical facilities. The sensitivity analysis performed in this research also emphasizes that stakeholders should 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.

Limitations

This study was performed for one of the largest telecommunications companies in the US. This company has a significant investment in IT mission-critical real estate, with tens of millions of square feet spread over thousands of properties across the US. As such, it was assumed that surveying the roofing professionals performing their construction and reconstruction projects would provide results that are beneficial across the industry. Although 46 verbal commitments were obtained out of the original sample of 62 roofing professionals, the actual response rate was lower at only 17 responses (or 27.4%) of those who were sent the survey. These responses were valuable in providing current material lifecycle costs and observing trends relative to vendor assessments of roof systems for mission-critical facilities; however, the study could have benefited from a larger sample size to reinforce the conclusions obtained from the results. It is believed that the data provided in this study is adequate for making relative comparisons, but that actual data should be cautiously used for estimating purposes. With a larger sample size, the research team could also assess whether geographic location influenced the individual responses and another variable should be added to the results. Finally, the sample could also be broadened beyond the subcontractor pool of a single telecommunications company, to ensure that the results represent the entire roofing industry in the US.

REFERENCES

Attaran, M. (2003). “Information Technology and Business-Process Redesign.” Business Process Management Journal, 9(4), 440–458. doi:10.1108/14637150310484508.

ANSI (2019). “Standard Outage Classification.” American National Standard for Telecommunications. American National Standards Institute, Inc.

Baskaran, B.A., Paroli, R.M., and Kalinger, P. (2007). “Advancements and Changes in the North American Commercial Roofing Industry.” Proceedings of International Conference on Building Envelope Systems and Technology, Bath, United Kingdom, 275–286.

Berdahl, P., Akbari, H., Levinson, R., and Miller, W.A. (2008). “Weathering of Roofing Materials – An Overview.” Construction and Building Materials, 22(4), 423–433. doi:10.1016/j.conbuildmat.2006.10.015.

Blackhurst, M., Hendrickson, C., and Matthews, H.S. (2010). “Cost-Effectiveness of Green Roofs.” Journal of Architectural Engineering, 16(4), 136–143. doi:10.1061/(ASCE)AE.1943-5568.0000022.

Bush, P.R., Crawford, G.L., Kriner, S., Miller, T., Praeger, C.E., Robinson, J., Scichili, R., and Shoemaker, W.L. (2016, October 19). “Cool Metal Roofing.” Retrieved from https://www.wbdg.org/resources/cool-metal-roofing.

Caballero, A. (2013). Information Security Essentials for IT Managers: Protecting Mission-Critical Systems. Computer and Information Security Handbook, 379–407. Morgan Kaufmann.

Cash, C.G. (2006). “2005 Roofing Industry Durability and Cost Survey.” Proceedings of the RCI 21st International Convention.

Coffelt, D.P. (2008). Roof Management Improvement: Improving Infrastructure Management Decision Making through a Consideration of Total Life Cycle Cost and Deterioration. PhD Dissertation, Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA.

Coffelt, D.P., Hendrickson, C.T., and Healey, S.T. (2010). “Inspection, Condition Assessment, and Management Decisions for Commercial Roof Systems.” Journal of Architectural Engineering, 16(3), 94–99. doi:10.1061/(ASCE)AE.1943-5568.0000014.

Coffelt, D.P. and Hendrickson, C.T. (2010). “Life-Cycle Costs of Commercial Roof Systems.” Journal of Architectural Engineering, 16(1), 29–36. doi:10.1061/(ASCE)1076-0431(2010)16:1(29).

Contarini, A. and Meijer, A. (2015). “LCA Comparison of Roofing Materials for Flat Roofs.” Smart and Sustainable Built Environment, 4(1), 97–109. doi:10.1108/SASBE-05-2014-0031

CPUC. (2018). “Analysis of Major Communication Outages in California during the 2017 January – February Storms.” California Public Utilities Commission.

Creswell, J.W. and Creswell, J.D. (2018). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. Thousand Oaks, CA: SAGE Publications, Inc.

Curtis, P.M. (2011). Maintaining Mission Critical Systems in a 24/7 Environment. Hoboken, NJ: Wiley-IEEE Press.

Daneshmand, M. and Savolaine, C. (1993). “Measuring Outages in Telecommunications Switched Networks”. IEEE Communications Magazine, 31(6), 34–38. doi:10.1109/35.214888.

DOD (2019). “UFC 3-110-03 Roofing, With Change 4.” United Facilities Criteria. Department of Defense.

FCC. (2016). “Glossary of Fields in NORS Reports.” Network Outage Reporting System. Federal Communications Commission.

Gold, L. (2007). “Disaster Recovery Planning: How do you Measure up?” Accounting Today, 21(7), 31–35.

Guyer, J.P. (ed.) (2018). An Introduction to Roofing Systems. Guyer Partners.

Hosseini, M., Tardy, F., and Lee, B. (2018). “Cooling and Heating Energy Performance of a Building with a Variety of Roof Designs; the Effects of Future Weather Data in a Cold Climate.” Journal of Building Engineering, 17(2018), 107–114. doi:10.1016/j.jobe.2018.02.001.

Jordan, J.W., Kimble, R.A., and Sharer, A.J. (2018). “Commercial Roofing Condensation – Lessons Learned.” Proceedings from Eight Congress on Forensic Engineering, Austin, Texas, 12–22. doi:10.1061/9780784482018.002.

Kaplan, J., Forrest, W., and Kindler, N. (2008). “Revolutionizing Data Center Energy Efficiency.” McKinsey & Company.

Kern, H., Nemiro, G., and Galup, S. (2000). IT Organization: Building a Worldclass Infrastructure. Prentice Hall.

Liotine, M. (2003). Mission-Critical Network Planning. Artech House.

McIntyre, J.K., Winters, N., Rozmyn, L., Haskins, T., and Stark, J.D. (2019). "Metals Leaching from Common Residential and Commercial Roofing Materials Across Four Years of Weathering and Implications for Environmental Loading." Environmental Pollution, 255(2019): 113262. doi:10.1016/j.envpol.2019.113262.

McNally, T. (Ed.). (2011). Polymer Modified Bitumen: Properties and Characterization. Elsevier.

NRCA (2016). "2015-2016 NRCA Market Study." National Roofing Contractors Association.

Petrinovich, C.A. (2020). Roof Material Suitability for IT Mission-Critical Facilities. MS Thesis, Construction and Facilities Management, Brigham Young University, Provo, Utah.

Robin, M.L. (2000). "Fire Protection in Telecommunication Facilities." Process Safety Progress, 19(2), 107–111. doi:10.1002/prs.680190211.

Smith, T. (2016, October 5). "Roofing Systems." Retrieved from https://www.wbdg.org/guides-specifications/building-envelope-design-guide/roofing-systems.

Sproul, J., Wan, M.P., Mandel, B.H., and Rosenfeld, A.H. (2014). "Economic Comparison of White, Green, and Black Flat Roofs in the United States." Energy and Buildings, 71(2014), 20–27. doi:10.1016/j.enbuild.2013.11.058.

Taylor, T. (2019). "Reflective Roofing Use on Commercial Buildings in the United States: An Energy Type and Cost Analysis." Buildings, 9(10), 212. doi: 10.3390/buildings9100212.

Testa, J. and Krarti, M. (2017). "Evaluation of Energy Savings Potential of Variable Reflective Roofing Systems for US Buildings." Sustainable Cities and Society, 31(2017), 62–73. doi:10.1016/j.scs.2017.01.016.

Uhlman, K.L. (2006). Corporate Transformations and Collaborative Partnerships in Mission Critical Facilities: A Delphi Study (Doctoral dissertation, University of Phoenix).

Vanier, D. (1998) "Product Modeling: Helping Life Cycle Analysis of Roofing Systems." CIB Report, 423–426.

Woodell, E. (2015). Mission-Critical Facilities Management: For the Non-Engineer. United States: CreateSpace Independent Publishing.