# Construction Technologies and Practices in Sustainable Airport Development

by

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# ABSTRACT

Airports are a critical component of a region's network and socioeconomic development. Regardless of the type of airport–commercial, general, regional, national, or international–their construction and development are highly advantageous to communities. Some advantages include, but are not limited to new job opportunities, access to the global market, and increased economic activity. Nonetheless, airport development has some downsides that a community must always account for. These downsides directly impact the sustainability of a region; greenhouse gas (GHG) emissions, energy inefficiencies, water pollution, air pollution, and waste are just a few examples. However, twenty-first century global sustainability efforts are shifting the dynamic of sustainability practices in the U.S. The fight for a balance between socioeconomic benefits and the minimization of negative environmental impacts is advancing thanks to the development and implementation of sustainable practices and technology. For instance, U.S. airport development has seen a rise in the use of sustainable construction technologies and practices. Some of the examples of construction technologies and practices implemented in sustainable airport development are virtual design and construction, Spot by Boston Dynamics, prefabrication, and others. The multiple-case studies based on these technologies and practices indicate joint efforts for sustainability by the aviation and construction industries.

# DEDICATION

I would like to dedicate this achievement to my family and friends for their unwavering support and love throughout my educational journey. No effort on my part will be enough to thank you for your encouragement, patience, and understanding.

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I would like to extend my gratitude to my committee for their valuable guidance in my research and for taking the time to serve as committee members. I sincerely appreciate their support and encouragement.

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ACRONYM LIST

| | |
|---|---|
| AC | :Advisory Circular |
| ACI | :Airports Council International |
| ACRP | :Airport Cooperative Research Program |
| ADOT | :Arizona Department of Transportation |
| BIM | :Building Information Modeling |
| CAPA | :Centre for Aviation |
| CDA | :Chicago Department of Aviation |
| CII | :Construction Industry Institute |
| DEN | :Denver International Airport |
| DFW | :Dallas-Fort Worth International Airport |
| EPA | :Environmental Protection Agency |
| FAA | :Federal Aviation Administration |
| GHG | :Greenhouse Gasses |
| GIS | :Geographic Information Systems |
| GPR | :Ground Penetrating Radar |
| HVAC | :Heating, Ventilation, and Air Conditioning |
| HWD | :Heavy Weight Deflectometer |
| IVR | :Immersive Virtual Reality |
| LAX | :Los Angeles International Airport |
| LEED | :Leadership in Energy and Environmental Design |
| MSC | :Midfield Satellite Concourse |
| NAPFT | :National Airport Pavement Test Facility |

| | |
|---|---|
| NDT | :Nondestructive Testing |
| ORD | :Chicago O'Hare International Airport |
| PCI | :Pavement Condition Index |
| PSPA | :Portable Seismic Pavement Analyzer |
| ROI | :Return on Investment |
| RTRP | :Rail-to-Rail Profiler |
| SAM | :Sustainable Airport Manual |
| SEA | :Seattle-Tacoma International Airport |
| USGBC | :U.S. Green Building Council |
| VDC | :Virtual Design and Construction |

# CHAPTER 1

# INTRODUCTION

## Background

Industries from all sectors of the global economy rely on efficient forms of transportation to increase their operational performance. Being able to transport goods and people in a reliable and timely manner is highly sought after. For this reason, airports have become an element of high value to national infrastructure. From a socioeconomic perspective, airports support outsourcing, supply chains, and tourism, enable international investment, and encourage innovation by enabling a globalized network. Their largely positive socioeconomic impact is clearly supported by data that indicates airports "account for more than 7 percent of national GDP and support more than 6 percent of the country's workforce" ([Facts about commercial airports], n.d.). This is just a sample of the total benefits that underscore the importance of airports to communities and metropolitan areas. To put things into perspective, there are 41,700 airports around the world and nearly 20,000 of them are found in the United States (Carlier, 2023). According to the Airport Construction Database CAPA, these numbers are expected to increase. Over the course of one year, eight new airports were constructed in the United States and 13 airports implemented new runways. This does not include projects on runway extensions, new terminals, and terminal extensions ("New airports," n.d.). Despite the fact that airport construction and development is beneficial for the U.S. economy, there are concerns pertaining to sustainability.

According to the Environmental Protection Agency (EPA), sustainability is meeting human needs while safely co-existing with Earth's environment (Environmental

Protection Agency, 2022). Correspondingly, the act of pursuing sustainability entails the development and conservation of conditions that fulfill the needs of today without compromising the needs of future generations (Environmental Protection Agency, 2022). Therefore, sustainability requires a multidisciplinary approach that takes into consideration environmental, social, and economic concerns (Environmental Protection Agency, 2022). In airport construction and development, pursuing sustainability is better described as a balance between the economy, environment, community, and operations (Federal Aviation Administration, 2022).

The pursuit of sustainability can be addressed in the construction and development of airports. Their abundance, along with the importance they hold, makes them a key component for sustainable development in the nation. Airports are in an undeniably unique position in which they must augment the socioeconomic benefits they bring, while simultaneously minimizing negative environmental impacts. This dual purpose is encouraging airports to implement sustainable construction technologies and practices in their development projects. By redirecting their focus towards supporting a sustainable and resilient future, airports are able to engage in innovative decision-making and set ambitious goals that address and ensure the inclusion of sustainability.

**Purpose and Scope**

This thesis provides a synthesis of construction technologies and practices found in sustainable airport development across the United States. In order to obtain an in-depth, multi-faceted view, this thesis includes multiple case studies on construction technologies and practices used in sustainable airport development. The intent of this report is to determine the current economic, social, and environmental effectiveness of construction technologies and practices. The data for this report was collected solely through web-based research. The effectiveness was measured by accounting for economic, social, and environmental improvements or advantages, some of which were cross referenced with statistics.

Specific research questions for this report include:

- What is sustainability?
- What are some examples of sustainable pre-construction, construction, and post construction technologies and practices used in airport development across the United States?
- What are the economic benefits of sustainable pre-construction, construction, and post construction technologies?
- What are the economic benefits of sustainable pre-construction, construction, and post construction practices?
- What are the social benefits of sustainable pre-construction, construction, and post construction technologies?
- What are the social benefits of sustainable pre-construction, construction, and post construction practices?
- What are the environmental benefits of sustainable pre-construction, construction, and post construction technologies?
- What are the environmental benefits of sustainable pre-construction, construction, and post construction practices?

# CHAPTER 2

# LITERATURE REVIEW

## Defining Sustainability

According to the 1987 Brundtland Report, "sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" (World Commission on Environment and Development, n.d.). Similarly, the EPA states, sustainability is built around the following idea, "everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment" (Environmental Protection Agency, 2022). More modern definitions define sustainability in a much more eloquent manner. One example is provided by the Sustainability Committee at the University of California, Los Angeles, which produced a relevant study entitled "the integration of environmental health, social equity, and economic vitality in order to create thriving, healthy, diverse, and resilient communities for this generation and generations to come" ("What is sustainability?," n.d.). If analyzed closely, all these definitions express how sustainability is a multidisciplinary concept. Definitions of sustainability consistently include three core concepts: economic, social, and environmental (Mollenkamp et al., 2022). Very often, these three core concepts are informally referred to as profits, planet, and people (Mollenkamp et al., 2022).

Economic sustainability is the concept of ensuring resources are used efficiently in order to sustain operations and return a profit (Airports Council International, 2021). This concept is designed around the idea of creating long-term economic prosperity while also managing the environmental and social aspects of activities. Ultimately, by focusing on the conservation of renewable and nonrenewable natural resources used during operations, an organization can directly or indirectly contribute to the local, national, or international economy (Airports Council International, 2021). For the purpose of this report, economic sustainability is defined as ensuring resources are used efficiently to maintain operations and create profit.

Social sustainability is the concept of accounting for the positive and negative effects humans have on society (Airports Council International, 2021). From an individual perspective, this constitutes standards of living such as health, safety, shelter, water, and food. From an organization's perspective, this means ensuring the welfare of employees, customers, and local communities (Airports Council International, 2021). This is achieved by adopting objective and ethical approaches (Airports Council International, 2021). For the purpose of this report, social sustainability is defined as the social impact created by construction technology or practices.

Environmental sustainability is the concept of ensuring natural resources are conserved and protected in order to maintain current and future ecological balance (Mollenkamp et al., 2022). This includes the ability of stabilizing or improving the quality of life by living within the carrying capacity of Earth's life support systems (Mollenkamp et al., 2022). Achieving this is possible by utilizing natural resources at a sustainable rate in order to limit environmental damage (Airports Council International, 2021). Some examples of consumable natural resources are fossil fuels. For the purpose of this report, environmental sustainability is defined as a reduction in the negative environmental impact caused by the use of construction technology or practices.

## Defining Airport Sustainability

As previously mentioned, sustainability has multiple related definitions offered by different entities due to its multidisciplinary nature. The following definitions are examples of the polysemous traits of sustainability in relation to airports. According to the Federal Aviation Administration (FAA), airport sustainability is based on actions that "reduce environmental impacts," "help maintain high, stable levels of economic growth," and "help achieve social progress" (Federal Aviation Administration, 2022). A different definition offered by the Environmental Affairs Committee working for the Airports Council International-North America claims sustainability is a "holistic approach to managing an airport so as to ensure the integrity of the economic viability, operational efficiency, natural resource conservation, and social responsibility of the airport" (Pfeifer, n.d.). Another definition for airport sustainability can be found in the Airport Cooperative Research Program (ACRP) *Synthesis 10: Airport Sustainability Practices.* This synthesis states that airport sustainability is "a broad term that encompasses a wide variety of practices applicable to the management of airports;" these practices must protect the environment and promote social and economic progress (Berry et al. 2008). Unlike the previous sources, the Sustainable Aviation Guidance Alliance (SAGA) does not provide a specific definition for airport sustainability. Instead, it encourages organizations to adopt unique definitions that suit them the best, all of which are generally based around economic stewardship, economic vitality, and social responsibility ([Article about sustainability], n.d.). From the definitions above, it can be concluded that sustainability in aviation is defined by results rather than characteristics, features, or qualities. In all essence, sustainability is a value judgment on the subject in question.

## Drivers And Barriers for Airport Sustainability

A study performed by the ACRP determined the prevailing reasons for implementing airport sustainability practices are climate change and stakeholder relations (Berry et al. 2008). Further studies on the topic were made; in 2010, a survey performed by the ACRP showed the top 5 drivers of airport sustainability efforts: “cost reductions, desire for improved sustainability performance, neighbors and community, and leadership in the industry” (Thomson & Delaney, 2014). However, there are variables that challenge the goals and implementation of airport sustainability practices. The following are key barriers to the implementation of airport sustainability practices: competing priorities amongst managers, lack of funding, inability to form partnerships, and failure to acknowledge sustainability issues (Thomson & Delaney, 2014).

## Defining Construction Technologies

The construction process is a long and complex operation that includes development of specific requirements applied to particular design. The process can be divided into six main steps: conception, design, preconstruction, procurement, construction, and post construction (monday.com, 2020). Throughout these steps, detailed organization is required from multiple entities to deliver the best product possible. A relatively new way of enhancing this process is through the adoption of construction technologies. Research shows that the adoption of construction technologies impacts three key items in the construction industry: productivity improves by 30 to 45 percent, material predictability becomes more accurate, and material reliability increases (Construction technology, n.d.). According to the Construction Industry Institute (CII), construction technologies are “innovative tools, machinery, modifications, software, etcetera used during the construction phase of a project that enables advancement in field construction methods…" (Construction technology, n.d.). Some examples of construction technologies seen in airport development include the following: geographic information systems (GIS), building information modeling (BIM), Energy Star certified products, and component tracking systems.

**Defining Sustainable Construction Practices**

Construction practices, also known as "best construction practices," refer to certain processes or methods that guarantee optimal project performance when properly implemented (Best practices, n.d.). In order to be considered a best construction practice, the method or process must be widely used and validated by the construction industry (Best practices, n.d.). In addition, optimal project performance is not measured on a cost, safety, or timeliness basis, but rather on improvements on the stability and predictability of project performance (Best practices, n.d.). Most recently, the concept of best practices in construction has merged with sustainability; the new term is sustainable construction practices (Jenks et al., 2011).

According to *Report 42: Sustainable Airport Construction Practices* by the Airport Cooperative Research Program (ACRP), sustainable construction practices are practices that provide sustainable advantages during all phases of the construction process (Jenks et al., 2011). Out of the entire process, the steps that hold the most influence on the sustainability of a project are planning and design (Jenks et al., 2011). During these steps, decisions are made on whether sustainable construction practices should be implemented, and if so, which; for example, Leadership in Energy and Environmental Design (LEED) based designs, construction methods, equipment, and sustainable materials (Jenks et al., 2011). The reasoning behind their high level of influence is due to the chain reaction created by these decisions relative to other phases of the construction process.

## Case Studies

The following case studies provide information about construction technologies and practices recently used in sustainable airport development. In order to better illustrate this information, the case studies are divided into three sections: pre-construction, construction, and post construction. In addition, each of the three sections have two subsections: technology and practices. The economic, social, and environmental effects of these technologies and practices are covered within the studies.

### *Pre-Construction Technology: Virtual Design & Construction*

Virtual reality is an artificial, fully digital, computer-generated environment which provides an immersive experience for its users by projecting images on head mounted displays (Tall, n.d.). Virtual design and construction (VDC) is technology that branches off virtual reality; it uses building information modeling (BIM) along with other data to simulate virtual designs and construction (Boggus & Blizzard, 2017). Using VDC allows project stakeholders to view a virtual version of the finalized project before real life construction even begins; this facilitates problem detection and promotes innovative solutions for said problems (Boggus & Blizzard, 2017). In addition, VDC is a multipurpose technology that can be used to address several other components of a project such as scheduling, logistics, safety, and cost (Boggus & Blizzard, 2017).

In 2019, the nation’s leading aviation contractor, Hensel Phelps Construction Group, utilized VDC during its participation in the Midfield Satellite Concourse (MSC)

North Gates project at Los Angeles International Airport (LAX) (“Aviation construction,” 2019). The aviation contractor participated in the renovation of nine of the ten concourses; some of the renovations included “ticketing areas, departure and mezzanine levels, security screening checkpoints…reconfiguration of aircraft gate systems, installation of checked baggage inspection systems and facilities, and installation of information technology services” (“Aviation construction,” 2019). According to Hensel Phelps Construction Group, the design teams found the use of VDC particularly helpful during the design of complex vertical conveyor systems and the baggage handling systems; it helped make the most of these systems while meeting clearance requirements (“Aviation construction,” 2019). Virtual reality technology was also used to determine concourse layout; space for restrooms, main core, open atrium, etcetera (“Aviation construction,” 2019). By implementing VDC, the design team was able to clearly see the way the models were or “were not interacting with the surrounding spaces” by analyzing lighting, effect of the sun, glass placement, color, and even material use (“Aviation construction,” 2019).

### *Economic Sustainability*

Economic sustainability is ensuring resources are used efficiently to maintain operations and create profit. By implementing VDC technology into the construction process, particularly preconstruction, a business can reach economic sustainability through several pathways. To begin with, the use of VDC increases the accuracy of pre-construction cost analysis, this is because VDC technology uses BIM data (Boggus & Blizzard, 2017). The use of VDC further increases the accuracy of the cost analysis by allowing real-time interdisciplinary collaboration–architects, engineers, and contractors–

to better judge the scope of work (Virtual reality, n.d.). In addition, having a virtual version of the real construction helps detect design errors and create a reliable construction sequence (Virtual reality, n.d.). This reduces costs by decreasing the probability of construction rework expenditures due to mistakes or missteps and increases the overall efficiency of the construction process (Virtual reality, n.d.). Based on a 2014 study conducted by Mortenson Construction, the use of VDC increased productivity on the average project by 25 percent or more, thus reducing the average project schedule by 32 days (*The importance of virtual design and construction*, 2014). This resulted in a 2.95 percent average direct cost reduction (*The importance of virtual design and construction*, 2014). Overall, the implementation of VDC resulted in efficient and systematic use of resources, improved operational efficiency, and reduced costs.

***Social Sustainability***

As previously mentioned, social sustainability is defined by the social impact created by technology or practices. The application of VDC technology has had a social impact on its users. The design team at Hensel Phelps claimed that being able to explore different possibilities and showcase virtual models to their clients improved their decision-making process ("Aviation construction," 2019). In addition, Hensel Phelps Construction Group noticed an improvement in the collaborative nature of the company and project stakeholders; VDC functions in a manner that allows multiple people to collaborate on a single project simultaneously, thus limiting miscommunication errors ("Aviation construction," 2019). Other construction companies have claimed that the use of VDC enhanced customer experience. Corgan Principal Brent Kelley said, "Our clients can spend as little as 30 seconds inside the interactive model and see the amount of information that may have taken 20 drawings to communicate before" (Willey, 2017). Another social benefit of VDC usage is increased safety; offering virtual training for hazardous and complex activities reduces risks and enhances safety for the employee and construction equipment (*The importance of virtual design and construction*, 2014).

#### *Environmental Sustainability*

According to the EPA, in 2018, the US generated over 600 million tons of construction related waste–construction, demolition, renovation (Environmental Protection Agency, 2023). Implementing VDC technology helps address this environmental issue by reducing construction related waste. By creating different models, design teams are able to reduce waste throughout the construction process by optimizing the usage of materials. According to Mortenson, the implementation of VDC resulted in a reduction of construction waste by 30 percent (*The importance of virtual design and construction*, 2014). In addition, 35% of the waste produced was diverted from landfills (*The importance of virtual design and construction*, 2014). Overall, being able to generate different models through VDC allows design teams to choose the most sustainable design for a project.

### *Pre-Construction Practice: Sustainable Airport Manual*

According to the Arizona Department of Transportation (ADOT), construction manuals are handbooks that contain administrative practices and inspection procedures specific to a construction project (Fay, n.d.). They are accessible on-site throughout the project's lifecycle and are mainly utilized by the project managers, office personnel, inspectors, and engineers (Fay, n.d.). Construction manuals contain information regarding accident procedures, structure, materials, surveying, records and reports, demolition and renovation, and final cleanup (Fay, n.d.). In the aviation industry, FAA advisory circular (AC) 150/5370-10, *Standards for Specifying Construction of Airports*, is analogous to the ADOT's construction manuals–it contains information on methods and materials utilized in the construction of airports (Federal Aviation Administration, 2018). The AC 150/5370-10 is divided into 13 parts: general contract provisions, general construction items, sitework, base courses, stabilized base courses, flexible pavements, rigid pavement, surface treatments, miscellaneous, fencing, drainage, turf, and lighting installation (Federal Aviation Administration, 2018).

In 2003, inspired by AC 150/5370-10, the Chicago Department of Aviation (CDA) became a pioneer in sustainability guidance by developing the sustainable design manual; the first ever guidance for sustainable airport development (Rhee & Frame, 2018). In 2009, the sustainable design manual became one of the many components of the Sustainable Airport Manual (SAM); a more robust and comprehensive set of guidelines that addresses sustainable practices in planning, design and construction, operations and maintenance, and concessions and tenants (Rhee & Frame, 2018). Over the last 20 years, the CDA has updated the SAM several times based on new lessons, methodologies, technology, LEED standards, and authorities (Rhee & Frame, 2018). One of the first additions to the SAM was a rating system for measuring sustainable accomplishments on airport projects developed by the CDA (Rhee & Frame, 2018). This was followed by the addition of an award system used for recognizing the sustainable achievements of designers and contractors (Rhee & Frame, 2018). Today, the SAM is used in projects of all sizes: airport master plans, utilities plans, operations plans, etcetera (Rhee & Frame, 2018). The main purpose of the SAM is to provide airport specific recommendations of measurable sustainability goals and targets that can be officially implemented in the construction plans of a project (Rhee & Frame, 2018).

Currently, the CDA and Chicago O'Hare International Airport (ORD) are implementing SAM strategies on the multiple projects that encompass the O'Hare 21 vision (CDA Media Relations, 2020). O'Hare 21 is the vision for a modernized ORD; it covers aspects such as gate improvements, airfield reconfiguration, construction of two satellite terminals, and modernization of existing terminals (CDA Media Relations, 2020). For O'Hare 21, the SAM redirects focus on sustainability by recommending the use of the following at ORD: energy and water metering and submetering, charging stations for electric vehicles, improved strategies to reduce solar gain, a grazing herd, an apiary, an indoor aeroponic garden, and LEED building certification (CDA Media Relations, 2020). According to the airport's SAM, each and every recommendation will create a positive impact on operations, the environment, and community (CDA Media Relations, 2020).

***Economic Sustainability***

Incorporating the SAM during the early phases of a construction project can reap many economic benefits. The SAM can help increase cost awareness by offering recommendations with anticipated budgets (Jenks et al., 2011). Following SAM recommendations can also help construction projects reach cost objectives (Jenks et al., 2011). In addition, many of the guidelines for sustainable practices offered in the SAM reduce energy, resource usage, and waste, thus contributing to cost savings (Rhee & Frame, 2018). Even the practices recommended for employees could increase cost savings due to increased efficiency and productivity (Rhee & Frame, 2018). Implementing SAM guidelines will cost money, but the benefits far exceed the cost.

### *Social Sustainability*

The SAM has a direct impact on social sustainability in several different ways. First of all, offering recommendations for sustainable practices increases awareness on sustainability, eases decision making processes, and gives direction to a project by creating sustainable goals. In addition, components of the SAM such as the rating and awards system encourage growth in sustainability efforts (Jenks et al., 2011). Another key benefit of the SAM is its applicability to just about any airport development project (Rhee & Frame, 2018). This creates positive social impacts by improving communication through the use of common language when creating sustainable goals. The use of common language improves communication at an internal and external level; this is supported by the ease in public reporting and the seamless workflow preceding the use of the SAM (Jenks et al., 2011). In addition, good communication resulting from the use of SAM guidelines promotes awareness about economic viability, operational efficiency, natural resources conservation, and social responsibility to the local, state, and national community (Jenks et al., 2011).

### *Environmental Sustainability*

The SAM is not a regulatory document; it is simply a guidebook for sustainability at airports. Nonetheless, following the recommendations offered in the SAM could have a range of positive environmental impact. This is because each SAM recommendation is designed to incorporate environmental sustainability into each construction project (Jenks et al., 2011). For example, the SAM for ORD offered some of the following recommendations: use of regional materials, recycling content, using sustainable temporary construction materials, sustainable landscaping, and alternate fuels for equipment (Rhee & Frame, 2018). Considering everything mentioned, the byproducts of using the SAM result in environmental sustainability.

### ***Construction Technology: Spot the Robot***

In 2016, Boston Dynamics revealed Spot, a nimble quadruped robot with sensor technology that efficiently automates the data collection process in the construction industry ([Webpage about Spot], n.d.). Spot features unrivaled, canine-like mobility that allows it to probe hazardous areas under any kind of weather conditions ([Webpage about Spot], n.d.). Other features include remote access and autonomous self-charging abilities. In addition, controlling Spot is easily achieved through a tablet application ([Webpage about Spot], n.d.). To best fit the robot's usage, the application can be tailored with Boston Dynamics' "network of third-party software" ([Webpage about Spot], n.d.). Some of Spot's uses and abilities include: thermal inspection, gauge reading, site documentation, radiation detection, leak detection, noise anomaly detection, gas detection, tunnel inspection, digital twin creation, telemedicine, and search and alert ([Webpage about Spot], n.d.). Performing these tasks is possible due to the variety of sensors and cameras the robot can be equipped with ([Webpage about Spot], n.d.).

In 2020, the nation's leading contractor, Hensel Phelps Construction Group, took over Denver International Airport's (DEN) Great Hall renovation and expansion project (Phillips, 2020). Early into the project, Spot was integrated into the DEN project as a result of Hensel Phelps partnering with Boston Dynamics (Phillips, 2020). The integration of Spot improved the scanning workflow due to its ability to autonomously capture highly detailed, 360-degree, single-file scans of the jobsite (Phillips, 2020). For this particular project, Spot was equipped with Trimble X7 laser scanners directly connected to Trimble software–a Boston Dynamics platform (Phillips, 2020). Through Trimble, scans were analyzed and compared to BIM models while on-site; doing this helped pinpoint incongruities ("See spot scan," 2020). To further encourage autonomy, Spot was programmed with scanning routes and a predetermined schedule; if scans were needed outside scheduled hours, Hensel Phelps had the ability to send out robots with the push of a button ([Webpage about Spot], n.d.).

### ***Economic Sustainability***

The upfront capital investment for Spot is relatively high, 74,500 US dollars, but integrating Spot into a construction project maximizes the project's return on investment (ROI) (Ackerman, 2020). The robot easily outperforms humans. Spot can perform for extended periods of time, without rest, in harsh weather conditions, in unsafe environments, and with higher workloads. Thus, integrating it into a construction project increases productivity and profits while simultaneously decreasing costs. Spot also increases efficiency. A scan that would take hours, up to days, to complete, now can be done in a couple of minutes and with superior quality ("See spot scan," 2020). In addition, the redundancy Spot brings–comparing scans on Trimble with BIM models–helps minimize rework, thus reducing expenses due to construction errors.

### ***Social Sustainability***

Integrating Spot into a construction project has many different social benefits, particularly in the health and safety of employees. Spot performs jobs in hazardous areas. This reduces employee exposure to risks or hazards that pose a significant risk for injuries or death and can also detect safety issues while scanning; therefore, it helps prevent injuries.

In addition, Spot has telehealth abilities that can track and detect employees' health status. Remote operation capabilities along with the ability of Spot to perform labor-intensive tasks eliminates human risk factors such as fatigue and stress. From a long-term perspective, Spot also helps address labor shortage issues. A job that was once performed by a team of people can now be performed by a single robot, but this can be counterproductive by causing a job shortage ("See spot scan," 2020).

### *Environmental Sustainability*

The environmental benefits Spot brings to a construction project are all a result of the robot's precision, labor automation, and multipurpose nature. Spot's high precision limits the need for construction rework; therefore, waste production is reduced, less materials are used, and resources are conserved. Labor automation also eliminates waste that could have potentially been caused by human workers. The multipurpose nature of Spot reduces the need to manufacture multiple machines or robots for specific purposes; the reduction in manufacturing reduces the negative environmental impacts that result from it such as air pollutants, toxic waste, water contamination, and use of non-renewable resources. In addition, Spot operates on electricity which helps maintain clean air. Nonetheless, the robot runs on relatively large lithium-ion batteries–5.2 kilograms–that could eventually harm the environment if improperly disposed of (Spot specifications, 2022).

### *Construction Practice: Prefabrication and Modularization*

In a general sense, prefabrication is a construction practice designed to streamline and optimize the productivity of a construction project by performing portions of the process off-site and shipping those portions on-site for installation (Team GSB, 2018). There are several categories under the umbrella of prefabrication, each differentiated by the process or materials used to deliver the final product (Team GSB, 2018). The different categories are panelized wood framing, sandwich panels, steel framing, timber framing, concrete systems, and modular systems (Team GSB, 2018). One of the most seen categories of prefabrication is best known as modularization (Deluxe Modular, 2019). Modularization consists of constructing the units of a building off-site, transporting and delivering them in pieces, and assembling them on-site to create a whole building (Team GSB, 2018). The off-site fabrication portion of the process occurs in a controlled environment such as a factory. Tasks remaining for on-site assembly include, but are not limited to, plumbing and electrical (Deluxe Modular, 2019). The goal of modular construction is to spend most fabrication time in the off-site facility and spend as little time as possible on-site (Deluxe Modular, 2019).

In February of 2021, Dallas-Fort Worth International Airport (DFW) began the demolition of Terminal C (“Archer Western,” 2022). Two months later, in April 2021, construction commenced for the new High C Gates (“Archer Western,” 2022). In June of 2022, DFW opened the High C Gates to traveling passengers (“Archer Western,” 2022). This became possible with the implementation of modular construction; between August and September of 2021, DFW became the first U.S. airport to use prefabricated modules for the construction of its new, two-level concourse (“Archer Western,” 2022).

Construction contractor, The Walsh Group-Archer Western, built and delivered the six modules that formed the new DFW High C Gates; each module weighed 900,000 pounds and had dimensions of 86 feet by 86 feet by 33 feet ("Archer Western," 2022). All modules were fabricated with "steel frames, glass walls, concrete floors, and insulated metal panels, along with roofs made of concrete and poly-iso roof membrane" ("Archer Western," 2022). Once the modules were completed, The Walsh Group-Archer Western used a never-before-used delivery method: self-propelled modular transporters ("Archer Western," 2022). In total, it took a total of six nights to complete the delivery; transport from the factory to the jobsite took approximately 45 minutes or less (Cho, 2021).

***Economic Sustainability***

Time is a valuable resource preserved through modular construction. At DFW, the physical construction of High C Gates took around a year and a half to complete–demolition to opening–whereas traditional construction projects for the construction or renovation of a concourse take up to five years ("Aviation construction," 2019). Prefabrication and modularization expedited the construction process at DFW; simultaneous demolition and construction reduced the construction schedule by four to five months, which yielded a 20 percent savings ("Archer Western," 2022). If done meticulously, modularization can prevent cost overruns. However, expedited construction practices must be monitored closely to ensure errors are not made, leading to the necessity to implement costly and time-consuming corrective measures (Team GSB, 2018) In addition, there are higher costs resulting from the logistic complexity of modularization: transportation, equipment assembly, specialized skilled labor, extra supervision, and repair costs associated with modules that may be damaged at some point in the process (Team GSB, 2018). A study performed in 2019 demonstrated that there is an opportunity for 20 percent savings in prefabricated construction, “but at a risk of up to 10 percent cost increases” if logistics costs outweigh labor savings (Bertram et al., 2019). Moreover, modular construction helps preserve the quality of materials. Reduced exposure to the fluctuations in climate reduces the risk of damage (Team GSB, 2018). Operating from an established location such as a factory offers safe storage and limits costs due to lost or misplaced materials (Deluxe Modular, 2019).

***Social Sustainability***

The social benefits resulting from modular construction are heavily inclined towards the health and safety of employees. Compared to a jobsite, building in a factory setting allows for better control and monitoring of health and safety and decreases employee exposure to unsafe weather or hazardous working conditions (Deluxe Modular, 2019). Working away from a busy jobsite increases overall project coordination since there are “fewer trades competing for the same space” (Bertram et al., 2019). In addition, operating from a factory setting allows for stability in the employees’ life since there is no need to follow temporary projects (Bertram et al., 2019). Nonetheless, there are some social disadvantages associated with modular construction. Logistically, the module manufacturer assumes an inordinate amount of responsibility. If they make one little mistake, the structural integrity of the module or building could be compromised (Team GSB, 2018). In addition, coordinating the delivery of the module could also be a logistical nightmare; the delivery of six modules for the DFW project involved a team that spent up to 20 hours a week coordinating logistical requirements (Cho, 2021). Engineers assume critical responsibilities such as accounting for the weight of each module, height based on clearance requirements, configuration of the transport vehicle, airfield pavement elevation differences, and temporary supporting structures (Cho, 2021).

#### *Environmental Sustainability*

Employing a modular approach in a construction project has environmental benefits such as better waste management and reduced air, water, and noise pollution (Deluxe Modular, 2019). Modular prefabrication reduces construction waste due to the process' greater accuracy, consistency, and reliability when compared to traditional, on-site construction (Deluxe Modular, 2019). Another factor that helps reduce waste is directly related to building in a factory environment; since many elements of a building are being constructed simultaneously, there is constant need for materials, so any remaining excess will be readily used (Deluxe Modular, 2019). Regarding emissions, manufacturing modules produce 41 to 45 percent less carbon emissions than conventional construction methods ("Modular construction," 2022). Factors contributing to lower emissions include waste reduction and the use of fewer carbon intensive products such as concrete and steel ("Modular construction," 2022).

### *Post Construction Technology: Structural Nondestructive Testing Technology*

Airport pavement is designed to provide a firm, resistant, year-round-use surface that supports aircraft loads and traffic volume (Federal Aviation Administration, 2021). The structural components of airport pavement consist of the surface, base, subbase, and subgrade (Federal Aviation Administration, 2021). To ensure safe airport operations, it is essential to perform evaluations on the pavement's ability to bear varying "types, weights, or volume of aircraft traffic" (Federal Aviation Administration, 2021). The first step of the evaluation process is visual inspection which consists of surface, subsurface, and drainage pattern examinations; this helps determine structural distresses (Federal Aviation Administration, 2021). During visual inspection, the integrity of the pavement is rated using the Pavement Condition Index (PCI); the score received helps determine if taking pavement samples will be required (Federal Aviation Administration, 2021). Samples are gathered through excavation pits, cores, or borings and are sent to a laboratory where pavement conditions underneath the surface are examined (Federal Aviation Administration, n.d.). Despite the effectiveness of this collection method, it can be quite costly and possibly disrupt airport operations during periods when the inspection process renders the pavement inaccessible to aircraft (Federal Aviation Administration, n.d.).

Research experiments performed at the FAA's state-of-the-art National Airport Pavement Test Facility (NAPTF) found an alternative method of assessing airport pavement: nondestructive testing (NDT) technology (Federal Aviation Administration, n.d.). Using NDT technology eliminates the need to remove, and further damage, airport pavement for evaluations (Federal Aviation Administration, n.d.). In addition, the use of NDT technology expedites the data collection process. In close collaboration with air traffic controllers, the tests can take 2 to 3 minutes to complete (Federal Aviation Administration, 2011). Using NDT technologies also increases the efficiency of evaluations since up to 250 different locations can be tested in a single day (Federal Aviation Administration, 2011).

NDT technology can be compared to a tessera (a single component of a mosaic). Each piece of technology offers unique, uncorrelated data, but when used in conjunction, the data they provide helps determine pavement conditions (Federal Aviation

Administration, n.d.). This premise was supported during construction cycle number eight; research teams at the NAPTF were able to measure and observe structural and functional characteristics and changes in airport pavement by using and combining the following NDT technologies: KUAB Heavy Weight Deflectometer (HWD), Portable Seismic Property Analyzer (PSPA), Inertial Profiler, SurPro 2000, Dipstick, Straightedge, Rail-to-Rail Profiler (RTRP), Truss Profiler, Joint Groove Profiler, Wayling 2D and 3D Imaging, Ground Penetrating Radar (GPR), ELAtextur, and MIT Scanner BT (Federal Aviation Administration, n.d.). All these technologies proved reliable for airport pavement evaluation purposes due to the several functions they were able to offer– mimicking aircraft loads, monitoring, imaging, detection, and measuring (Federal Aviation Administration, n.d.).

Despite all the advantages NDT technology offers, there are some limitations (Federal Aviation Administration, 2011). First and foremost, NDT technology fails to provide details on "engineering properties…such as grain-size distribution" (Federal Aviation Administration, 2011). Moreso, quantitative data mainly relies on "structural models and software algorithms that follow structural theory and performance models that are significantly different from traditional pavements" (Federal Aviation Administration, 2011). Last but not least, data collected on subgrade strength is not as reliable; conclusions may be inaccurate depending on climate conditions such as prolonged dry periods or thaw weakening of pavement in the springtime (Federal Aviation Administration, 2011).

### *Economic Sustainability*

From an economic standpoint, utilizing NDT technologies for airport pavement evaluation is much more sustainable than traditional evaluation methods (Federal Aviation Administration, n.d.). First of all, NDT technology is a cost effective and affordable approach for conducting airport pavement evaluations (Federal Aviation Administration, n.d.). Its affordability allows for regular testing which protects high value assets and encourages preventative maintenance. Performing preventative maintenance reduces the degree of pavement breakdown, thus increasing its longevity; by the time maintenance is performed, costs will be lower. In addition, the use of NDT technology increases efficiency and productivity; this combination translates to cost reduction. To put this into perspective, NDT technologies are able to collect data from up to 250 locations in one day because of their convenient, portable size (Federal Aviation Administration, 2011). This efficiency also decreases downtime, or completely eliminates the need to cease operations, thus allowing for airports to continue making money. Despite all these benefits, inaccuracy due to external, uncontrollable factors could yield negative economic results.

#### *Social Sustainability*

The use of NDT technologies in airport pavement evaluations have a positive social impact; these technologies do not disturb airport operations (Federal Aviation Administration, n.d.). Since airport operations are not disrupted, flights are not delayed or canceled. This increases predictability and customer satisfaction for passengers and affected industries that rely on efficient airport operations. In addition, using NDT allows early detection of wear and tear on pavement; this increases the safety of employees by providing a surface that meets standards.

***Environmental Sustainability***

By increasing the longevity of airport pavement, demolition and construction is reduced and so is the environmental impact resulting from these activities. Additionally, the use of NDT technologies eliminates the need to take multiple direct samples, which eliminates pavement waste. Once the samples are analyzed, they cannot be returned to their original state; therefore, they become waste.

***Post Construction Practice: Indoor Air Quality***

Indoor air pollution refers to the deterioration of indoor air quality (IAQ) due to a buildup in particulate matter, carbon monoxide, lead, ground-level ozone, sulfur dioxide, nitrogen dioxide, and more ("Managing air quality," 2022). The presence of indoor air pollutants can negatively affect the environment, human health, and cause property damage ("Managing air quality," 2022). Research on the topic has demonstrated how different factors such as inadequate ventilation, temperature, occupant density, and types of activity performed have a significant impact on IAQ (Zanni et al., 2018). For these reasons, the EPA developed standards and regulations that help limit and manage the buildup of indoor air pollutants and contaminants ("Managing air quality," 2022).

Furthermore, construction and renovation projects consist of various practices that contribute to the degradation of IAQ (U.S. Green Building Council, n.d.). Combining this with the traffic and activity patterns found in airports makes airport development a hotspot for indoor air pollutants (Zanni et al., 2018). For this reason, it is important that both industries combine efforts for maintaining clean air. In relation to air quality management, post construction is marked by the conclusion of all indoor construction activities (“Managing air quality,” 2022). Once these activities conclude, there are two pathways for addressing degraded IAQ: flush-outs and air testing (U.S. Green Building Council, n.d.). Flush-outs can be performed prior or during occupancy; it essentially is the act of forcing outdoor air inside a building so that pollutants and contaminants can be dispersed (U.S. Green Building Council, n.d.). The second pathway, air testing, is solely performed prior to occupancy; it is done by mimicking airflow conditions and patterns that occur when a building is occupied, taking multiple air samples, and comparing them to EPA standards for IAQ (U.S. Green Building Council, n.d.). The number of samples required depends on building size and the total amount of ventilation systems (U.S. Green Building Council, n.d.). If specific samples do not meet IAQ standards, the area where the sample was taken is flushed out and retested. The process repeats until all samples meet IAQ standards (U.S. Green Building Council, n.d.).

Airports have further addressed IAQ by investing in the installation of air cleansing systems. In 2022, DFW concluded installation of its latest addition to indoor heating, ventilation, and air conditioning (HVAC) systems (“$5.4 million,” 2020). The nine-million-dollar project consisted of installing a total of 993 Ultraviolet-C units in various areas across terminals A, B, D, and E (“$5.4 million,” 2020). Since their installation, the Ultraviolet-C units have been operating 24 hours, seven days a week, performing five to seven complete-building air cycles each hour (“$5.4 million,” 2020). The airport’s effort to enhance air quality within its terminals has been a success. Fundamentally, Ultraviolet-C systems will have a 99.9 percent efficiency. The blue light technology instantly eliminates pathogens in the air (“$5.4 million,” 2020).

### *Economic Sustainability*

As previously mentioned, indoor air pollutants harm human health ("Managing air quality," 2022), resulting in reduced employee productivity, increased absences from work, instances of premature deaths, and exorbitant costs related to mitigation efforts. Ergo, post construction practices that ensure IAQ lead to a healthy workforce, which leads to profits. For example, performing air quality tests helps focus on areas that require attention. This helps conserve resources and time by avoiding expending energy in areas that already meet EPA standards. The result is an overall improvement in efficiency, time savings, and reduced cost. Moreover, airport initiatives that support IAQ may have differing economic benefits. Consider DFW; the initial investment for their IAQ system was quite large–worth millions of dollars. In 2020, their projected investment for the project was five million dollars. Upon completion in 2022, the total cost of the project was over nine million dollars ("$5.4 million," 2020). Aside from a high initial investment, additional labor may be required to maintain the IAQ system, thus increasing operating costs. Nonetheless, research done by the World Green Building Council indicates that good IAQ practices "can save as much as 79 percent on energy bills" ("Improving indoor air quality," 2023). Further studies performed at Carnegie Mellon University estimated that the average ROI for implementing good IAQ practices is 120 percent ("Improving indoor air quality," 2023).

### *Social Sustainability*

As previously mentioned, IAQ directly affects human health; if good IAQ is not maintained, people can become sick and ultimately suffer from premature death. Maintaining clean air increases human health, performance, and comfort ("Fact sheet," 2022). A study performed by Harvard compared employees in environments with good versus poor IAQ (“Improving indoor air quality,” 2023). The results from the study demonstrated that working in environments with good IAQ boosted cognitive performance by 61 percent and productivity by 10 percent (“Improving indoor air quality,” 2023). In addition, good IAQ practices and systems increase safety in the workplace; their implementation helps eliminate biologically harmful pollutants, contaminants, pathogens, and allergens (“Improving indoor air quality,” 2023). Another large social factor linked with IAQ is security (“Fact sheet,” 2022). Clean indoor air serves as a protective barrier for the public; it increases the feeling of security from the spread of airborne diseases (“Fact sheet,” 2022).

***Environmental Sustainability***

The implementation of good IAQ practices and systems can help reduce energy consumption. Improving IAQ increases the efficiency of HVAC systems in a few ways, the most notable being that it keeps the coils and any other type of heat exchanger cleaner for a longer period (“How proper coil,” 2017). The cleaner it is, the more energy it can transfer. Consequently, this improvement in efficiency means that less energy is used under the same conditions. On the other hand, not maintaining good IAQ can have the opposite effect and further strain HVAC systems, thus increasing total energy demand. The increase in energy demand also results in an increase in GHG and all pollutants involved in the production of electricity.

# CHAPTER 3

# METHODOLOGY

This section provides details about the mixed methods multiple-case study design used for this report. There are also specifics on web-based data collection, multiple-case study selection, and data analysis. Further details regarding the web-based literature review and the multiple-case study design are explained in the data analysis section of this paper. The latter part of this section covers limitations resulting from the use of qualitative research, multiple-case study design, and web-based data collection.

## Research Designs

### *Sequential Mixed Methods*

In order to gain a better insight into sustainable construction technologies and practices used in airport development, a two-phase sequential mixed methods research design was implemented. A two-phase sequential research design refers to the order in which data belonging to two research methods is presented (Creswell, 2008). Mixed methods research is defined by the combination of qualitative and quantitative research methods (Creswell, 2008). Qualitative research consists of textual analysis while quantitative research consists of numerical analysis; the researcher is responsible for correlating the data from each research method through analysis (Creswell, 2008). In this report, mixed methods were applied in the following way: the researcher presented ideas and analysis of text and supported the analysis with statistical data. By doing this, the researcher was able to triangulate statistics from qualitative research and the "detail of qualitative research" (Creswell, 2008). This allows for comparative analysis.

### *Multiple-Case Study*

A multiple-case study research design is best suited for research that seeks to produce an in-depth, detailed examination of two or more items or events within a real-life context (Creswell, 2008). This report consisted of six carefully selected case studies. Each case study has its respective summary and analysis. This will allow the researcher to develop cross-case conclusions.

## Research Methods

### *Data Collection Tools*

The data collected for this report is mainly from primary and secondary sources. The data collection method for this report is web based, resulting in higher accessibility of data, and allowing for a diversity of information. To ensure the most relevant information was obtained, during the data collection process, keywords related to the research topic were identified and utilized. In addition, the data collection tools for this research consisted of the following eight search engines:

- Google Search Engine
- EPA Search Engine
- FAA Search Engine
- ACI Search Engine
- CII Search Engine
- SAGA Search Engine
- National Center for Biotechnology Information Search Engine
- U.S. Green Building Council Search Engine
- SAGE Publications

### *Multiple-Case Study Selection*

The three main requirements for selecting the case studies for this report consisted of the following:

- Selecting cases that aligned with the research topic
- Ensuring that the case studies are relevant to today
- Ensuring that the case studies are universally applicable

### *Data Analysis*

A literature review allows the researcher to explore and analyze the most recent and relevant information possible. Data was found in the form of books, articles, reports, syntheses, interviews, and more. The literature review allowed the researcher to develop a solid background on the research topic, which enabled the researcher to implement the mixed methods multiple-case design. During the qualitative portion of the process, the researcher was able to triangulate findings across government agencies, airports, contractors, institutions, and councils. Consequently, this enhanced the researcher's ability to identify patterns, themes, and categories in real-life events (Bass et al., 2018). With a comprehensive understanding of the research topic, the researcher was able to perform comparative analyses between the cases, thus allowing the researcher to develop cross-case conclusions (Gustafsson, 2017).

## Research Biases

As an enthusiast for sustainability, the researcher may have had a biased stance when initiating this report. Regardless, the bias was acknowledged and a technical writing style was implemented in order to avoid this bias. Other steps to avoid this bias include cross referencing textual data with other textual data as well as statistical data.

During the data collection process, the researcher may have faced some biases such as search engine bias and position bias. Research has demonstrated that search engines are biased due to their predictive algorithms that base the results on the user's preferences (Han et al., 2021). This was addressed by periodically clearing the historical search data website cookies from the device used for research. Position bias refers to a tendency found in search engine users in which interaction with top ranked items is greater than with lower ranked items, despite the item's relevance (Han et al., 2021). This was addressed by analyzing and screening data when first interacting with it.

**Research Limitations**

Limitations for mixed methods research include but are not limited to:

- More complex to perform compared to qualitative or quantitative
- Requires more research expertise when collecting and analyzing data
- Time consuming process

Limitations for multiple-case study design include but are not limited to:

- Sacrifice depth of each case study
- Time constraints caused by volume of data limit depth of case studies

Examples of limitations for web-based data collection include but are not limited to:

- Limited access to certain documents
- High volume of data can impact selection of relevant data
- Website ranking on search engines create bias
- Predictive algorithms from search engines create bias

# CHAPTER 4

# RESULTS

## Pre-Construction

Research findings on VDC technology involved a number of factors that influence sustainability at an economic, social, and environmental level. This technology offers the following economic benefits: increased accuracy of pre-construction cost analysis, increased productivity on the average project by 25 percent or more, reduced schedule on the average project by 32 days, and direct cost reduction by 2.95 percent. The key social takeaways are improved collaboration, limited miscommunication errors, improved decision-making processes, increased employee safety, and improved customer satisfaction. Environmental benefits from using VDC are 30 percent reduction in construction waste on the average project, reduced waste during construction by optimizing material usage, and encouragement of the most sustainable design for a project. In addition, VDC aids with the coordination of waste distribution; a study showed that 35 percent of waste produced during a project was diverted from landfills.

Research findings on the SAM demonstrated that following this set of guidelines can have a myriad of influences on the sustainability of a project. The following economic benefits can be seen from implementing certain SAM guidelines: increased cost awareness due to budget predictions, increased likelihood of reaching cost objectives for a project, cost savings by reducing waste production, cost savings by decreasing the consumption of energy and other resources, and increased profit from employee efficiency and productivity. The following are social benefits that can be seen from implementing certain SAM guidelines: increased awareness on sustainability, improved decision-making processes, encouragement of sustainability efforts due to its universal applicability, improved communication, improved workflow, and it develops a sense of direction for a project by creating goals. The following are environmental benefits that can be seen from implementing certain SAM guidelines: methods of conservation for energy, water, waste, soil, and other resources; protocols, restrictions, and regulations for construction and renovation; recycling; IAQ management; designs for indoor and outdoor building connectivity; and designs for daylight view and lighting optimization.

**Construction**

Research findings on Spot, the quadruped robot, amounted to a list of economic, social, and environmental benefits. Incorporating Spot into a construction project can result in the following economic advantages: increased profits due to increased productivity, increased efficiency due to day-long processes being completed in minutes, reduced construction time and costs due to rework minimization, and overall cost reduction of project due to maximize ROI. The following are social benefits resulting from incorporation Spot into a construction project: reduced employee exposure to risks and hazards, increased safety due to Spot’s ability to scan for safety issues, improved employee health monitoring due Spot’s telehealth abilities, elimination of certain human risk factors due to Spot’s remote operation feature, and addressing labor shortage issues due to Spot’s multitasking abilities. Environmental benefits resulting from Spot’s integration into a construction project are: reduced waste due to limited rework, reduced material usage due to Spot’s high accuracy, waste elimination by replacing human workforce, clean air conservation due to Spot being electrically powered, and reduced environmental impacts from manufacturing due to Spot's multipurpose abilities–reduces the need to manufacture multiple machines.

Research findings demonstrated the extent of the economic, social, and environmental influences prefabricated construction practices can have on a project. The following are benefits resulting from prefabricated construction: reduced project schedule due to simultaneous demolition and construction, 20 percent in project savings due to reduced project schedule, prevention of cost overruns due to meticulous construction, cost savings due to reduced rework resulting from accuracy of factory setting construction, preserved quality of materials due to factory setting, and reduced costs on lost or misplaced materials due to safe material storage in factory setting. Prefabrication has some economic downsides such as costly and time-consuming corrective measures and the risk of up to 10 percent cost increase due to logistics costs outweighing labor savings. The following are social benefits resulting from prefabricated construction: improved control and monitoring of health and safety due to indoor setting; decreased employee exposure to outdoor weather risks and hazards; increased overall project coordination due to elimination of competition for workspace; and a stable lifestyle for the employees due to the elimination of need to follow transient projects. Social disadvantages of prefabrication include logistical complexity and inordinate amounts of responsibility on a single entity. Environmental benefits resulting from prefabrication are: reduced air, water, and noise pollution; improved waste management; reduced waste production due to accuracy, consistency, and reliability of factory setting; reduced excess material waste; and reduced GHG emission by 41 to 45 percent.

**Post Construction**

Research findings on NDT technology used in pavement evaluations involved a number of factors that influence sustainability at an economic, social, and environmental level. Economic benefits resulting from the use of NDT technologies is that: the technology is affordable and cost effective; increased testing frequency which protects high value assets from degrading to a no-return point; encouragement of preventative maintenance which reduces the overall costs of actual maintenance; increased efficiency by making it possible to test 250 locations in a day; and decreased downtime therefore allowing airports to continue making money. Social benefits resulting from the use of NDT technology include increased customer satisfaction due to a decrease in downtime and increased safety due to early detection of wear and tear. Environmental benefits resulting from the use of NDT technologies include reduced environmental impacts related to demolition and construction due to increased pavement longevity resulting from use of NDT technology; and elimination of pavement waste resulting from direct sampling.

Research findings on the implementation of IAQ practices and systems resulted in a large set of sustainability outcomes. From an economic standpoint, some advantages are overall improvements in efficiency, time savings, and cost reduction are seen due to air quality tests; savings of up to 79 percent on energy bills due to efficient HVAC systems; and an average ROI of 120 percent from implementing good IAQ practices. Some disadvantages are high initial investment, cost of systems can lead to cost overrun, and increased operating costs due to additional labor needed to maintain systems. The social benefits of good IAQ practices and systems are: increased human health and comfort;

increased cognitive performance 61 percent; increased productivity by 10 percent; increased safety by elimination of biologically harmful pollutants, contaminants, pathogens, and allergens; and increased feeling of security amongst the public due to the protective barrier created by these systems. The environmental benefits of implementing good IAQ practices and systems include increased system efficiency which results in lower energy demand and therefore indirectly reduces the release of GHG and pollutants involved in the production of electricity.

# CHAPTER 5

# DISCUSSION AND RECOMMENDATIONS

## Discussion

The focus of this report was to determine the economic, social, and environmental effectiveness of construction technologies and practices currently being implemented in airport development. The results from the acquired data, as discussed in Chapter Three, show that these construction practices and technologies clearly include efforts targeted at sustainability. The literature suggests that each construction practice and technology implemented during airport development focuses to a different extent on sustainability aspects. While some practices and technologies have direct economic, social, and environmental impacts, others have indirect impacts. Indirect impacts are considered the level of influence due to a domino effect resulting from the practice or technologies described. For example, IAQ increases HVAC efficiency which reduces energy consumption and therefore reduces the release of pollutants related to the production of electricity.

Furthermore, the literature highlights certain commonalities that are present in all the mentioned technologies and practices. Some commonalities include the increase of accuracy, productivity, efficiency, and safety in construction projects. Other commonalities gravitate towards the decrease of cost, waste production, resource usage, and project duration. The degree of effectiveness varies amongst all case studies. In addition, there are also common features specific to each construction phase. For example, the pre-construction phase highlights the importance of exceptional communication. The construction phase highlights the importance of material usage optimization and limiting rework. The post construction phase highlights the importance of implementing predictive and preventative maintenance. Commonalities were also found within the subcategories: technology and practice. Technology appears to be better tailored for specific purposes while practices are more systematic and better for addressing larger concepts.

Incorporating these practices and technologies in airport development indicates that the construction and aviation industry are cooperating in trying to offset the negative impacts they create while simultaneously thinking about the future and how to further reduce or even eliminate negative environmental impacts. Given the current context, it seems that sustainability will continue to be ingrained in the development of construction practices and technologies. The economic benefits and the demand for environmentalism are two large factors influencing the adoption of sustainability methods and approaches. Even though social benefits are not as quantitatively measurable as economic and environmental benefits, the development of holistic and transdisciplinary evaluation approaches, efficiency and productivity for example, are directing attention towards social sustainability.

**Applicability of Research Results**

The main purpose for developing this report was to identify a collection of construction technologies and practices found in sustainable airport development. This report can serve as a learning foundation for future research in that it offers a well-versed background on sustainability, construction, and airport development. The report may also be beneficial to those involved in airport development or construction projects who are exploring potential construction technologies and practices with proven success.

**Recommendations for Future Research**

Future research may include, conducting a single case study on one of the technologies or practices mentioned above and gathering qualitative data that supports or challenges its sustainable advantage. Value would be added through in-depth, primary research that includes first-hand experiences and opinions. Another suggestion may be to conduct a case study on a specific sustainability topic such as energy management or water conservation at one or two airports and calculate the effectiveness of these sustainable approaches from a cost and resource savings perspective.

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