A SCIENTOMETRIC ANALYSIS OF SMART SENSORS IN FACILITY MANAGEMENT AND APPLICATIONS IN AIR FORCE OPERATIONS

THESIS

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Abstract

The United States Air Force has identified the usage of innovative solutions to perform facility maintenance through the publication of the Infrastructure Investment Strategy in 2019. With a desire to conserve fiscal and personnel resources, the Air Force has identified that the existing way of performing facility maintenance is too costly and inefficient and new methods are needed to fulfill this goal. One method to achieve this goal has been the idea of further implementation of smart sensors to monitor installed assets on Air Force installations. Smart sensors act as a force multiplier with their ability to perform both remote asset monitoring and basic troubleshooting functions. The installation of smart sensors will help Air Force facility managers and other decision-makers optimize their workforce and monetary resources.

To investigate the areas in which smart sensors can be implemented to assist facility managers to optimize their limited resources, this research consists of a scientometric analysis to identify areas of research quantitatively and qualitatively in this field. Existing literature related to smart sensors in facility management operations were compiled and trends were analyzed to determine the ways in which researchers have been applying this technology. Titles, abstracts, and keywords were used to perform frequency, networking, and clustering analysis. This research effort serves to provide ways in which Air Force installations can implement smart sensors in a way that fulfills the initiatives posed in the Infrastructure Investment Strategy.

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I. Introduction

The United States Air Force published its Infrastructure Investment Strategy, known as the I2S, with the intent of modernizing Air Force installations to make them more lethal power projection platforms (*U.S. Air Force Infrastructure Investment Strategy*, 2019). A notable message delivered in this document is the fact that Air Force installations are aging and require modernization to ensure they perform at a high level to counter new adversaries and challenges faced around the globe. One of the methods to modernize facilities which was identified is implementation of smart facility technology. With the cost of maintaining and sustaining installations across the Air Force constantly increasing, new and innovative solutions such as smart technologies are necessary to ensure taxpayer dollars are being spent in a cost-effective way. Smart facilities utilize sensors which transmit data about the asset performance that decision-makers can use to determine when to perform preventive maintenance (PM) and more intensive corrective maintenance (CM) actions as assets begin to degrade. Limitations exist with this new technology that must be considered before its full-scale adoption in Air Force facilities.

Background

As of 2019, there were 180 Air Force bases worldwide with a Plant Replacement Value (PRV) of $263 billion (*U.S. Air Force Infrastructure Investment Strategy*, 2019).

Over the last two decades, $33 billion in maintenance has not been accomplished, and this value is expected to triple over the next 30 years (*U.S. Air Force Infrastructure Investment Strategy*, 2019). Failure to modernize infrastructure and spend money efficiently will eventually lead to mission failure and degradation of support functions to Airmen and their families. The I2S proposes three ways to revitalize and restore airbases: restore readiness to power projection platforms, perform cost effective modernization of infrastructure, and drive innovation in the way the Air Force performs facility management (*U.S. Air Force Infrastructure Investment Strategy*, 2019). The last two parts of this statement are where the idea of incorporating smart sensor technology becomes pertinent. By incorporating new technology, the Air Force intends to improve infrastructure while at the same time reducing the cost of facility maintenance (*U.S. Air Force Infrastructure Investment Strategy*, 2019).

With improving semiconductor technology and increased internet speeds, sensors are becoming incorporated in more ways that affect modern living. Almost all current automobiles use sensing technologies such as computer-controlled fuel injection and emissions systems to operate at their most efficient levels. Most residences have some sort of smart thermostat installed to control indoor air temperature, thus leading to efficiencies in the way we heat and cool our dwellings. With the advent of smartphones, there are a multitude of sensing abilities that people carry around with them nearly 100% of the day, which has not only improved the ways humans communicate with each other but has created efficiencies in the way people live every day. Applying smart sensing in facility management is a further extension of applying sensor technology in all aspects of modern life and looking for areas in which efficiencies can be gained.

Anything can be considered smart technology as long as it has the ability to gather, process, and exchange digital information (Niu et al., 2016). In a sensing network, the sensing elements are referred to as nodes. These nodes become “smart sensors” when they can 1) provide data, information about data quality, and a measure of the health of the node; 2) embody specification/identification data; and 3) communicate through networks using common internet protocols (Gurkan, 2012). By incorporating these smart objects into facilities and using the information they provide, the facility should be able to record and report to decision-makers/engineers its performance history, predict remaining lifetime, suggest maintenance work, and provide early warning for defects and damages (Zhang & Lu, 2008).

Smart technologies have gained prominence through their usage in the industrial and aerospace sectors. The implementation of smart sensors dates back to their use in the late 1970s in the aerospace and mechanical engineering field to monitor vibrations and control the shape of large flexible space structures (Zhang & Lu, 2008). The emerging idea of the fourth Industrial Revolution, or Industry 4.0, has gained traction since the dawn of the 21st century. In industrial applications, sensors have been used to monitor the health of industrial assets and determine their current operating conditions and lifespan (Wang et al., 2017). Their successful use in various industries has led to increased interest in their application in construction and the life-cycle maintenance of buildings and infrastructure systems (Zhang & Lu, 2008). Applications of sensors in the monitoring of civil infrastructure has been a popular research area; however, the bulk of that research occurred in the laboratory with limited scope (Stajano et al., 2010). Over time, more and more research has been performed, with new applications being field tested.

Smart sensor technology has been identified as being incorporated into the asset management process. The Air Force is required to perform asset management on installed infrastructure assets based on the guidelines in Executive Order 13327, which was enacted in 2004. The entity within the Air Force tasked to complete asset management is the Air Force Civil Engineer community. There are currently limited smart sensing technologies in use on Air Force installations, such as Supervisory Control and Data Acquisition (SCADA) systems being used on wastewater systems to monitor and control the performance of these infrastructure systems and Heating Ventilation and Air Conditioning (HVAC) controls being connected to an Energy Management Control System (EMCS). These systems are not standardized in implementation across the Air Force, and their usage is to primarily provide simple monitoring and troubleshooting functions.

With the application of smart sensors in construction being an evolving field, coupled with a limited adoption of remote sensing capabilities in current Air Force facility management (FM) operations, a knowledge gap has emerged. The application in current FM operations will need to be quantified based on existing research in the field. The goal of incorporating smart sensing technologies into the FM process will be to create efficiencies in operations and resource usage.

Problem Statement

The Air Force's desire to modernize its facility management operations drives the need to explore the current state of smart facility management research. A significant amount of research has been completed regarding applications of smart technology and these results need to be quantified. The overarching problem statement for this thesis is: The usage of smart sensor technology has occurred in research settings; however, there is a gap in the literature regarding its applications in the facility management profession and specifically in maintaining the Air Force's worldwide inventory of 180 bases. The key takeaway in this research will be to identify the areas in which this powerful tool can provide the Air Force Civil Engineer community the ability to remotely assess the condition of assets and facilities, and identify ways in which sensors can provide operational efficiencies.

Research Questions

This research will identify which areas of research have been investigated in smart sensor driven facility management and the key areas that can be applied to Air Force operations. To facilitate this objective, the following investigative questions are addressed.

1. What is the current status of published research in the field of smart sensors in facility management operations?
2. What are the themes that exist in current smart sensor research? Which of these applications are the most researched?
3. Where can existing research on smart sensor technology provide benefits?

4. What operational efficiencies can be gained in using increased incorporation of smart sensor technology?

Methodology

To address the research objectives, a scientometric analysis was performed to review the evolution of smart sensor research and its application in facility management operations. Publication data was gathered using the Scopus online database. The NVivo software was used to do queries of keywords and find clusters of key concepts. Visualizations of existing research included publication date and co-word analysis; additionally, clustering was done to show research status quo and existing themes within this area of research, along with new innovations which are occurring. To visualize the trends that arise, VOSviewer was utilized. Through keyword clustering, it was anticipated that several themes will emerge. These themes showed the areas in which existing research has been applied in the field and will provide Air Force decision-makers with information to apply new technologies within existing FM operations.

Assumptions/Limitations

The field of smart sensor technology is expansive in its application area, so assumptions and limitations will be necessary to narrow the scope of this research. The scope of this research will be limited to applications in facility management. Through the literature review process, multiple examples of sensors applied in the manufacturing and industrial applications were encountered. This research will primarily deal with facilities typically encountered by Air Force Civil Engineers which require constant condition monitoring and evaluations.

Air Force Civil Engineers are also subject to guidance and regulations which dictate the ways in which FM operations are to take place. While examples of this guidance will be presented, this research will not be an all-encompassing look into the processes which are currently in place, and the way in which they can be modified will not be proposed. This research will identify areas which should be investigated as potential areas for sensor adoption.

An assumption that will be made is that the Air Force communication network will have the capability to support new smart sensors. Integration into existing communications networks will likely require network upgrades and regulation changes. This research will primarily investigate the usefulness of the sensors themselves, with further research being necessary to determine how existing communication infrastructure will need to adapt to increased demands.

A limitation exists in the data set used in the analysis. Only journal articles from peer-reviewed literature were used in the analysis portion of this research. Only journal articles published in English were considered. There may very well be articles published in other languages that have pertinence to this research that were not considered.

Organization/Purpose of Remaining Chapters

Chapter II will provide a review of peer-reviewed literature with regards to smart sensor technology as applied in facility management operations, along with associated needs in its implementation and concerns with adoption. Chapter III will outline the methodology used to analyze the trends and themes that are present in this area of research. Chapter IV will discuss the results of the scientometric analysis, with Chapter V drawing conclusions and recommendations for applications in Air Force operations.

II. Literature Review

A literature review was performed to gain background knowledge regarding smart sensors and their application in the field of facility management (FM). Defining and understanding basic concepts which are present in smart sensor technology was the primary goal of this chapter. A basic understanding of the facility management field and its practices, as well as a history of sensor applications in all fields leading to their use in the construction and FM field, will be discussed. A surface level understanding of the technology which is enabling sensor usage, to include the types of connections that are being used and explored, the network types that are in use, and an introduction to building information modelling (BIM), will be included. Existing sensor applications that the Air Force has employed in the past and is eyeing to deploy will also be covered. Previous scientometric analyses relating to this field and their findings are presented to identify previous studies which can be applied in this context. Throughout this section, the concerns regarding sensor usage will be discussed.

Facility Management

All buildings, regardless of size, require FM to ensure proper performance over their lifespan. The Oxford Dictionary defines facilities management as “the maintenance of an organization’s buildings and equipment” (*Facilities Management*, 2022). There are several groups that have their own definitions of FM. The International Standards Organization (ISO) defines FM as an “organizational function which integrates people, place, and process within the built environment with the purpose of improving the quality of life of people and the productivity of the core business" (*Facility Management*, 2021). The International Facility Management Association (IFMA) defines FM as "a profession encompassing multiple disciplines to ensure functionality, comfort, safety, and efficiency of the built environment by integrating people, place, process, and technology" (*What Is Facility Management*, 2021). At the core of both definitions presented by the two organizations is improving quality of life by incorporating people, place, process, and technology. Using these two definitions, the use of innovative technologies, like smart sensing capabilities, creates opportunities for the FM field to improve the life of people who use the facilities by improving the way in which processes are performed. Organizations will have to employ varying degrees of FM, depending on the number and size of facilities under their control. Sensors provide efficiencies to existing practices, which leads to a higher quality of service provided by the facility manager. Improvements in the ways an organization performs FM can lead to efficiencies and higher effectiveness, which has the ability to significantly affect operation cost, energy consumption, indoor comfort, and in a grander scheme global climate (Xu et al., 2019).

The Air Force has taken the operational efficiencies that new technological advances can create into consideration when it wrote their Infrastructure Investment Strategy (I2S) in 2019. The purpose of this document was to:

> guide facilities sustainment, restoration, modernization and recapitalization requirements and investment in a way that restores readiness to our power projection platforms, cost effectively modernizes our infrastructure, and drives innovation into our installation management practices. Four imperatives will align and unify infrastructure investment efforts: adequate, stable funding; smart infrastructure business management; unified efforts across the enterprise; and revitalized squadrons. (*U.S. Air Force Infrastructure Investment Strategy*, 2019)

The Air Force maintains 180 bases worldwide with an estimated plant replacement value (PRV) of $263 billion dollars. PRV is defined as "the cost in current year dollars to design and construct a replacement facility to modern standards using modern construction costs (materials and labor), excluding site preparation, earthwork, landscaping, and surveys/studies" (*U.S. Air Force Infrastructure Investment Strategy*, 2019). With such a large number of facilities and value under the control of a single, albeit large, organization, each of the 180 bases involved will require their own FM organizations to manage and maintain these facilities. Incorporating new and innovative technologies will enable an improvement to processes and the quality of life to those who work, live, or visit those bases. Explicitly called out in the I2S is an initiative to utilize facilities management technologies and to "implement the use of state-of-the art building monitoring systems, predictive condition-based facility maintenance technologies, and artificial intelligence" (*U.S. Air Force Infrastructure Investment Strategy*, 2019).

The operating period of a facility is where the majority of its life-cycle cost occurs. Design, development, and construction can account for up to 25% of a facility's cost, contrasted with up to 75% of the cost being incurred during the operating period that can last 25-30 years after initial design and development ("Smart Sensors, IoT, and BIM Offer Key Benefits for Building Management.," 2020). With this information, there is a large benefit associated with being able to effectively manage and conserve resources when possible.

A large amount of research and funding has been invested in improving the way FM is being performed worldwide. It has been projected that the FM field will grow to

$945.11 billion by 2025 (Araszkiewicz, 2017). With a growth in the amount of money invested into the field, it can be expected that more money will be poured into the use of innovative technologies.

Smart Technology Overview/History

To enable the Air Force's objective of utilizing innovative building monitoring systems, an understanding of the history of smart technology is necessary. It is imperative to contextualize the usage of smart sensing for remote monitoring of assets to understand the way in which they will create efficiencies in facility management operations. Singh (2005) outlines the evolution of sensors since their inception in which they were initially used to extend mechanical power by artificial means via actuators and watermills, steam and combustion engines, and eventually the electromotor. With the introduction of computing power, data can be acquired to correct errors in automated processes and adapt as circumstances change. With silicon technology advancing at a rapid rate, sensors are the heart of instrumentation systems that are 'smart' in nature. Smart sensors can be defined broadly as a chip with sensors and a digital interface (Singh, 2005).

The implementation of smart sensors dates to their use in the aerospace and mechanical engineering field in the late 1970s (Zhang & Lu, 2008). Sensors were used to monitor vibrations and shape control of large flexible space structures. Their successful use in the aerospace industry has led to interest in the construction sector. The term smart sensor itself was likely coined in the mid-1980s (Frank, 2013). In industrial applications, sensors have been used to monitor the health of industrial assets and determine their operating conditions and eventual lifespan calculations. Application of sensors in the monitoring of civil infrastructure is a popular research area; however, the bulk of this research has occurred in the laboratory with limited scope (Stajano et al., 2010).

The concept of the Fourth Industrial Revolution, or Industry 4.0 as it is commonly referred to in the literature, is the idea of incorporating increasing interconnectivity and smart automation into the industrial sector. Industry 4.0 uses information and communication technologies used in the manufacturing sector to drastically increase the capabilities of current value chains (Wang et al., 2017). Applying these concepts helps plant managers understand the state of all their equipment at a moment's notice, thus maximizing machinery up-time. Sensors are embedded in equipment to determine its optimal operating conditions in a concept known as curative maintenance (Rabatel et al., 2011). When faults are detected, a computer system will know when the piece of equipment is in a deteriorated state and will notify operators when maintenance is needed. By applying sensors in industrial applications, the aim is to create vast improvements in order to shorten production times, which makes processes more efficient and can save millions of dollars for the plant operator (Rabatel et al., 2011). An increase in the usage of sensors in the industrial sector is expected and was projected to occur as database standards and benefits of remote diagnostics were better understood (Singh, 2005).

Sensors are being integrated into almost all aspects of modern living. The constant usage of electronics, gadgets, and cell phones gives researchers confidence that accelerometer, touch screen, proximity, temperature, and other miniaturized sensors are becoming more and more sensitive and reliable (Abruzzese et al., 2020). Smartphones are an example of the ability for sensor applications to be scalable. With the proliferation of mobile devices, it can be stated that their mass production and operation is feasible. Information about the environment, human movements, and personal health are constantly being tracked via smartphones, and the information is easily sharable to other users (Ahrend et al., 2021). The ways in which this information is shared will be discussed later in this chapter when discussing the advantages that 5G technology offers in wireless sensor networks.

The usage of smart sensing in facilities has been referred to in a concept known as smart facilities or smart buildings. Multiple definitions exist for what constitutes a smart facility. Generally, they are characterized as facilities with an interconnected system that can perform building automation and provide managers information as to facility performance, thus creating efficiencies and eco-friendly operating conditions (Araszkiewicz, 2017). Smart facilities are a broader usage of smart sensor technologies, as they are used to control multiple processes in facilities.

The application of smart sensing technology to the civil engineering and facility management fields is constantly growing. The global machine monitoring market is projected to grow from $2.06 billion as of 2020 to $2.77 billion by 2025 (Ziegelaar et al., 2020). The smart building global market is projected to grow from $66.3 billion in 2020 to $108.9 billion in 2025, and the value of the revenues in the internet of things (IoT) in the smart building global market will rise from $42.8 billion in 2020 to $65.2 billion in 2025 (Li et al., 2021). As has been alluded to, the bulk of these applications are not used in the field but in carefully controlled laboratory and research settings with limited application to real-world FM environments. To caveat the growth of this industry, it must be noted that most of the applications which have been in place are in research settings, with growing usage in field applications.

Sensor Connections

A sensor on its own may be a novel device, but multiple sensors monitoring an entire building system connected in a network provide more data to a facility manager. Sensors come in many shapes and sizes for the various applications for which they are being applied, and the way they are connected has implications on the way they transmit data and need to be maintained. Both wired and wireless sensors have extensive research being completed as to which is the right application, with the latter method using the latest technology to improve the way sensor information is being transmitted.

Wired communication links can vary, and they include methods such as optical fiber, broadband/baseband coaxial cable, and twisted pair cable (Goswami, 1993). Optical fiber is the latest method by which sensor networks are being connected. Optical fiber has its advantages, as it has durability enough to withstand extreme temperatures from between -200 to 800°C and is corrosion resistant; another advantage is in the replacement of multiple local sensors as it can act as a sensing element along its entire length (Wijaya et al., 2021).

If presented with a long distance over which data needs to be transferred, a wired connection can prove to be a limitation. The cost of the infrastructure associated with a wired sensor network can be greater than those that are wireless. Wired structural monitoring systems installed in tall buildings have been estimated to cost about $5,000 per sensing channel, and in one case, the cost of installing over 350 sensing channels on a suspension bridge was about $8M (Lynch & Loh, 2006). Dedicated communications and power lines are necessary to make these sensors feasible. The wiring arrangement in structures can be difficult; they are vulnerable to electromagnetic interference and are subject to high labor and material costs due to running miles of wire (Zhang & Cheng, 2012). Due to the high costs of a wired system, wireless sensing capabilities have become a more enticing option to groups who have assets spread out over a long distance, as well as those with smaller budgets who are looking to incorporate smart sensing capabilities.

Wireless connectivity has been the focus of research due to the cost prohibitive nature of wired sensors as discussed. Ziegelaar et al. (2020) outline a method for low-power, long-range sensor frameworks that addresses concerns with connection and power. These sensors mainly use radio frequencies to transmit data using computer off-the-shelf (COTS) microcontrollers, aiming to have each device cost about $80 and be treated as a semi-disposable asset. These sensors have an expected range of data transmission of approximately 3 km without any errors in the data (Ziegelaar et al., 2020). Further research is necessary as this concept is less than a year old; however, options such as these make the incorporation of sensors easier and less cost prohibitive. This application was ideally intended to be used on spread-out assets which require infrequent inspections, like road signs and power poles (Ziegelaar et al., 2020). However, wireless communication reliability is influenced by characteristics like communication range, physical interference, multi-path effects, and noise, which all contribute to data loss (Linderman et al., 2010). The need for reliability of sensor data transmission depends on their application. In many applications, it is not critically important if a small percentage of packets are lost; but in areas such as structural health monitoring (SHM), it is vital to have a protocol that guarantees reliable transmission of data because features of the response characteristics may be affected by data loss (Pakzad et al., 2008).

The simplest form of wireless data transmission is via radio signal. Salehi et al. (2021) discuss the challenges with self-powered sensors and the difficulty in signal communication. Existing self-powered sensors use Radio Frequency Identification (RFID) scanners to read data, and this comes with its own set of limitations. Powering RFID sensors can be a challenge, as the signal produced can be weakened by the item being monitored, which can affect the read/write range of the sensor. In addition, the sensor can be affected by environmental factors such as high pressure, temperature, and humidity, which can alter the sensor's reliability under harsh conditions (Salehi et al., 2021). Radio frequency is an older technology for data transmission; however, there are newer ways to perform this task that are ever evolving.

Recently, the introduction of Fifth Generation (5G) broadband cellular network technology has been eyed as a method to increase the effectiveness of wireless sensing capabilities. The use of 5G connectivity has been proposed for new systems such as smart homes, health-care applications, smart agriculture, and pollution detection, with research being done to address design principles and limitations (Mazied et al., 2019). Using 5G will require rethinking the way that sensors send information and communicate as well as addressing future security issues. Mazied et al. (2019) propose a generic framework for 5G wireless control plane design; however, it needs increased research to quantitatively evaluate how these designs will perform in practice. The rollout of 5G is currently ongoing, with telecom providers and/or local governments deciding which areas are going to be getting this network coverage, with the rate of the rollout being hard to predict (Ahrend et al., 2021).

Wireless sensor networks present power concerns and an associated cost element. Unlike conventional wired sensors, wireless sensors have no convenient form of power delivery and battery power is probably the most widely used power supply in wireless sensor networks (Zhang & Cheng, 2012). Selection of the optimal transmission power is critical when installing these sensors, as higher transmission power allows longer communication distances, but it also results in higher power consumption per sensor node (Linderman et al., 2010). Batteries also introduce an added cost and maintainability aspect to sensor networks. Batteries have a limited useful life, and their eventual replacement will require a dedicated maintenance schedule.

The installation of sensors will be done either by retrofitting the existing infrastructure or incorporating them into newly constructed assets. Niu et al. (2016) discuss the concept of Smart Construction Objects (SCO), which are defined as construction resources that have been made smart by adding the capabilities of sensing, processing, computing, networking, and reacting. SCOs can then be transitioned for use in FM once a facility has been constructed. The research by Niu et al. (2016) uses the example of piles, which are a necessary building foundation component that are hard to inspect and perform condition monitoring once they are installed, as they are buried underground to provide structural support. By installing sensors during construction, a facility manager possesses the ability to monitor pile condition over time and push information on the real-time status of the facility at preset intervals, or whenever necessary (Niu et al., 2016). Moving forward, the design and incorporation of smart sensor networks will need to be considered in facility construction and the upkeep of these networks incorporated into recurring maintenance costs.

To justify the usage of sensor networks to provide information to support decision-making, the data that they are producing must be accurate and useful. Speaking intuitively, if a sensor produces false data that shows an asset is deteriorating, additional inspections by a craftsperson will be required to determine if that asset is in fact deteriorating. When a sensor provides false information for a component that requires a labor-intensive repair to maintain operability, the sensor has cost the user money that did not have to be spent. Data can also be difficult to interpret, and there needs to be an accurate representation of data in order to be able to determine its usefulness (Rabatel et al., 2011).

Sensor network data will enable the FM community to perform data-centric decision-making. Broo and Schooling (2020) discuss the issues that data-centric decision-making will have in maintaining smart infrastructure, and these challenges in an Air Force context will be discussed. These challenges include availability, accessibility, quality, volume, heterogeneity, and longevity. While there may be a lot of data being created, the availability of useful data and the extraction of such data is a challenge. Data accessibility is of concern in organizations that have restrictive privacy policies, which includes organizations like the Air Force. The right people need to have access to the data they need at the right time in order to make timely decisions. The quality of the data is a concern due to poor data quality management practices. Specified training will be needed to maintain the data of smart systems, and this is a problem in the Air Force due to the lack of personnel who have the knowledge needed to maintain these systems. Analyzing and processing large amounts of data can be complicated and resource intensive. Heterogeneity deals with the different forms of data which will be created in a sensor network. Data processing tools will be necessary to compile and process this data in order for it to be useful. Data longevity is about the long-term availability of asset information. Limited bandwidth for storage is often present on Air Force installations, so being able to store the data for usage later will pose a challenge moving forward (Broo & Schooling, 2020).

Networking and Security

To be successful, smart sensors require networking capabilities for information flow and control (Gurkan, 2012). Notably, the Institute of Electrical and Electronics Engineers (IEEE) have proposed the IEEE 1451.1 Standard for Smart Sensor Networks, which aims to harmonize standards with networking and data acquisition of sensors. This new protocol has been theorized to be useful in sensor control of traffic signals in metro areas, automobile controls, environmental conditions, roadways, civil structures, and animal habitats (Gurkan, 2012).

Cyberattacks pose a challenge to any system which is connected to the internet. With an increasing number of items being a part of the IoT, the number of sites for potential attacks is also increasing. Cyberattacks happen seemingly constantly and are national news when they affect large infrastructure systems or leak public data. Notably, the retail chain Target experienced a cybersecurity attack and data breach around

Thanksgiving 2013. This attack resulted in credit card data being stolen from each of the company's 1,797 stores. Hackers were able to gain access through the store's climate control systems (Manworren et al., 2016). Even though Target had heavily invested against a cyberattack, breakdowns and ignored warning signs of an impending attack led to a large data breach, which ultimately cost Target $10 million along with the cost of reduced public confidence in their ability to keep personal data secure.

Smart sensor networks are vulnerable to a cyberattack by the nature of their networking. With sensor networks being deployed on a large scale, coupled with their open nature of wireless communications, a networked control system has vulnerabilities to a cyberattack (Zedan & El-Farra, 2021). Attacks can take many forms and have multiple bad outcomes that can occur based on the system being attacked. As an example, if a water distribution network is attacked via its sensor network, information can be stolen from its customers, a water supply for an entire region can be cut off, or even a dam or reservoir can be flooded (Moazeni & Khazaei, 2021).

Public data leakage that could result from smart sensor networks is of concern after system installation. A relevant example discovered in the literature was from a tunnel and a bridge in the United Kingdom. Two data managers had differing views on whether data should be readily available to the public. The bridge manager saw no reason to keep the data confidential; however, the tunnel manager wanted to know any potential safety concerns before data was released to the public (Stajano et al. 2010). The Air Force must address the level of risk they are willing to take with releasing asset data to the public. With the bridge and tunnel example, the tunnel is in plain sight, and people can drive across it and see if it is deteriorating; however, the tunnel is harder for the public to judge its condition. Similar tradeoffs must be addressed before implementation by the Air Force. There could be unintended consequences by providing too much data in response to a Freedom of Information Act (FOIA) request.

Building Information Modelling

Smart technologies provide a large amount of data; without a method to store, monitor, and maintain this data though, it is useless to a facility manager. Integration into a building information modelling (BIM) system would best enable access to accurate and timely facility information. BIM can provide capabilities such as locating components, checking maintainability, and using its visualization capabilities to analyze and control capabilities of installed assets (Zhang et al., 2015). A BIM system would be able to provide real-time access of data visualization and energy monitoring (Suprabhas & Dib, 2017). These systems must be able to effectively gather and produce a model that a decision-maker can access to determine the condition of the asset in question. Systems designed for FM require a vast amount of features to be useful, such as monitoring material assets, controlling and planning renovations, reporting and managing failures via helpdesk style systems, or space management (Araszkiewicz, 2017).

The FM field is growing more and more complex, with facilities becoming more sophisticated than those built in years past. Each asset in a facility has an associated cost tied to its installation in addition to an operation and maintenance cost (Suprabhas & Dib, 2017). With the inclusion of smart technologies in these facilities, the need for a computerized solution becomes paramount to the success of smart technology integration. While not necessarily used just for smart environments, BIM systems have been developed that include the software used to collect, sort, and analyze building information (Zhang et al., 2015). Applications of BIM have been studied in the architecture, engineering, construction, and FM industries (Liu et al., 2020).

Aside from the ability to process the increasing data produced by smart technology, BIM is a critical tool for decision-makers wishing to integrate smart technologies. It has the ability to provide a contrast between the information that sensors are producing and known constraints of the system, thus allowing for validation of sensor performance (Zhang et al., 2015). In addition, sensors that are being used in a wireless sensor network (WSN) are likely to be made by different manufacturers; therefore, an interface is necessary to be able to take different data types and profile them through an information exchange interface (Zhang et al. 2015).

Currently there are multiple pieces of software used to provide BIM capabilities to facility managers. Pereira et al. (2021) outline the different types of software in current usage and categorize them into BIM modelling, energy monitoring, and software development. According to their systematic literature review, 94 software systems were found to be in current use. For BIM modelling, the most used software was Autodesk's Revit program. For energy monitoring, EnergyPlus is the most commonly used software in the field. New tools identified for software development were mainly produced using Dynamo, Grasshopper, and MATLAB. Most self-developed tools are used as plugins that operate in Revit (Pereira et al., 2021).

Current Air Force Applications

With sensors being applied and researched at an increasing rate, the Air Force has been operating varying forms of smart sensors on bases for some years now. These vary in system complexity but have proved to be valuable tools in maintaining base infrastructure. Further technology advancement and adoption is the goal of the Installation Investment Strategy.

Supervisory Control and Data Acquisition (SCADA) systems are widely used on wastewater systems to monitor overall system performance. A SCADA system can be defined as the control and monitoring of various processes from a centralized control, thus enabling operations control from that location (Goswami, 1993). They are used to collect and process information; as faults are detected, they are reported to a central hub, where an operator can see how a component is operating in real-time and decide which course of action is needed to restore the component to an operational capacity. SCADA systems currently mainly use older technology such as push buttons, selector switches, potentiometers, annunciator panels, and chart recorders, with many of these technologies being in existence since the 1950s (Goswami, 1993). The age of SCADAs is something that has been noticed in research. Since the initial investment and installation are costly and time consuming, the lifespan of a SCADA needs to be maximized, which causes many of the existing SCADA systems to be considered legacy products that need to be updated to modern technology (Sheng et al., 2021).

In accordance with AFI 32-1001, HVAC controls shall be connected to an Energy Management Control System (EMCS). These in a sense serve as smart sensor networks, as there is a network of sensors and actuators placed on environmental control systems throughout the base. These sensors and actuators serve the purpose of being able to modify settings in facilities and detect when faults are present so that a technician can either troubleshoot the system over the network or perform maintenance actions on location. Smart thermostats are another type of sensor that have been implemented on Air Force bases. By implementing smart thermostats in cities around the United States, it has been reported that there is an HVAC energy savings ranging from 20 to 40% (Pang et al., 2021).

Most bases have taken advantage of lighting and energy upgrades as a part of Energy Savings Performance Contracts (ESPCs). An ESPC allows federal agencies, such as the Air Force, to "procure energy savings and facility improvements with no up-front capital costs or special appropriations from Congress" (*Energy Savings Performance Contracts for Federal Agencies*, n.d.). These contracts contain lighting sensors and other energy upgrades with an aim to reduce the amount of energy that the Air Force is using in an effort to meet federal sustainability goals. In efforts studied in the literature, estimates show that about 25% of costs associated with energy consumed in large facilities can be attributed to lighting (Wang et al., 2015). Wang et al. (2015) also address the design of smart sensor networks to be able to effectively reduce costs of energy in large facilities. They show that by incorporating a sensor network, and by using lux sensors combined with occupancy sensors, efficiencies can be gained by reducing the amount of lighting throughout the facility. Energy savings can also be attributed to occupancy based controls, with a 24% savings being experienced (Dikel et al., 2018).

Current Air Force bases are also investing in new smart technology applications. Most notably, Tyndall AFB is incorporating smart sensing technology in areas that are currently undergoing reconstruction after Hurricane Michael in 2018. Due to the extent of damage that was sustained from the Category 5 hurricane, the majority of the installation is incorporating smart technologies as it aims to be “The Base of the Future.” New building standards are planning on incorporating “smart-building sensors” (Koopman, 2020). Currently on the base’s flight line, sensor systems are planned to detect the condition of pavements and determine when maintenance is needed on particular sections (Lozano, 2021). In addition to this type of technology, 5G technology has been installed to increase connectability across the installation (Kanowitz, 2020). Currently, the Air Force has 5G initiatives to bring it to ten other bases.

The Air Force has a simple BIM system known as NexGen IT, which is based on the IBM Tririga platform. With this system, maintenance items are planned and tracked. The planning is initially done by maintenance craftspersons; however, the system also generates work actions based on the schedule set from guidance sent by higher headquarters.

Another set of asset management tools which is not only in use by the Air Force but across the Department of Defense are sustainment management systems (SMS). These systems are web-based software applications developed by the United States Army Corp of Engineers Engineer Research and Development Center’s (ERDC) Construction Engineering Research Laboratory (CERL) which tracks asset condition based on manual inspections and can help to project when an asset is set to fail based on its own internal algorithms (*Sustainment Management System*, 2020). Condition ratings from this system are mandatory when deciding if large amounts of money are necessary to be spent to upgrade assets.

At this time, the scope of software that is available to the Air Force is limited. Only Air Force mandated IT systems can be used for data collection, input, and maintenance. The use of SMSs are authorized per AFI 32-1001, but only those which have been vetted for use are able to be used.

Previous Scientometric Analyses and their Findings

There have been multiple studies using either a scientometric or bibliometric process to study research topics in smart sensing and the usage of BIM systems. As these two systems are often linked in their usage in FM practices, it is appropriate to investigate research into both fields of study. The relevant research presented in the literature was mirrored for use in this research.

Liu et al. (2020) used a bibliometric analysis to research the progression of BIM-based smart facility management (BIM-FM). Their goal was to analyze the domain knowledge to identify the research trends, challenges, and needs within the field of BIM for FM. A total of 590 articles were analyzed that were published between January 2004 and March 2010. A keyword co-occurrence and citation analysis were conducted using VOSviewer. Six categories of research were found via their clustering analysis: 1) as-built/as-is data acquisition, 2) interoperability, 3) sustainability, 4) life-cycle collaboration and integration, 5) information communication and visualization, and 6) knowledge-based FM. As-built/as-is data acquisition was determined to be the largest cluster of frequent keywords, and it demonstrates that gathering these vital pieces of information is requisite in FM practices. Challenges arise when gathering this data, such as updating as-is models based on building maintenance records and recording occupancy status for energy and emergency management practices. Interoperability is considered the core of BIM technology, as it minimizes reworking of modelling building information. BIM can assist in sustainability practices and will continue to be an important research topic moving forward. Integrating BIM in FM during a facility's life-cycle will be crucial, especially during the project handover between the construction phase and the FM phase of a facility. Being able to handle the building information to facilitate FM activities is covered in the information communication and visualization cluster, as new innovative ways are being created to handle a facility's information. Knowledge-based FM represents research efforts which are dedicated to predictive and preventive maintenance, with the intent of automating these maintenance activities. In their analysis, the following was found to be the most prevalent research needs facing BIM-FM researchers: interoperability, data requirement, BIM-augmented reality/virtual reality (AR/VR) integration considering human-machine interaction, heterogeneous data integration such as maintenance record, BIM-IoT integration for smart FM, and knowledge-based FM (Liu et al., 2020).

He et al. (2017) applied a scientometric approach to construct knowledge maps for the managerial areas of BIM (MA-BIM), which is defined as organizational and legal strategies for coordinating and managing overall project information and processes, as well as aligning project policies to improve the level of BIM adoption and implementation. The managerial areas of BIM have the potential to coordinate and manage overall project information and processes, as well as align organizational strategies within a complex project environment. A keyword and abstract term analysis of 126 related papers from 2007-2015 was performed to develop the current status and future directions. Eight prominent research themes were present their study: 1) collaborative working environment, 2) innovation, 3) stakeholder/actor network, 4) spatial visualized management, 5) BIM adoption, 6) transmission, 7) conceptual framework, and 8) O&M.

Li et al. (2021) studied smart building research and applied a co-citation method to determine the main areas of study. A total of 346 papers published between 1984 and 2020 were included in their analysis. Of these papers, it was shown that wider attention was paid to smart buildings since 2010, which has gained even more traction closer to the time of the study's publication. Five research clusters were found and mapped in this analysis: 1) lighting, 2) occupancy detection, 3) thermal comfort, 4) integration and operation (control), and 5) occupant behavior modeling. From these five research clusters, two main themes arose: 1) IoT WSN and cloud computing for automation control and 2) the balance between energy efficiency and human comfort based on continuous monitoring and machine learning (Li et al., 2021). Their research was notable for analyzing the ways in which smart building research is being used to shape directions for occupant-centered smart buildings, which mainly deals with human comfort and energy usage, directing its focus directly into the area of HVAC and lighting controls.

Pereira et al. (2021) conducted a scientometric and systematic review of BIM literature to improve building energy efficiency. A total of 219 publications published from 2009-2019 were collected from four databases (ScienceDirect, Google Scholar, American Society of Civil Engineers (ASCE) library, and the Institute of Civil Engineers). Five main categories were created: 1) BIM technologies, 2) BIM model-based tool development, 3) sustainable buildings, 4) hygrothermal design, and 5) training.

The identification and ranking of the most prevalent software currently in use was a key takeaway from their research, with 94 different software tools being identified as either in use or being used for research purposes. The interoperability between different tools was identified as being a challenge in further industry-wide adoption of BIM technology. As has been seen before, BIM technology can be used to create more efficient and sustainable facilities, as new building technology such as innovative insulation methods and design of glass panels can be modeled in a facility and their effects monitored (Pereira et al., 2021).

Araszkiewicz (2017) investigated the state of practice and research challenges in the applications of digital technologies in facility management. Articles in their study were gathered from Google Scholar and Scopus with publication dates from 2010-2016. A total of 33 articles were chosen to be the most appropriate, as their concentration was on commercial and industrial property. Advanced electronics and computer science in smart facilities was divided into four main categories: 1) energy efficiency, 2) human security systems, 3) telecommunication systems, and 4) workplace automation. Combining all four into one coherent system was the key takeaway (Araszkiewicz, 2017).

Conclusion

Through this literature review, the history and evolution of smart sensor networks was introduced. The way in which they are connected in networks and data transmissibility was also discussed. To process the information gathered, BIM systems are necessary, which include critical software to enable the usage of sensor networks. Current and projected usage of sensor technology in the Air Force was also discussed, highlighting the fact that their adoption is behind the level at which research is being performed. Examples of scientometric analyses which have already been done were also discussed, which showed that there are similarities in the areas which are currently being researched with regards to smart technology in FM applications.

III. Methodology

This chapter will discuss the methodology used to conduct research into smart sensor usage in the facility management (FM) field. An overview of scientometrics will be presented first. The data collection techniques and the way that a final data set of journal articles was achieved for the final analysis will then be shown. These methods will be used to answer the research questions that were posed in Chapter I.

Scientometrics Overview

To determine the areas of FM where smart sensors have been researched and applied, a scientometric analysis was performed. Hook and Börner (2005) classify scientometrics as a form of knowledge domain visualization (KDV), which is defined as "the graphic rendering of bibliometric data designed to provide a global view of a particular domain, the structural details of a domain, the salient characteristics of a domain (its dynamics, most cited authors or papers, bursting concepts, etc.), or all three." Two other similar types of study, which are often used along with scientometrics, are bibliometrics and informetrics (Hood & Wilson, 2001). Bibliometrics can be classified as "a study or measurement of format aspects of texts, documents, books, and information" and is most often used in fields of library and information science (Chellappandi & Vijayakumar, 2018). Scientometrics is a KDV approach performed in the field of information science, which aims at the quantitative study of science (Hook & Börner, 2005). It examines the "quantitative aspects of the production, dissemination, and use of scientific information with the aim of achieving a better understanding of the mechanisms of scientific research as a social activity" (Chellappandi & Vijayakumar, 2018). Since scientometrics involves quantitative studies of scientific activities, it overlaps with bibliometrics (Hood & Wilson, 2001).

Scientometrics were used to explore the field of smart sensors in facility management operations. This study will mirror those presented in Chapter II by identifying patterns which exist in the literature. This process was focused on answering the investigative questions presented in Chapter I.

This research relied heavily on the use of text data mining (TDM) tools. TDMs are tools which enable "discovering useful knowledge to help in processing information and improving the productivity of knowledge workers" (Ur-Rahman & Harding, 2012). The tools that were used in this research were NVivo Release 1.5.2, Zotero 5.0.96.3, and VOSviewer v1.6.17.

NVivo is a software created by QSR International to perform quantitative data analysis. Ideally it is used for analysis of structured or unstructured text, audio, video, and image data (*About NVivo*, 2022). In this case, it was used to analyze structured data from a research database, as NVivo has been highlighted as a program which has great usage in literature reviews.

Zotero is a free open-source citation management software created by the Corporation for Digital Scholarship, which can be used to collect, organize, and analyze research (*About Zotero*, 2021). Using this software was beneficial throughout the entire research process not only for managing the literature, but it also provided the ability to sort and filter the selected article dataset for content. It also has the ability to export files which can be read by NVivo.

VOSviewer is an open-source software tool which has the ability to create maps based on network data and for visualizing and exploring the maps it creates. Its main purpose is to analyze bibliometric networks, but it can create, visualize, and explore maps based on any type of network data. VOSviewer can be used to construct a network of scientific publications, scientific journals, researchers, research organizations, countries, keywords, or terms, and can be connected via co-authorship, co-occurrence, citation, bibliographic coupling, or co-citation links (van Eck & Waltman, 2018).

Paper Retrieval

This process used the online research database Scopus to find articles for the research. The Scopus database contains over 84 million records from 25,800 active peer-reviewed journals from over 7,000 publishers (*Scopus Fact Sheet*, 2022). This database was chosen because it was the primary database available for usage through the D'Azzo Research Library on the AFIT campus.

Keywords used in the search were "facility management", "smart sensors", "preventive maintenance", "corrective maintenance", and any form of the words which could commonly be encountered in a keyword search; this was accomplished by using stem words. Appendix A shows the query used in Scopus to develop the initial article data set. Scopus allows for a title, abstract, and keyword search; the abstract and keyword search were used for the research. Only articles from the peer-reviewed literature and published in English were considered. Due to the vast number of sources which Scopus can pull from, areas in arts, earth sciences, immunology, chemistry, and many others were excluded from the search to narrow the search to the applicable field.

Scopus is able to provide large amounts of data about the articles in its database. The pieces that were primarily used for analysis were the title, abstract, author, index keywords, citation data, and date of publication. The initial data set included 345 articles, which was pared down to 279 articles after reviewing each article's content. During this research, abstracts and keywords were chosen to identify the articles in the Scopus database that were applicable. Articles were primarily excluded if they did not have any applicability to the application of smart sensors in FM operations. The excluded articles contained information with industry specific topics, to include Industry 4.0 and assembly and machining plant applications. Many of the other excluded articles contained information about facilities and applications which did not pertain to Air Force Civil Engineer operations, such as wind turbines and other power generation techniques.

Articles were exported from Scopus as .RIS files, which can be read by the Zotero software, and also as .csv files, which are more easily understood by VOSviewer. Once imported into Zotero, the titles, abstracts, and keywords were able to be sorted. Articles which were deemed not pertinent were removed from the dataset in both Zotero and in the .csv file, which was opened using Microsoft Excel. Microsoft Excel was used to gather and sort both author and index keywords in the dataset. It provided initial statistics for the frequency of keywords in the article dataset and acted as a check for the analysis completed using NVivo and VOSviewer.

Analysis

Information about the articles in the dataset was extracted using Microsoft Excel. Basic data about the date of publication was gathered to visualize the date ranges and trends related to the number of publications by year. In Excel, information tied to the publications which this dataset drew its articles from were investigated, as frequently occurring words in journal titles were gathered to see if there were any trends related to publication type.

With the pertinent article dataset, the titles, abstracts, keywords, and citation data were uploaded into the NVivo software. Abstracts and keywords were coded into NVivo for further querying. Coding in NVivo is defined by the software publisher as a collection of references from files about a specific theme, topic, concept, idea, or experience, which can be either descriptive or analytical (*About NVivo*, 2022). Performing the coding process on each of the selected articles allowed for querying word occurrence in both the abstracts and keywords of the dataset. Once all articles had been coded, a keyword and abstract frequency analysis were performed. NVivo can query using specific criteria, such as by exact matches, stem words, synonyms, specializations, and generalizations. Exact matches are querying based on the frequency of a specific word, with no conglomeration based on word definition. The example which is present in the software is the word "talk." Stem words are ones in which the word can have specific suffixes/prefixes, as in the word "talking." Synonyms are words which have similar meanings, like "speak" and "talk." Specializations are words like "whisper" and "talk." Generalizations include themes, like the word "communicate" and the word "talk." In this analysis, exact word matches were the type of querying which was performed in the abstract and keyword analysis. Based on the results NVivo created, words were combined with their plural form, and words commonly used in speech were excluded, like using, paper, also, results, etc.

To perform a visualization of the topics in the dataset, VOSviewer was called upon. The .csv files which had been maintained with the data from the filtering process were uploaded into VOSviewer. Here, a combination of title and abstract along with a separate keyword analysis was performed, and network maps and clusters were created highlighting the key areas of research. In doing the title and abstract analysis, words which were common in research documents were excluded, such as paper, methodology, research, etc. VOSviewer allows users to select words based on a relevance ranking. Relevance ranking is similar to the exclusion method used with the NVivo querying. The VOSviewer manual states that "one typically does not want to include general terms, for example, terms such as 'conclusion', 'new method', and 'interesting result'." By default, 40% of terms are excluded based on relevance, but the developers recommend experimenting with the effects of excluding more or less terms (van Eck & Waltman, 2018). Terms were clustered based on the method of association strength. This is the default method VOSviewer uses to normalize the strength of the links between each of the nodes. Weights were assigned based on the number of occurrences in the data set. Full counting was used in this analysis, which is shown in Figure 1.

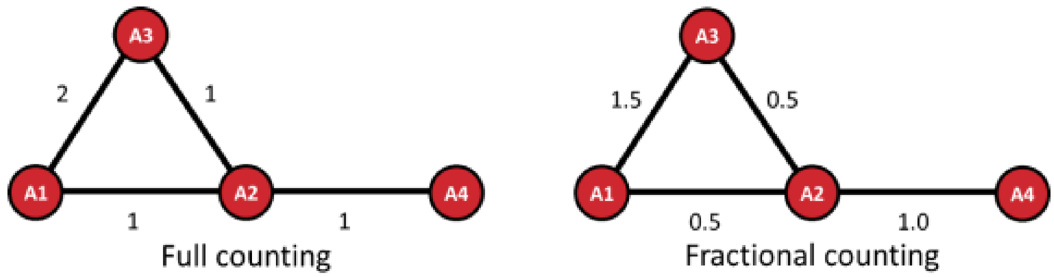

Figure 1. Full Counting vs Fractional Counting (*About NVivo*, 2022)

Full and fractional counting methods are mainly used in constructing co-authorship networks; however, they have applicability in keyword linking as well. Perianes-Rodriguez et al. (2016) highlights differences between the two methods. Full counting assigns links as number of occurrences, as seen in the left example in Figure 1. Items A1 and A3 have two links between them and the rest only have one link. Fractional counting is used to reduce the influence of items with many links. Fractional counting has the ability to assign equal weight to all actions, and full counting has actions which can have more weight than others (Perianes-Rodriguez et al., 2016). In this case, we are analyzing word occurrence and not co-citation or authorship analysis, so the disadvantages associated with full counting will not be as prevalent.

The minimum strength needed to draw lines between nodes was set to 5, and the maximum number of lines which could be drawn in the network was 900. Minimum strength determines the minimum strength of links which are displayed in the visualization, which in this case would be 5, as was specified to be the minimum number of occurrences of a keyword (van Eck & Waltman, 2018). Small clusters were combined with larger ones. During the keyword clustering, the overlay visualization function was used to determine the number and average date of occurrences.

To illustrate the outlined methodology, Figure 2 provides a flow chart of these processes. Three phases are outlined in this figure: the selection process which covers the way in which the dataset was compiled and filtered; the review process containing the qualitative review, a content analysis, and the quantitative review; and the contributions from this research containing general knowledge and specific knowledge sections. Further information regarding the metrics described in the contribution portion of Figure 2 will be discussed in the results and discussion portion of this research. From this process, several conclusions were formed, which are discussed in the following chapter.

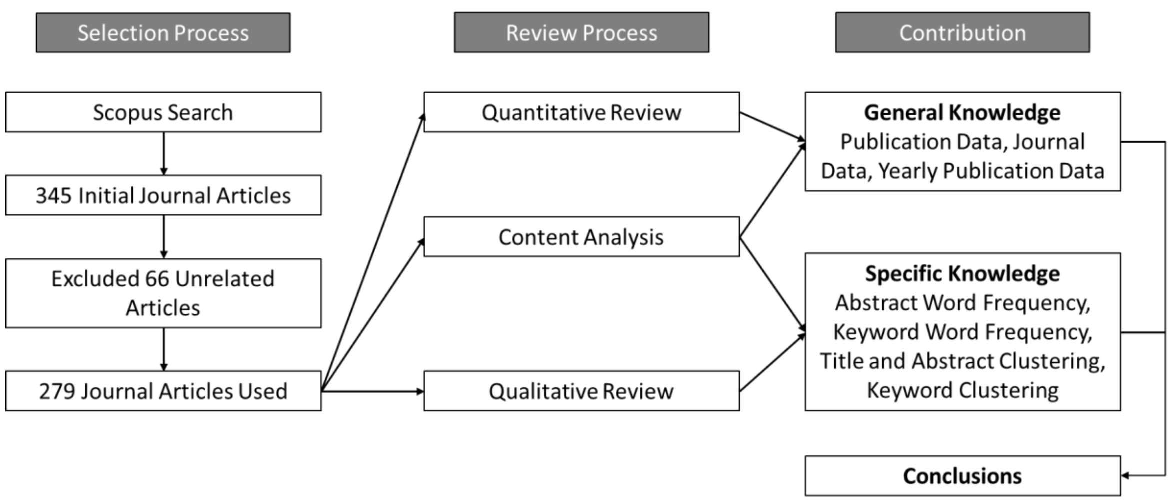

Figure 2. Research Methodology

Conclusion

This chapter presented the methodology used to gather a data set and perform a scientometric analysis of the topics involved in the application of smart sensor technology in FM practices. The web database Scopus was used to search and compile articles to be analyzed. Once the articles that were deemed irrelevant for this analysis were excluded using Zotero and Microsoft Excel, the article data set was uploaded into NVivo to perform queries of the abstract and keyword data. To perform networking and clustering analysis, VOSviewer was employed. The results of this methodology are presented and discussed in Chapter IV.

IV. Results and Discussion

This chapter will be used to provide and discuss the findings from using the methodology outlined in Chapter III. The objective of this chapter is to discuss how the analysis was used to answer the investigative questions posed in Chapter I pertaining to research which had been completed on the use of smart sensors in facility management applications. This chapter will explore data about the types of publications which were used for this analysis and the number of journal articles published by year. Keyword and abstract queries and their findings will be presented, along with the similarities present in each. A combination title and abstract visualization and a separate keyword visualization were performed, and research clusters were created from the terms present in this network diagram. Finally, findings and conclusions will be presented.

Publication Data

In total, the search in Scopus resulted in 345 journal articles, which was then narrowed down to 279 articles with publication dates between the years of 1987 and 2022. The dataset used for this research came from 152 different publication titles. Table 1 shows the top ten publication titles present in the dataset. Of the journals used for this research, 117 publication titles produced a single journal article.

Table 1. Top 10 Publications

Rank	Publication Title	Articles	Average Year of Publication	Percentage of Final Dataset	Impact Factor
1	Energy and Buildings	22	2016	7.89%	5.879
2	Automation in Construction	16	2015	5.73%	7.700
3	Building and Environment	12	2018	4.30%	6.456
4	Energies	10	2019	3.58%	3.004
5	Sustainable Cities and Society	9	2017	3.23%	7.587
6	Facilities	8	2010	2.87%	N/A
7	IEEE Access	7	2019	2.51%	3.367
8	Journal of Facilities Management	6	2016	2.15%	N/A
9	IEEE Internet of Things Journal	5	2019	1.79%	9.471
10	Applied Energy	4	2018	1.43%	9.746

The top publication from which articles were gathered was *Energy and Buildings*. This is an international journal which publishes articles regarding the use of energy in buildings. Elsevier's description of this journal states that the "aim is to present new research results and new proven practice aimed at reducing the energy needs of a building and improving indoor environment quality" (*Energy and Buildings - Journal - Elsevier*, 2022). As the search for articles mainly centered on an innovative technology's application into improving a facility's efficiency, it is not surprising that this journal contained a large number of publications, containing 7.89% of the articles used in the analysis.

Automation in Construction and *Building and Environment* had the second and third most articles present, with percentages of 5.73 and 4.30, respectively. According to Elsevier, *Automation in Construction* "publishes refereed material on all aspects pertaining to the use of information technologies in design, engineering, construction technologies, and maintenance and management of constructed facilities" (*Automation in*

Construction - Journal - Elsevier, 2022). One of the journal's focus areas concentrates on facilities management, management information systems, and intelligent control systems, which is the focus of this research. Elsevier states that *Building and Environment* is an "international journal that publishes original research papers and review articles related to building science, urban physics, and human interaction with the indoor and outdoor built environment" (*Building and Environment - Journal - Elsevier*, 2022). Of note relating to the purpose of this research is the aim to investigate technologies, especially smart technologies, and integrated systems for high performance buildings.

To determine the importance of each journal, the Journal Impact Factor (JIF) was collected for the top ten appearing journals (see Table 1). The JIF is calculated by Clarivate Analytics as the "ratio between citations and recent citable items published" and is "calculated by dividing the number of current year citations to the source items published in that journal during the previous two years" ("The Clarivate Analytics Impact Factor," 1994). The impact factors used were taken from the year 2021, which uses the citation data from the previous two years. The numbers indicated by the impact factor show the frequency which the articles published in each journal are cited in other publications in the previous two years. For example, the articles in Energy and Buildings were cited on average around 6 times each in 2019 and 2020. In the top ten journals present in the dataset, the articles in the *IEEE Internet of Things* and *Applied Energy* receive the most citations on average. For the journals for which an impact factor was available, it was greater than 3, which is representative of a good journal publication.

The top 10 publications comprise three journals that contain the word energy and its plural form in their title, with another containing sustainable. The combined percentage of these four journals is 16.13%. With the further analysis presented in this section, the prevalence of applications in energy savings will become more apparent. Smart sensor technology has a vast impact on energy conservation, as this is an area which is constantly being optimized.

Also of note is the type of journals present in the dataset. Searching by the title of each publication used in the dataset, the subject matter of each of the publications can be inferred. Table 2 shows a breakdown of the journal types by title that were encountered.

Table 2. Journal Type by Title Keyword

Journal Title Contains	Number of Publications	Number of Articles	Average Date of Publication
building	10	49	2016
engineering	38	48	2015
energy/energies	9	42	2016
computer/computing	27	36	2015
IEEE	18	34	2016
technology	17	24	2014
construction/constructed	6	24	2013
sustainable/sustainability	6	17	2018
facility/facilities	5	15	2011
communication	11	11	2016

Exploring the titles of the dataset resulted in 10 main topics. Several of the words were present in multiple journal titles, such as energy and buildings. The Institute of Electrical and Electronics Engineers (IEEE) publishes many journals which were encountered in this research, a total of 18 were present containing 34 articles. The terms building and engineering appeared in the most articles, which can be expected based on the initial search performed to obtain the articles used in the research. Publication sources which contained energy in their titles appeared 42 times, and sustainable and sustainability appeared 17 times.

Investigation into journal titles allowed for a brief introduction to the dataset. The key ideas from journal titles will foreshadow the topics which will be seen as more investigation into the article dataset is done. Technology, computing, and communication publications were present, which indicates that ideas regarding innovation will be present. Application areas which will be seen later, such as energy and sustainability, will continue to be key topics moving forward.

Number of Publications by Year

An investigation into the number of journal articles published by year was also performed. Articles in this dataset were present from the years 1987-2022. This data is shown in Figure 3, which shows the number of articles published by year. The data presented in Table 3 shows the number of publications which were published post 2007, which is where the upward trend in Figure 3 begins.

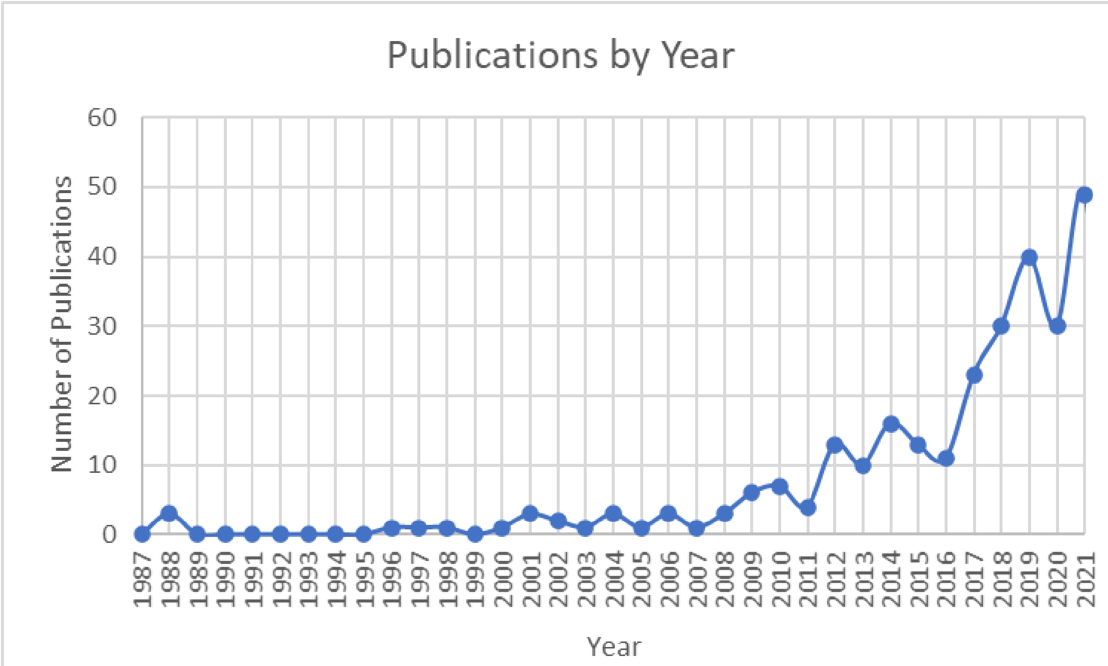

Figure 3. Number of Publications by year

Table 3. Publications from 2007-2021

Year	Publications	Percentage of Total
2021	49	17.56%
2020	30	10.75%
2019	40	14.34%
2018	30	10.75%
2017	23	8.24%
2016	11	3.94%
2015	13	4.66%
2014	16	5.73%
2013	10	3.58%
2012	13	4.66%
2011	4	1.43%
2010	7	2.51%
2009	6	2.15%
2008	3	1.08%
2007	1	0.36%

The average date of publication was 2016. Article publications were low prior to 2007. After 2007, the number of articles published by year trends upward, with the most articles being published in 2021. The data set used also included articles which have been slated to be published in upcoming journal volumes, with 3 articles found with a publication date of 2022. These were excluded from both Figure 3 and Table 3 to not give the appearance that a negative trend was occurring, as the entire year has not occurred yet.

Table 3 shows the number of publications from 2007-2021. From 1988-2021, the average number of articles was 8.3 per year. With 49 articles being published in 2021, and with a noticeable trend upward, it can be assumed that there will be even more articles related to smart sensors in facility management published in the years to come.

It has been noted that the number of articles which are being published are increasing year by year. The National Science Board, a section of the National Science Foundation of the United States, tracks trends of articles published throughout the world. Figure 4 shows the number of articles published in the science and engineering (S&E) fields by year from 1996-2018 (White, 2019).

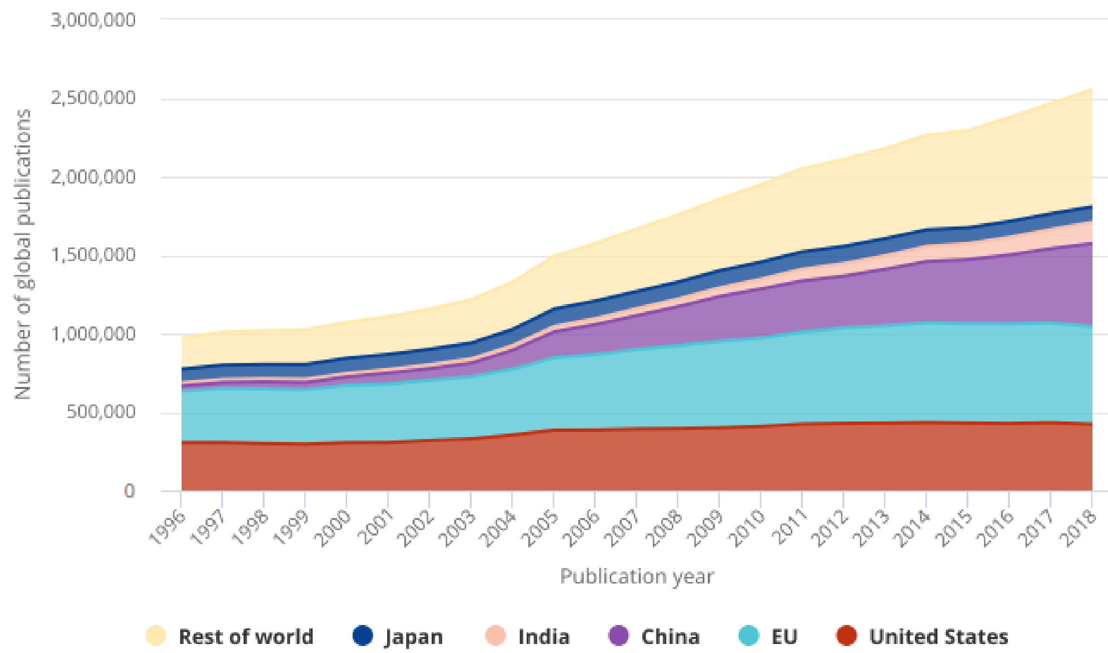

Figure 4. S&E articles: 1996-2018 (Source: National Science Foundation)

This figure shows that publication output has steadily increased since the turn of the millennium. A constant increase has been experienced within the last two decades. In the article dataset used in this research, a similar effect was experienced; however, the publications did not have a sharp increase until 2007. With more articles being published in general across the S&E fields, more articles in the area of smart sensor research will likely be experienced as well.

Abstract Queries

Abstract queries were performed using NVivo. Queries followed the methodology which was outlined in Chapter III. Exact word matches were performed in this case. Terms in this query had to contain a minimum word length of 4 characters.

The top 75 words were initially discovered; after excluding plural forms and common suffixes, the top 50 words were isolated. Table 4 shows the words and associated word counts from the abstracts, ranked by number of occurrences.

Table 4. NVIVO Abstract Word Frequency

Rank	Word	Count	Rank	Word	Count
1	building(s)	991	26	detection	118
2	system(s)	650	27	comfort	110
3	data	497	28	design	110
4	energy	485	29	research	102
5	sensor(s)	480	30	developed	96
6	management	410	31	indoor	90
7	based	314	32	network	90
8	information	245	33	intelligent	89
9	smart	236	34	technologies	85
10	model(s)	208	35	cost	75
11	facility/facilities	202	36	services	72
12	control	182	37	thermal	72
13	application(s)	169	38	development	69
14	environment(al)	167	39	wireless	69
15	monitoring	160	40	learning	67
16	time	159	41	devices	66
17	performance	150	42	existing	65
18	maintenance	142	43	value	62
19	technology/technologies	139	44	level	61
20	integrated/integration	133	45	power	61
21	consumption	129	46	effective	60
22	real	129	47	software	60
23	approach	126	48	conditions	58
24	efficient/efficiencies	126	49	fault	58
25	occupancy	124	50	operation	58

Based on the search terms used in Scopus and the subject matter of interest, "building" was the most frequently encountered word. Disregarding this term, as it was used in the initial Scopus search, the term "system" was the second most common word in the abstracts, followed by data and energy. There was a high prevalence of publications that had to do with energy efficiency, as the word energy occurred 485 times in the abstracts; indoor comfort-related words, such as occupancy, comfort, indoor, and conditions were also common. Further clustering of the terms found in the abstracts will be discussed when doing the abstract and title network analysis in VOSviewer.

Keyword Queries

In addition to the abstract query, a keyword query was performed using NVivo. Exact word matches were performed in this case as well. Terms in this query had to contain a minimum word length of 4 characters. The top 75 words were initially discovered; after excluding plural forms and common suffixes, the top 50 words were isolated. The top 50 words found in this query are presented in Table 5, ranked by number of occurrences.

Table 5. NVIVO Keyword Frequency

Rank	Word	Count	Rank	Word	Count
1	building(s)	684	26	office	58
2	system(s)	426	27	utilization	57
3	energy	374	28	automation	56
4	management	373	29	indoor	54
5	sensor(s)	242	30	time	54
6	intelligent/intelligence	179	31	technology/technologies	53
7	information	156	32	design	49
8	data	151	33	consumption	45
9	network(s)	147	34	electric	45
10	smart	126	35	performance	44
11	control	125	36	algorithms	43
12	detection	100	37	conditioning	41
13	monitoring	89	38	ventilation	41
14	internet	86	39	occupancy	39
15	power	80	40	decision	38
16	wireless	77	41	thermal	38
17	facility/facilities	76	42	based	36
18	learning	76	43	comfort	36
19	environment(al)	73	44	conservation	36
20	things	70	45	real	36
21	model(s)	69	46	computer	35
22	efficiency	66	47	quality	35
23	maintenance	64	48	machine	31
24	fault	63	49	multi	31
25	analysis	58	50	software	31

Results of the keyword query are similar to those of the abstract query, since by terms used in the initial Scopus search were used in the keyword query. However, in this query, the word “energy” was the third highest. The words which were present in both queries will be shown in the following section, along with their associated ranks. To better visualize the relationships between terms, clustering analysis was performed and will be discussed when doing the keyword analysis in VOSviewer.

Similarities in Abstract and Keyword Frequency

Similarities are present between the abstract and keyword search. For example, building, system, energy, and sensor all appeared within the top 5 of both queries. In total, 30 words appeared in both queries, and Table 6 shows these topics. Associated ranks for all terms as they appeared in both queries are also displayed. Terms which appeared in the original search in Scopus are shaded in gray, as their high frequency is expected.

System is the second highest ranking word in both queries. Energy and indoor air quality are common topics once again and show up in both queries. Data and data management techniques, which included words like data, information, model, monitoring, and software, are common due to the necessity of BIM systems in the field of smart sensor applications. Additionally, the word wireless shows up in both queries, which is due to increased research into applications of wireless sensing systems.

A scatter plot was created to display the relationship between the co-occurring abstract terms and keywords present in the dataset. This plot is shown in Figure 5. By plotting the terms on each axis, there is an upward trend indicated as keyword and abstract count increase. However, there is not any noticeable trend for terms with a keyword occurrence below 100 or an abstract occurrence below 200.

Table 6. Words Found in Both Queries

Word	**Abstract Rank**	**Keyword Rank**
building(s)	1	1
system(s)	2	2
data	3	8
energy	4	3
sensor(s)	5	5
management	6	4
based	7	42
information	8	7
model(s)	10	21
facility/facilities	11	17
control	12	11
environment(al)	14	19
monitoring	15	13
time	16	30
performance	17	35
maintenance	18	23
technology/technologies	19	31
consumption	21	33
real	22	45
occupancy	25	39
detection	26	12
comfort	27	43
design	28	32
indoor	31	29
thermal	37	41
wireless	39	16
learning	40	18
power	45	15
software	47	50
fault	49	24

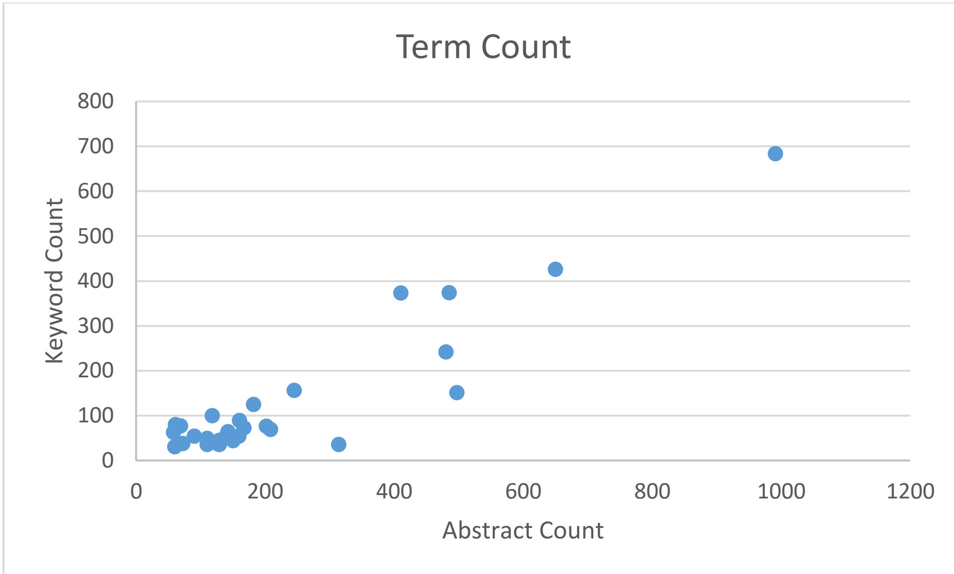

Figure 5. Keyword vs Abstract Count

Title and Abstract Networking

The title and abstract visualization was performed using VOSviewer. The terms were paired based on association strength. Figure 6 shows the associated network diagram created from the terms in the titles and abstracts. To better analyze the terms present in the network diagram, the term clusters are described in Table 7. The three separate colors present in the network diagram indicate that three main clusters were formed. Words which had the highest frequency, as indicated by text size on the network diagram, are highlighted in bold. Terms which were included in the initial Scopus search are in italics.

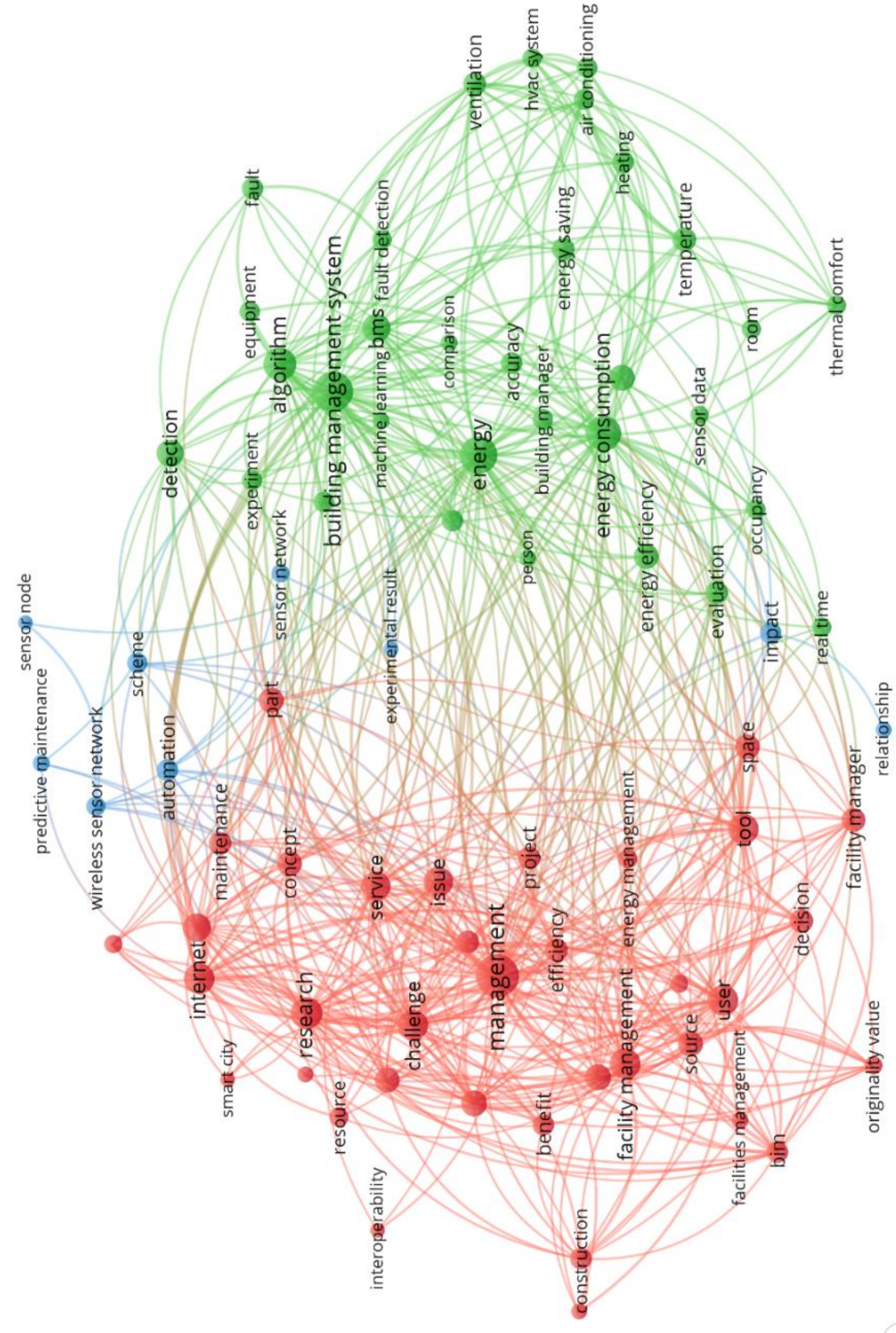

Figure 6. Title and Abstract Clusters

Table 7. Title and Abstract Clusters

#	Number of Terms	Term Cluster	Cluster Subject Category
1	36	advance, architecture, benefit, bim, challenge, concept, construction, decision, efficiency, energy management, *facilities management, facility, facility management, facility manager*, industry, intelligent building, interest, internet, interoperability, IOT, issue, maintenance, **management**, opportunity, originality value, part, project, research, resource, security, service, smart city, source, space, tool, user,	Management and Usage
2	32	accuracy, air conditioning, algorithm, bms, **building management system**, *building manager*, comparison, control system, demand, detection, energy, **energy consumption,** energy efficiency, energy saving, equipment, evaluation, experiment, fault, fault detection, heating, hvac, hvac system, machine learning, measurement, occupancy, person, real time, room, sensor data, temperature, thermal comfort, ventilation	Energy Efficiency/Indoor Air Quality
3	9	**automation**, experimental result, impact, *predictive maintenance*, relationship, scheme, sensor network, sensor node, wireless sensor network	Automation/Networking

The three clusters found in Figure 6 had to do with the following topics: management and usage, energy efficiency/indoor air quality, and automation/networking. From the initial abstract queries performed earlier, having these terms clustered provides a better grasp of each of the research areas prevalent in this particular data search. The following sub-sections present the interpretation and discussion of each category in detail.

- **Management and usage (red cluster):** This cluster contains applications of smart sensors, and the way in which their usage is managed. Management, which has the highest frequency, and other topics such as energy management, FM, and BIM also appeared in this cluster. Topics which are used in management practices were prevalent, such as benefit, challenge, decision, issue, and opportunity. The proper management of sensor networks will enable the best usage of this resource.
- **Energy efficiency/indoor air quality (green cluster):** Energy efficiency has been discussed previously when talking about the types of journals within the dataset. Energy consumption was one of the most frequent words in this cluster; related words included demand, energy, energy efficiency, and energy saving. Branching from the topic of energy efficiency is ensuring that HVAC systems are operating at their optimal levels, so words such as air conditioning, control system, heating, HVAC, HVAC system, occupancy, room, temperature, thermal comfort, and ventilation are all present as well. To manage energy and HVAC systems, a building management system has high frequency, and this also follows the fact that a computer aided system, or BIM, is necessary to handle sensor data.
- **Automation/networking (blue cluster):** The automation cluster shows the areas in which sensors are being used to help facility managers simplify their practices. This cluster is smaller than the other two and highly linked to them. Automation had the highest frequency, and by automating the way in which sensors perform, they achieve their maximum usefulness. Items that deal with the networking of sensors, such as sensor network, sensor node, and wireless sensor

network are present as well, and these terms are linked to the increased research in maximizing the efficiency of sensor networks, of which, experimental result and scheme are present in this cluster.

Keyword Networking

The keyword visualization was performed using VOSviewer. For this portion of the analysis, both author and index keywords were used. In a similar fashion to the title and abstract network diagram, like terms were clustered based on their association strength. The resulting network diagram is shown in Figure 7, with research clusters associated by like color. Statistics related to the average date of keyword usage were also found, and Figure 8 shows each node in the network diagram with the average year of publication according to the corresponding coloring scheme. To better show the terms which are present in the keyword analysis, Table 8 shows the five clusters with terms and associated cluster subject categories which were formed by performing the network analysis. Words with high occurrence are highlighted using bold text. Terms which were included in the Scopus search are in italics.

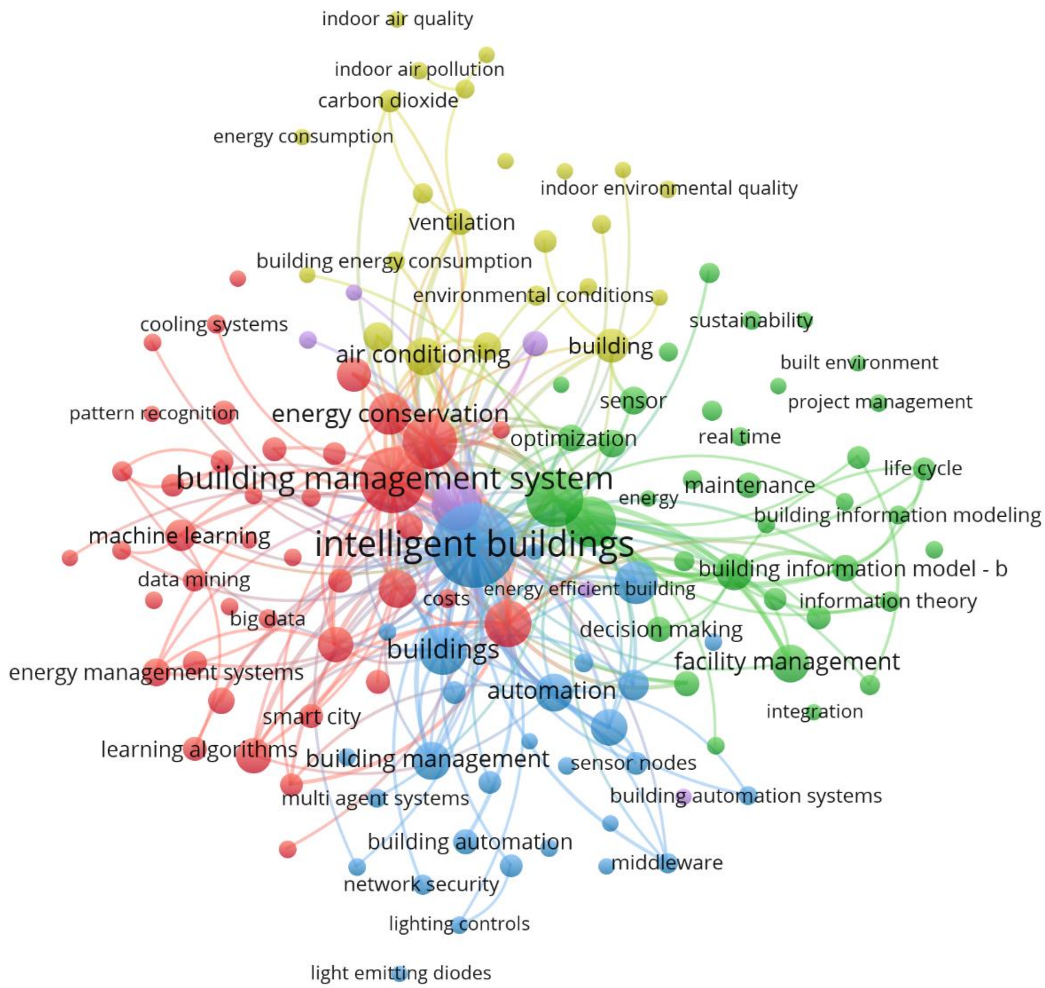

Figure 7. Keyword Network Diagram

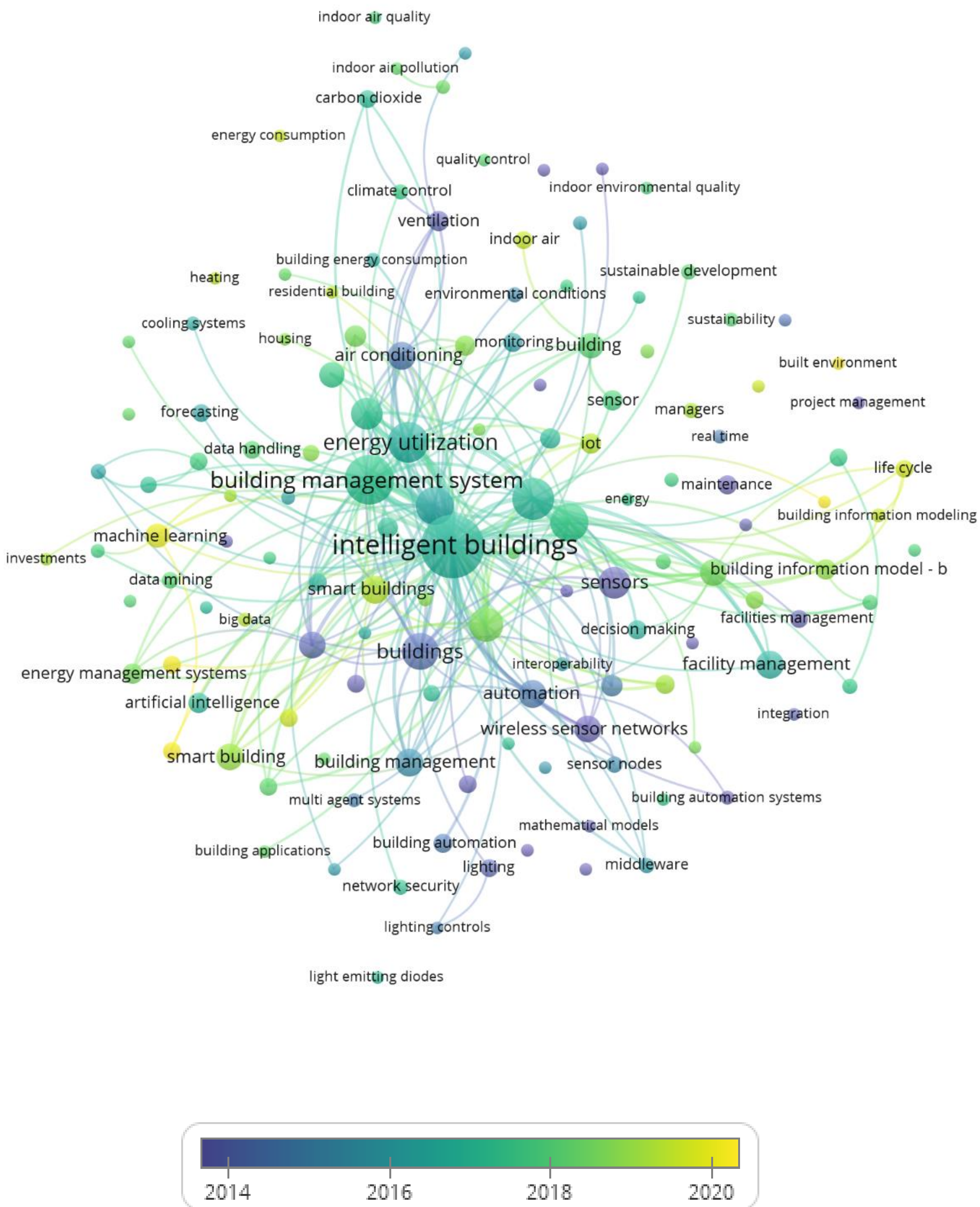

Figure 8. Keyord Network Diagram By Year

Table 8. Keyword Term Clusters

#	Number of Terms	Term Cluster	Cluster Subject Category
1	41	anomaly detection, artificial intelligence, big data, building applications, building energy management, **building management system**, building energy management systems, cooling systems, costs, data handling, data mining, decision trees, deep learning, digital storage, electric power transmission, embedded systems, energy conservation, energy management, energy management systems, energy utilization, fault detection, forecasting, genetic algorithms, heating, historic preservation, internet of thing (iot), **internet of things**, investments, learning algorithms, learning systems, machine learning, neural networks, pattern recognition, *predictive maintenance*, real time systems, reduce energy consumption, *smart building*, *smart buildings*, smart city, smart grid, smart power grids	Innovation
2	36	actuators, **architectural design**, bim, building information model, building information modeling, building information modelling, built environment, computer simulation, condition monitoring, construction industry, data integration, data visualization, decision making, digital twin, electronic data interchange, energy, environmental monitoring, facilities management, *facility management*, **information management**, information theory, integration, internet of things (iot), iot, life cycle, maintenance, managers, **office buildings**, optimization, project management, real time, sensor, sustainability, sustainable development, three dimensional computer graphics, visualization	Technology Focus Areas
3	29	algorithms, **automation**, building automation, building automation systems, building management, building management systems, ***buildings***, cost effectiveness, data acquisition, heating ventilation and air conditioning, in-buildings, intelligent agents, **intelligent buildings**, interoperability, light emitting diodes, lighting, lighting controls, mathematical models, middleware, multi agent systems, network protocols, network security, ontology, performance assessments, semantics, sensor networks, sensor nodes, *sensors*, wireless sensor networks	General Applications and Challenges
4	23	**air conditioning**, air quality, building, building control, building energy consumption, carbon dioxide, climate control, commercial building, commissioning, control system, demand-controlled ventilation, energy consumption, environmental conditions, hvac, indoor air, indoor air pollution, indoor air quality, indoor environmental quality, occupancy detections, quality control, thermal comfort, ventilation, wireless sensor	Indoor Air Quality
5	6	building performance, **energy efficiency**, energy efficient building, housing, monitoring, residential building	Energy Efficiency

Keyword clustering discovered five clusters: 1) sensor innovation, 2) technology focus areas, 3) applications of smart sensors, 4) indoor air quality, and 5) energy efficiency. Of note in three of the five clusters, the idea of a BIM system appeared, indicating the importance of the system in enabling all functions of smart sensing. The following sub-sections present the interpretation and discussion of each category in detail.

- **Innovation (red cluster):** This cluster deals with new and innovative items which are enabling further usage of smart sensor technology. Terms in this cluster generally have a higher average occurrence year than the average of 2016. Common terms present were the concepts of artificial intelligence (AI) (Avg. Pub. Date 2016), big data (Avg. Pub. Date 2019), data mining (Avg. Pub. Date 2018), deep learning (Avg. Pub. Date 2019), genetic algorithms (Avg. Pub. Date 2012), internet of things (IOT) (Avg. Pub. Date 2018), machine learning (Avg. Pub. Date 2019), and pattern recognition (Avg. Pub. Date 2018). Constant innovation is driving the field further and providing new usage areas for facility managers.
- **Technology Focus Areas (green cluster):** This cluster deals with new areas in which smart sensors are being applied and the technology which is being employed. Architectural design is one of the highest research areas, which shows optimization of component design to be the most efficient and cost effective. More computer and computation related terms appear in this section, such as BIM (Avg. Pub. Date 2018), computer simulation (Avg. Pub. Date 2008), data integration (Avg. Pub. Date 2018), data visualization (Avg. Pub. Date 2017), electronic data interchange (Avg. Pub. Date 2019), information management

(Avg. Pub. Date 2017), and three-dimensional computer graphics (Avg. Pub. Date 2017). The concept of digital twin (DT) (Avg. Pub. Date 2020) is defined as "a realistic digital representation of physical assets, processes and systems, which could mimic their real-world behavior" (Xie et al., 2020). Xie et al. (2020) state that DT has formed into an approach to manage, plan, predict, and demonstrate building assets by encapsulating all FM information. The ability to apply computer modelling will be useful to facility mangers as it will allow them to see all relevant information in a virtual world and optimize their FM practices. The occurrence of data visualization, integration, and three-dimensional graphics in this cluster also deals with the idea of a DT for FM practices.

- **General Applications and Challenges (blue cluster):** General applications deals with existing areas of application of sensor technology. Similar to the title and abstract clusters, the idea of automation appears in this cluster. Once again, the importance and existing usage of BIM systems is pivotal to making the sensor network operational and useful. Energy related terms also appear in this section, with HVAC (Avg. Pub. Date 2018), light emitting diodes (LED) (Avg. Pub. Date 2017), lighting (Avg. Pub. Date 2014), and lighting controls (Avg. Pub. Date 2015). Ideas relating to the networking challenges posed by smart sensors, like interoperability (Avg. Pub. Date 2016), data acquisition (Avg. Pub. Date 2017), middleware (Avg. Pub. Date 2015), network protocols (Avg. Pub. Date 2008), and network security appear as well
- **Indoor Air Quality (yellow cluster):** Appearing again is the application of smart sensors to improve indoor air quality maintenance practices. This area highlights

the notion that innovation is occurring in the area of HVAC and environmental controls. Terms such as demand-controlled ventilation (Avg. Pub. Date 2015), occupancy detection (Avg. Pub. Date 2015), and wireless sensor (Avg. Pub. Date 2017) were encountered in this cluster.

- **Energy Efficiency (purple cluster):** Topics in energy efficiency are fewer than those in the other clusters and are dependent on the other topics to make happen. The average occurrence of energy efficiency in this cluster occurs at the mean year of 2016, with the concept of an energy efficient building having an average occurrence earlier in 2011. Improving energy efficiency will aim to minimize costs to the overall organization, as previous literature has also highlighted.

Findings

Through word frequency and clustering techniques, this research found several themes which can be used to answer the proposed research questions. Table 9 shows the research clusters which were created, which will serve as the basis of the final key topics of this research. From the previously performed term frequency and publication data, applications and concerns in Air Force operations will be presented.

Table 9. Research Clusters

Clustering Data	Clusters
Title and Abstract	Management and Usage Challenges Energy Efficiency and Indoor Air Quality Automation and Networking
Author and Index Keywords	Innovation Technology Focus Areas General Application Areas Indoor Air Quality Energy Efficiency

These research clusters have similarities in their findings, with general ideas being discovered in the title and abstract clustering, and more focused areas of research found in the keyword clustering. This coincides with the fact that the title and abstract are simply overviews of what will be in an article, and the keywords are what the article will talk about in a more in-depth topical fashion. For example, both topics relating to energy efficiency were encountered together in the title and abstract clusters, and once the keyword clustering was performed, both topics were separated. Indoor air quality can be tied to the management of HVAC systems, which are generally made efficient through sensors due to their high energy usage.

Of note, through performing both the word frequency and clustering analysis in this chapter, was the prevalence of the Scopus search terms. These terms were noticed in both sets of analysis. Terms were removed when completing the word frequency analysis, as their high frequency was expected. During the clustering portion of this analysis, they remained as they were helpful in indicating which themes were present in each cluster. These terms did not dominate, and only the term buildings was a high frequency term during cluster analysis. Facility management and its seed terms were encountered frequently; however, other terms present in this cluster provided focus areas for the overall management of sensor networks. The removal of these terms during the clustering portion was considered but was not performed as they provide links between the ideas encountered in the research.

Combining and consolidating both network diagrams and associated clusters based on topic similarity, the following have been shown to be the key takeaways present in this dataset: 1) management, 2) automation and networking, 3) innovation and new technologies, 4) applications, and 5) energy efficiency. These topics will be discussed in greater depth and the applications and associated concerns that will be present in the Air Force context will be posed.

Management

Owing to the name itself, facility management requires proper management techniques to be performed at a high level. Although facility management was a word used in the database search and its prevalence in the querying and clustering processes is to be expected, it should be stated that there is a human factor in the facility management field that needs to be considered. The management of installed smart sensor networks include those who will perform the work, the software required to manage data, and the proper personnel who have the capability to perform management activities.

Frequently encountered was the importance of employing BIM systems in managing sensor networks. As has been stated, without a method to sort, collect, and manage the data being created by the vast array of sensors that are being employed, no usefulness is provided to a facility manager to perform their duties. Being able to model the information and visualize trends which are occurring in asset condition and performance gives facility managers the ability to gain awareness of the way their facilities are performing and where a fix may be necessary. The concept of the digital twin, with its ability to model buildings virtually was encountered, but with an average publication date of 2020, this concept is still new and will need more time to develop in the field before it will be viable in practice; it will need an even longer time before adoption by the Air Force. New technologies were also encountered, which will be discussed further in the innovation section.

While smart sensor networks will reduce the amount of labor required to perform inspections and diagnose system faults, the likelihood that sensors will eliminate in-person asset inspection will be low. The sensor inspection will act as a first notification of asset failure, and an additional person will be needed to verify system fault and the magnitude of the repair required. Over time, as technology improves and decision-makers feel more confident in the data they are getting from their sensor networks, they will be able to make more confident decisions without the need for in-person inspections.

With limited manpower resources available, and additional training being necessary to perform the management and maintenance required to operate a sensor network, the Air Force will need a solution as to who will perform this task. High deployment rates and military members constantly moving will limit the knowledge they will have of a particular base's sensor network and the intricacies in which it operates. A solution for a long-term entity to maintain the system, whether by contract or by government civilian employees, will need to be made to have an enduring knowledge of the system. This entity will also need to have the ability to run BIM systems for which military personnel are not currently trained.

The overall cost of installing and maintaining the system will be a major driving factor in whether sensors will be feasible in practice. The terms “costs” and “cost effectiveness” appeared in the keywords 7 and 9 times, respectively, and was the 35th ranked term in the abstracts, appearing 75 times.

Automation and Networking

Automation of processes is a goal for implementing smart sensors. The second highest percentage of articles in the dataset were from the journal *Automation in Construction*. The term “automation” had 24 keyword occurrences and was linked to “building automation systems.” Smart sensors, and their usage in the act of remote monitoring, will serve as a force multiplier and save manpower resources, which directly has a cost associated with it. The word “monitoring” appeared in the top 50 of both the abstracts and keywords, at 15 and 13, respectively. By remotely monitoring and diagnosing a problem, the need to physically inspect an asset is reduced but not eliminated. Additionally, being able to automate existing processes can serve as a potential area in which sensors can serve as a force multiplier.

The concerns and solutions associated with networking were encountered during the literature review portion, and this topic appeared in the analysis portion of this research. When new networks are created, either wireless or wired, an associated network protocol to transmit data is necessary. Network security will thus be of concern, as large amounts of data about potentially sensitive systems will be transmitted, and the Air Force will likely not want adversaries to have access to this data.

Interoperability, and its associated concerns as discussed in literature review, has implications in Air Force operations. Due to the geographic differences that the Air

Force experiences with their bases, assets likely come from different manufacturers, for example, HVAC chillers. The sensors to monitor one type of chiller could be incompatible with those on another, so a standardized sensor system across the Air Force's inventory of bases could prove to be a challenge. It has previously been stated that sensors are likely to be made by different manufacturers and applying this concept not only on one base but across the entire Air Force inventory can also pose a challenge.

To combat these issues, the DoD has implemented guidance for Facility Related Control Systems (FRCS). Knowing that control systems pose a threat to national security, the DoD has increased initiatives to cyber-secure mission-critical FRCSs. The United Facilities Criteria (UFC) 4-010-06, entitled *Cybersecurity of Facility-Related Control Systems*, was published in 2016 and was updated in 2017. This document serves as a guide to the way personnel throughout the DoD can have accountability of the security of FRCSs; however, it will need updating as new technologies are incorporated.

Innovation and New Technologies

As new computing technologies and techniques are being discovered and introduced, innovation in the FM field using disruptive technologies has been seen. Clustering showed that new data capturing and application techniques are making their way into the facility management field via smart sensors. Topics such as artificial intelligence, digital twin, genetic algorithms, and machine learning are popular buzzwords when talking about new technologies; it is no surprise then that these topics were present in this research. The topic of wireless sensor networks appeared during the analysis portion and was heavily discussed in the literature review. It was present in the top 50 words in abstracts and keywords, at 39 and 16, respectively, and was present in both network diagrams.

Applications

The application of smart sensors in FM operations was a motivation behind doing this research. Through all phases of a building's lifespan, sensors will be used to aid those managing these phases. To illustrate this, each construction phase and the sensor usage associated with it will need be outlined.

The word "design" appeared at 28 and 32 of the abstract and keyword rankings, respectively, and "architectural design" had 24 keyword occurrences. Sensor networks will need to be incorporated into the design of facilities. In addition to this, BIM technology can be used to design facilities, and then once constructed, the performance of the facility can be monitored.

Sensors involved in the construction phase did not appear in either of the queries or during the clustering process, which is likely due to the search which was performed. However, the application of sensors as smart construction objects (SCOs) was discussed in the literature review portion, and their incorporation from being used during the construction to maintenance phases of a building was briefly mentioned (Niu et al., 2016).

The operations and maintenance phase of a building is where sensors will be utilized the most. This will be the phase in which the building will be occupied and monitored. When a sensor detects that an asset has degraded, a maintenance action can be identified and predictive maintenance will be performed. Sensors will also perform quality control. When an asset has had a maintenance action performed to it, the sensor will know if this fix was correct and if the asset is performing at the baseline level; if not, a new fix will likely be needed.

Energy Efficiency

This research did not seek out but encountered sustainability practices. A particular subsection of sustainability, energy efficiency, was frequently encountered. Several ideas appeared regarding ways which sensors can save energy. Throughout this research, there was a continuing presence of energy-related topics and applications. Previous scientometric analyses into smart sensor applications have identified this topic as an outcome of increased technology incorporation and the outcomes of this research were similar in this way.

The general increase in the amount of research devoted to anthropomorphic climate change across all fields of study was experienced in this research, as the impacts smart sensors have on energy was a popular research topic. This trend can be seen as most of the articles which make up this dataset are from the year 2007 onward. Energy efficiency was a topic which was encountered in both sets of the querying and clustering portion of this research. The average occurrence of energy efficiency occurred at the mean year of 2016, with the concept of energy efficient buildings having an average occurrence earlier in 2011. Energy showed up in both the abstract and keyword queries, with a rank of 4 and 3, respectively.

Energy usage is a main topic of concern within the Department of Defense (DoD). The DoD uses more energy than any other federal agency, with 77% of the federal government's energy going toward the DoD; it also represents 2% of the department's annual budget (Greenley, 2019). Air Force energy usage accounted for 48% of the DoD total, with 11% of the total energy usage in the Air Force being used in facilities in the year 2017 (*Air Force Energy Flight Plan*, 2017). Total annual energy expenditures were $6 billion on energy, with 16% of this total being used in facilities as estimated in 2019 (Poland, 2019). The Air Force is utilizing energy savings performance contracts (ESPCs) to install energy savings improvements, and the usage of smart sensors could certainly be used in this field.

The suggested ideas to save energy in which smart sensors could be incorporated were lighting controls and occupancy sensors, both coupled with the use of energy efficient lighting such as light emitting diodes (LEDs). The DoD has published guidance for the management of lighting controls in UFC 3-530-01, *Design: Interior and Exterior Lighting and Controls.* This guidance states that occupancy sensors can save between 20-40% of energy if applied correctly, and it lists design considerations for the implementation of many different types of lighting, to include interior and exterior lighting (*Design: Interior and Exterior Lighting and Controls*, 2012).

The heating, ventilation, and air conditioning (HVAC) field and related topics were also encountered throughout both the literature review section and the analysis portion. HVAC has a significant cost portion tied to it as it consumes half of the energy in buildings and accounts for 20% of national consumption (Cheng & Lee, 2014). HVAC has importance in the way people perceive the way their facility is being maintained. Making sure indoor air temperature and quality is high is highly indicative of the perspective people have on the way their facilities are being taken care of. The DoD in general has a bad image regarding the way they are managing HVAC systems, mainly when dealing with family housing, and this issue has been a subject of numerous

Congressional inquiries (Ismay, 2019). A sensor application in cases like this can act as a quality control requirement for contractors, as the performance of systems in these facilities can be tracked and monitored, and a contractor can be held liable if they are not performing to the terms of their contract.

Conclusion

This section reviewed the results that were discovered using the research methodology introduced in Chapter III. Statistics relating to the dates of publication and types of publications that are present in the field of smart sensors in facility management were created and analyzed. Word frequencies, word networks, and clustering were performed in the aim of creating research themes in this field. Finally, a breakdown of research themes and Air Force applications were discussed with potential benefits and concerns.

V. Conclusion

The purpose of this chapter will be to highlight the results and applications of the findings from Chapter IV. These will then be used to answer the research questions which were posed in Chapter I. Potential application areas for the use of smart sensor technology in the Air Force will be discussed based on the answers to these research questions, and further areas of research will be presented.

Investigative Question 1

A total of 279 articles were chosen based on a Scopus search investigating facility management, smart sensors, and related maintenance terms. Research into this field remained stagnant prior to 2007, with 0-3 journal articles being published annually prior to this point. The average date of the selected publications is 2016. After 2007, a steady increase in publication frequency occurred, with the greatest number of journal articles being published most recently in 2021, at 49 total articles. This increase can only be expected to grow, as 3 articles were slated to be published in 2022 at the time of the data pull in late 2021.

An analysis of the publication titles that are publishing smart sensor related journals includes topics of buildings, engineering, and computer applications; additionally, sustainability and energy publications provide a fair amount of the literature used in this research. This can be attributed to sustainability efforts observed through all facets of the research. The application of sensors can optimize the ways in which energy is used and conserved, with considerable energy savings being seen once sensor technology is applied in practices.

Investigative Question 2

The analysis portion used word frequency querying, networking, and clustering techniques to study the frequency and relationships that were present in the titles, abstracts, and keywords of the selected articles. Through this analysis, five main themes arose: 1) management, 2) automation and networking, 3) innovation and new technologies, 4) applications, and 5) energy efficiency. These themes show an evolution of the field itself, from existing applications, to ways in which they are implemented and managed, to the innovations that are occurring. As new technologies are incorporated, interoperability between systems becomes critical. If systems are not able to communicate and provide data, they become a potential waste of fiscal resources.

Investigative Question 3

Smart sensors have benefits that will impact the way facilities are managed in the years to come. All phases of a building's life-cycle will be impacted by smart sensor incorporation. Design and construction will need to account for sensor networks and can leverage the technology to make this process more efficient. The operations and maintenance phase of a facility will benefit through the ability to remotely monitor assets within a facility and by performing fault correction without having to exert manual labor. Energy usage in the DoD is high, and the Air Force uses almost half of that energy. Facilities account for anywhere between 11-18% of the total Air Force's energy demands. Life-cycle costs can be decreased by incorporation of smart energy savings methods and smart heating, ventilation, and air conditioning practices.

New technologies are changing the way which sensor data is being managed and utilized. Disruptive technologies to include artificial intelligence, machine learning, building information modelling, and digital twins are making their way into facility management operations. Continued research will likely show benefits that incorporation of these technologies will have on facility management operations, and the Air Force should take note of these disruptive technologies.

The Air Force should use the information presented in this thesis to shape its smart sensor deployment in the following ways. Simple incorporation, to include energy and HVAC operations should be performed initially, to optimize these systems and aim to reduce energy consumption in the Air Force. The existing initiatives which are being conducted should remain in place, with a long-term focus being kept in mind. Next, the incorporation of newer technology should be researched and their validity into the infrastructure which is present should be analyzed. Finally, determining who should perform and maintain sensor networks should be determined on a cost-benefit basis, along with other criteria as is necessary.

Investigative Question 4

The types of operational efficiencies that smart sensors can provide are numerous. Employment of sensors coupled with BIM technology will allow for better modelling and maintenance of asset condition. This record will enable a facility manager to know the status of facility assets, to include age, location, maintenance logs, fault logs, and performance. Knowing the asset performance and intervening at the proper time to perform corrective action will save money and labor, knowing that the action was performed at the proper time. Computer simulations can enable the modelling of a facility and the way that a particular system could perform when a potential change is made to one of its components.

Direct monetary savings from sensors currently in place on Air Force installations result from energy savings measures. These include smart lighting controls and smart HVAC controls. Monitoring and having the proper indoor air quality and temperature in facilities not only saves money, but it also prevents complaints from building occupants, which cause the image problems the DoD currently faces.

The idea of process automation was encountered in this research. Sensors can automate mundane tasks which are often considered a labor drain. Further applications of this idea as applied to Air Force facility management will be discussed as an area of future research.

Research Significance

Several studies have been performed regarding smart sensors, BIM systems, and the future of facility management, but none of them were focused on the application of smart sensors and their effects on the FM process. This research took a more pointed approach into what is being done from a facility manager's perspective with the implementation of smart sensor technology, and how it is being used to make their jobs easier. An application to Air Force practices has not been accounted for prior to this study. This research showed that many of the same topics that have been reported in other studies will be encountered when applying smart sensors to facility management practices. Moving forward, Air Force leadership can use the findings of this research to investigate the usage and implementation of innovations that are occurring in the smart sensor field.

Recommendations for Future Research

Future research into the applications of smart sensors can branch out further than the areas addressed in this study. Analysis of this field of application has led to other areas which will need to be further investigated to enhance the way in which the Air Force will incorporate new technology to manage and maintain base infrastructure assets.

A sub-focus that was encountered during this research was the role of BIM technology in the field of smart sensors. The further usage and incorporation of BIM into Air Force operations should be studied. The Air Force's usage of software to manage its installed infrastructure is limited and has fallen behind the new information management systems that have been introduced. Through this research, Revit was observed as an off-the-shelf solution with widespread use in the commercial sector. Other software was observed for more specialized use, like energy monitoring; implementing these software packages could offer additional benefits. Of note when discussing BIM is that sensors may not work together. Ensuring interoperability between sensor types that are being installed will be a concern for designers in the field, and research can be done into which ones will work best on Air Force installations.

A further deep dive into process automation in the Air Force is necessary. The Air Force maintains Preventive Maintenance Task Lists (PMTLs) which outline the preventive maintenance that craftspersons are tasked to perform at each base. Within these task lists are items which can be automated using smart sensors, such as inspections and taking measurements. The automation of these work items and identification of areas which can be done by sensors can reduce the amount of work that is physically needed to be performed. Additional challenges will arise with further incorporation of smart sensors in preventative maintenance activities currently performed across the Air Force. A determination of who will perform sensor-related work is necessary, whether that be military, civilian, or contractor. Depending on who is chosen to complete the work, adequate training will need to be completed to have familiarity with sensor networks and their operation. With a vast number of installations, military members will have trouble getting acquainted with sensor systems across multiple bases, as there may be differences in each system and they move from base to base throughout their careers.

Applications of smart sensor technology in buildings and overall installation security is another area that could be of interest. Sensitive activities happen on Air Force installations, and smart sensors could influence the way that facilities are secured. To also aid in facility security, fire systems should be considered.

Summary

The purpose of this research was to identify the current state of smart sensor research in facility management operations in the Air Force. This was done under the guise of 2019's Infrastructure Investment Strategy, which is aiming to improve the way that the Air Force maintains its bases worldwide. Through a literature review and a scientometric analysis, the topics in this field were discussed both qualitatively and quantitatively. Themes in the research and new research directions were identified and will provide the Air Force new ways to apply sensor technology. The application of smart sensors will be used throughout all phases of a facility's life-cycle, from initial design all the way to determining the end of its useful life.

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Appendix A

Scopus Search

TITLE-ABS-KEY (("smart sensor*" OR "sensor*" OR "smart sens*" OR "smart building*" OR "smart facilit*") AND ("facility manag*" OR "predictive maintenance" OR "preventative maintenance" OR "correct* maintenance" OR "building manag*")) AND ("facilit*" OR "building*") AND (LIMIT-TO (SRCTYPE , "j")) AND (EXCLUDE (SUBJAREA , "bioc") OR EXCLUDE (SUBJAREA , "medi") OR EXCLUDE (SUBJAREA , "eart") OR EXCLUDE (SUBJAREA , "arts") OR EXCLUDE (SUBJAREA , "heal") OR EXCLUDE (SUBJAREA , "immu") OR EXCLUDE (SUBJAREA , "neur") OR EXCLUDE (SUBJAREA , "nurs") OR EXCLUDE (SUBJAREA , "phys") OR EXCLUDE (SUBJAREA , "agri") OR EXCLUDE (SUBJAREA , "vete") OR EXCLUDE (SUBJAREA , "chem") OR EXCLUDE (SUBJAREA , "phar") OR EXCLUDE (SUBJAREA , "ceng") OR EXCLUDE (SUBJAREA , "psyc")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "english")) AND (EXCLUDE (EXACTKEYWORD , "industry 4.0"))

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14. ABSTRACT
To investigate the areas which smart sensors can be implemented to assist facility managers to optimize limited resources, this research consists of a scientometric analysis to identify the areas of research quantitatively and qualitatively. Existing literature related to smart sensors in facility management operations were compiled and trends were analyzed to determine the ways in which researchers have been applying this technology. The title, abstracts, and keyword were used to perform frequency, networking, and clustering analysis. This research effort serves to provide ways in which Air Force installations can implement smart sensors in a way which fulfills the initiatives posed in the Infrastructure Investment Strategy.

15. SUBJECT TERMS
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