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The WIJE Editorial Office
Faculty of Engineering, The University of the West Indies, St Augustine
The Republic of Trinidad and Tobago, West Indies
Tel: (868) 662-2002, ext. 83459; Fax: (868) 662-4414;
E-mail: uwije@sta.uwi.edu
Website: http://sta.uwi.edu/eng/wije/

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Editor-in-Chief:
Professor Kit Fai Pun

Editorial

I. Notes from the Editor

The ongoing impact of COVID-19 pandemic has brought many challenges to many people and activities including the West Indian Journal of Engineering (WIJE) in the past year. The pilot testing of the WIJE-web project had been postponed. However, the Editorial Sub-committee has continued to plan and review the work for the Journal despite the unexpected constraints.

Since the last volume, the Journal had received a total of 29 research and technical papers seeking for possible publication. Articles were of a theoretical nature, were based on practical experience orto report a case study situation or experimental results. After the peer review process, a total of 5 papers were accepted for publications, yielding a successful acceptance rate of 17.2%, and another 17 manuscripts are under review, with an in-progress rate of 58.6%. The remaining 7 manuscripts were rejected. Besides, the Journal would assign DOIs to all the papers accepted and published, starting from this current issue.

II. About this Issue

In this Volume 44 Number 1, the Journal includes five (5) research/ technical articles. The relevance and usefulness of respective articles are summarised below.

E. Jaggernauth and **S. Rocke**, "Effectiveness of Paired Next Generation Firewalls in Securing Industrial Automation and Control Systems: A Case Study", investigated the challenges posed to management teams, across different industries and business domains in Trinidad and Tobago (T&T) and other countries in the Caribbean. The business of cybersecurity has been evolving dramatically. This paper focused on the effectiveness of next generation firewalls (NGFWs) in their defense against malware within Process Control Networks (PCNs). It was supported by real data from a process plant complex within T&T, as a case study.

The Government of Barbados has endorsed the approach of 100% renewable energy (RE) implementation by 2030. In their article, "Barbados towards 100% Renewable Energy: Case Scenarios for 2030 National Energy Target Plans", **S. Marshall** and **R. Koon Koon,** explored three distinctive annual growth rate (AGR) scenarios to assess the impact on the expected power generation, economic and environmental parameters through the period of 2019-2030. Notable findings at a high case scenario for 2030 (at an AGR of 3%) project a power generation of 1.343 Tera-watts-hour (TWh), which will displace 790,500 barrels of oil equivalent (boe), resulting in an abatement of approximately 0.95 million tons of carbon dioxide into the atmosphere.

Trinidad and Tobago (T&T) has been witnessing a growing interest and application of commercial and non-commercial operations of Unmanned Aerial Systems (UAS). **R. Al-Tahir** and **G.K. Lalla,** "Assessment of the Emerging Landscape of Unmanned Aerial Systems in Trinidad and Tobago", identified the emerging UAS landscape in T&T during the period 2015 to 2019. As such, this study maps and characterises the spatial and temporal patterns of UAS distribution, then appraises the various categories for the existing operations. To achieve these goals, this study utilised qualitative and quantitative techniques of Geoinformatics. The intent for this study is to provide a perspective on the growth and the implications of the UAS industry in T&T, and to guide strategic planning among organisations with a stake in the emergence of UAS into civil airspace.

N. Ramsamooj, "Spatio-temporal Kriging of Lower Caribbean Wind Data", considered imputation by spatio-temporal kriging using data from neighbouring locations. Temporal basis functions with spatial covariates are used to model diurnal wind speed cyclicity. The residual set of our spatio-temporal model is modelled as a Gaussian spatial random field. Fitted models may be used for spatial prediction, as well as imputation. Examples of predictions are illustrated using two months of hourly data from eight Caribbean locations with prediction accuracy being assessed by cross validation and residuals.

In the fifth article, "Advancing the Ultra High Frequency RFID in Industrial Applications: A Review", **T. Aleong** and **K.F. Pun** provided a review on the principle of Radio Frequency Identification (RFID) system operation using an extensive search of relevant articles from technology management and related journals over the past two decades. The review explored 1) the RFID tags operating in the ultra-high frequency (UHF) band, 2) analysed some of the major advancements of this technology in the field of sensor tagging solutions in the past two decades, and 3) discussed industry-based applications utilising UHF RFID sensor tagging solutions for process measurement data acquisition. Among the main challenges have been privacy and security concerns on their applications in industry. The paper then amalgamated a list of UHF RFID industry-based applications and shed light on critical areas of the UHF RFID Technology.

On behalf of the Editorial Office, we gratefully acknowledge all authors who have made this special issue possible with their research work. We greatly appreciate the voluntary contributions and unfailing support that our reviewers give to the Journal.

Our reviewer panel is composed of academia, scientists, and practising engineers and professionals from industry and other organisations as listed below:

The views expressed in articles are those of the authors to whom they are credited. This does not necessarily reflect the opinions or policy of the Journal.

KIT FAI PUN, *Editor-in-Chief*

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The University of the West Indies,
St Augustine, Trinidad and Tobago, West Indies

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Effectiveness of Paired Next Generation Firewalls in Securing Industrial Automation and Control Systems: A Case Study

Eddison Jaggernauth [a,Ψ]; and Sean Rocke [b]

Department of Electrical and Computer Engineering, The University of the West Indies, St. Augustine, Trinidad and Tobago, West Indies;

[a]Email: eddison.jaggernauth@icloud.com
[b] Email: sean.rocke@sta.uwi.edu

[Ψ] *Corresponding Author*

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Abstract: *Industrial automation and control systems (IACS) are oftentimes the backbone of businesses and critical infrastructure (CI) around the world. They underpin control of nuclear plants, refineries, manufacturing and distribution systems. Today, organisations are routinely targeted by cyber-attackers. Cyberattacks have been increasing in frequency and sophistication. This is especially true of those attacks directed against high-profile operations such as petrochemical refineries. Attackers invest considerable time and money to study a target and probe inherent weaknesses, which they eventually attempt, and succeed in some cases, to exploit. Historically, industrial networks were kept separate from corporate networks. However, significant efficiency gains and demands for digital interconnectivity have driven a convergence between operational technology (OT) and information technology (IT) systems. The business of cybersecurity has been evolving dramatically, posing significant challenges to management teams, across all industries and business domains. Countries within the Caribbean, such as Trinidad and Tobago (T&T), are by no means an exception given their dependence on the energy sector and supporting IACSs. This paper examines the effectiveness of next generation firewalls (NGFWs) in their defense of Process Control Networks (PCNs) against malware. It focuses on the case of a process plant complex in T&T.*

Keywords: *Industrial Automation and Control Systems (IACSs), Information Technology (IT), Operational Technology (OT), Next Generation Firewalls (NGFWs), Process Control Networks (PCNs)*

1. Introduction

The demand for information and communications technology (ICT) services is ever increasing as people and businesses desire to be more connected. This is evidenced by the emergence of the fifth generation (5G) networks and prospects of the Fourth Industrial Revolution (Industry 4.0). While Industry 4.0 has been of increased prominence in recent times, it is important to note that legacy Industrial Automation and Control Systems (IACSs) were engineered using cyber-technologies and tools from as early as the 1970s. The IACSs include: Distributed Control Systems (DCSs), Programmable Logic Controllers (PLCs), Supervisory Control and Data Acquisition (SCADA) and Process Control Networks (PCNs). This is in part due to the recognised benefits that cyber-technologies could provide for operations and management of PCNs and SCADA systems.

While the Internet of Things (IoTs) and Industrial Internet of Things (IIoT) improve the efficiency of remote monitoring and control of Process Control Networks (PCNs) and corporate networks, these technologies introduce security risk. Amongst these is the inherent vulnerability to cyber-attacks (Piggin, 2018).

Oversight agencies have compiled regulations and security standards to secure critical infrastructure (CI).. US-CERT (2006), under the remit of the Department of Homeland Security (DHS), established a Control Systems Security Programme (CSSP) of the National Cyber Security Division (NCSD). Its mandate includes the identification, analysis and reduction of cyber-risks associated with control systems. Table 1 enumerates other noteworthy IACS standards.

This paper provides a high-level insight into a case study undertaken within the energy sector of Trinidad and Tobago (T&T). The research findings are based on a real PCN production system rather than simulation-based data. A succinct overview of Next Generation Firewalls (NGFWs) and their role in cybersecurity are also included. A mix of industry experience, referenced scholarly content, and consultation of peers and solution providers, have provided support information, for the case study.

Every attempt has been made to anonymise organisation and vendor-sensitive information accessed, as part of the research initiative. The main study objectives were to:

Table 1. IACS Security Standards Based on Public Citations

Document (s)	**Publisher**
Good Practice Guide. Process Control and SCADA Security.	Centre for the Protection of National Infrastructure (CPNI).
Cyber Security Procurement Language for Control Systems.	Department of Homeland Security (DHS).
21 Steps to Improve Cyber Security of SCADA Networks.	U.S Department of Energy (DOE).
CIP-002-1-CIP-009-1.	North American Electric Reliability Corporation (NERC).
Guide to Industrial Control Systems (IACS) Security.	National Institute of Standards and Technology (NIST).
System Protection Profile – Industrial Control Systems.	National Institute of Standards and Technology (NIST).
ANSI/ISA-99/ ISA62433	The International Society of Automation (ISA).
Cyber Security for Critical Infrastructure Protection.	U.S Government Accountability Office (U.S GAO).

Source: Adapted from Sommestad et al. (2010)

1) Monitor a production PCN and an interconnected corporate LAN, for a one (1) month period, to capture statistics relating to the number of failed and successful penetrations of the PCN.
2) Test the hypothesis that having paired NGFWs minimise the risk of PCN threat penetration, from connected networks, by at least 50 %, and
3) Perform a cybersecurity audit and present recommendations for improvement, consistent with NIST SP 800-82 and ISA62443 standards.

The succeeding sections include an overview of cybercrime. This is followed by a summary of PCNs - their architecture, and some documented attacks against them. Highlights of Commercial Off The Shelf (COTS) products which support IACS cybersecurity is next. This is followed by an introduction to NGFWs. The paper then describes the research framework and presents the high-level results obtained. The paper ends with prospective steps.

2. Cybercrime on the Rise

A joint study between Accenture and Ponemon Institute suggested that out of approximately 1,000 cyberattacks, malware was the most prevalentoverall and, in many countries, the most expensive to resolve (Accenture, 2019). People-based attacks demonstrated some of the largest increases over that year. Ransomware attacks increased by 15 percent over one year and had more than tripled in frequency over two years. Phishing and social engineering attacks were experienced by 85 percent of organisations - an increase of 16 percent over one year. Those were disconcerting as people continued to be a weak link in cybersecurity defense. Figure 1 provides a comparison of average annual cost of cybercrime based on the study.

ICS-CERT (2016) conducted assessments in 12 of the 16 CI sectors in 2016. Those included the Chemical (7 assessments), Commercial Facilities (4), Communications (5), Critical Manufacturing (5), Dams (2), Emergency Services (3), Energy (22), Food and Agriculture (3), Government Facilities (10), Information Technology (3), Transportation Systems (10), and Water and Wastewater Systems (56).

The Water and Wastewater Systems and Energy Sectors, represented 60 percent of the overage assessments. Those industries were both heavily dependent on IACS to manage operational processes. Table 2 highlights the most prevalent weaknesses.

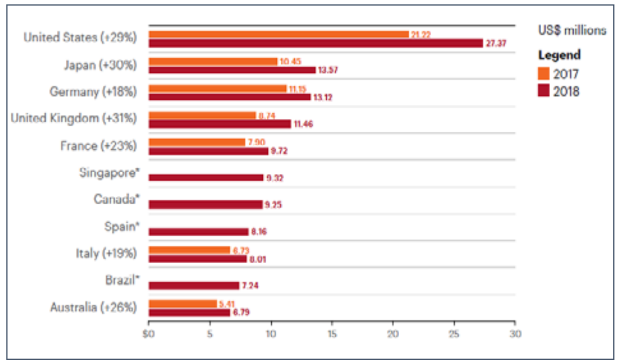

Figure 1. Average Annual Cost of Cybercrime by Country
Source: Abstracted from Accenture and Ponemon (2019)

3. PCN Architectures

A plant network may be considered as having four (4) layers or levels. Honeywell (2016) based on its Purdue model defines these levels as per Table 3 and Figure 2. ISA 62443 and NIST SP 800-82 also define similar levels.

Level 1 nodes are the heart of the control system. This network segment contains controllers, connections for servers and operator stations, supervisory control, connection to Level 1 and protection for Level 1, with access lists.

Level 2 nodes are the primary server, view and advanced control nodes for the process control system. Examples of Level 2 nodes include servers, stations, Advanced Control Environment (ACE) nodes, and Process History Database (PHD) collector nodes. These nodes are essential for operation of the process, but not as critical to control as the Level 1 nodes.

Level 3 nodes provide connections for Historians and Advanced Control. It also provides routing and access list controls.

Level 3.5 typical nodes are: Windows Server Update Services (WSUS), Anti-Virus Server, and Terminal Server. This level provides connectivity for devices to be accessed from the Corporate LAN and PCN. It forms a security zone between the PCN and outside networks.

Table 2. Risk Associated with FY 2016 Most Prevalent Weaknesses

Weakness Area (by Rank)	**Risk**
Boundary Protection	Undetected unauthorised activity in critical systems and weaker boundaries between IACS and enterprise networks.
Least Functionality	Increased vectors for malicious party access to critical systems and Rogue internal access established.
Identification and Authentication	Lack of accountability and traceability for compromised account and increased difficulty in securing accounts as personnel leave the organisation.
Physical Access Control	Unauthorised physical access to field equipment and locations provides increased opportunity to: Maliciously modify, delete, or copy device programmes and firmware, access the IACS network, steal or vandalise cyber assets and add rogue devices to capture and retransmit network traffic.
Audit Review, Analysis and Reporting	Without formalised review and validation of logs, unauthorised users, applications, or other unauthorised events may operate in the ICS network undetected detection.
Authenticator Management	Compromised unsecured password communications and password compromise could allow trusted unauthorised access to systems.

Source: Adapted from ICS-Cert (2016)

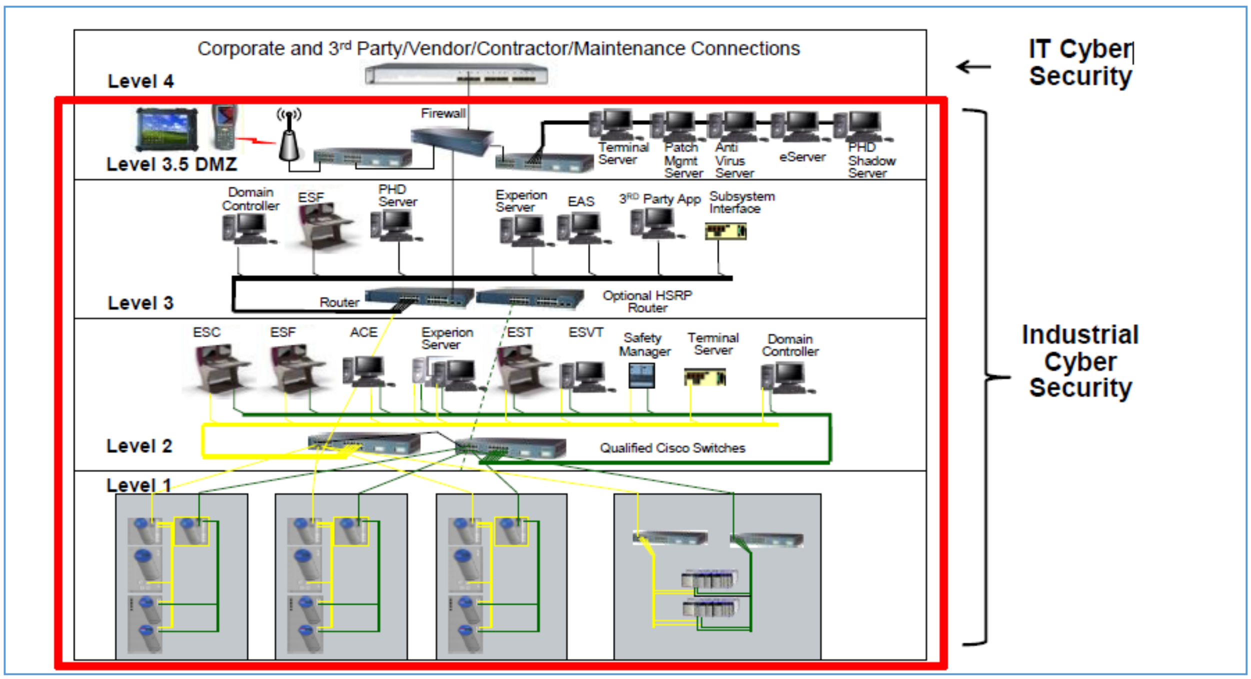

Figure 2. Depiction of Typical PCN 4 Level Architecture
Source: Based on Honeywell (2016)

Table 3. Plant Network Levels

Level	**Node Descriptions**
4	Plant Level Applications; clients for Historians and Advanced Control Applications.
3	Alarm servers and Advanced Applications (Non-Critical Control Applications).
3.5	Demilitarised Zones (DMZ) accessed from the Business LAN and the PCN.
2	DCS Stations, Supervisory Control, Operator Human Machine Interface (HMI) and Supervisory Controllers.
1	Real Time Control (controllers and Input - Output (IO)).

Source: Based on Honeywell (2016)

Level 4 is not part of the control network. It is usually managed by the Business IT department, separated by firewall and utilises open system LAN technology.

4. PCN Threats

Researchers continue to propose security enhancements for IACSs. However, there is scope for new research and subsequent solutions for securing control systems. These typically have their own specificity, when compared with securing traditional ICT networks (Cárdenas et al., 2011).

Credible threats that have penetrated PCNs include the Stuxnet worm. This is a malware which has the ability to reprogramme process plant controllers. Stuxnet can have malicious consequences, and it is inherently very difficult to detect by ICT defense systems. It exploits zero-day vulnerabilities, and as such, anti-virus software is not sufficient to preempt an attack (FortiGuard Centre 2016).

Cárdenas et al. (2011) suggested that the Stuxnet worm was one of the first cyber-attack against a SCADA system. The worm is extremely complex in design and targets specific IACS vulnerabilities. It was discovered as a programme, which spies on and reprogrammes IACSs; this is consistent with the work personified by FortiGuard Centre (2016).

Table 4. IACS Cybersecurity Incidents are Escalating

Year	Event	Year	Event
2000	A former employee of Hunter Watertech, the automation supplier to Maroochy Shire, took control of the wastewater management system, and released approximately 80,000 liters of sewage into local parks, rivers and the grounds hotel.	2013	Drug traffickers caught hacking into Antwerp container management system to locate containers with hidden drugs. The attack commenced with malicious software being emailed to staff, allowing remote access.
2003	The Davis-Besse nuclear power plant in Ohio, US, was infected with the Microsoft SQL "Slammer" worm, which resulted in a five-hour loss of safety monitoring.	2013	Alleged Iranian proxy hacktivist group attacked the Haifa Camel Tunnels - the largest tunnels in Israel - resulting in multiple closures over several days.
2005	Several rounds of Internet Worm infections disabled 13 of Daimler Chrystler's US automotive manufacturing plants offline for almost an hour. The Worm mainly affected Microsoft Windows 2000 systems, and (earlier versions) of Microsoft Windows XP.	2014	The Energetic Bear group, thought to be responsible for a reconnaissance malware designed to "discover" SCADA systems, that was detected on 2014 July 01; it targeted energy facilities located mainly in Europe and North America.
2010	Stuxnet worm discovered as the first IACS worm used to attack the Iranian nuclear programme and other targets.	2015	A Ukraine power company suffered from a power outage that impacted large regional area, the attack was carried out by hackers using Black Energy malware. The bug was planted into company's network using spam emails.
2011	Hack attacks on water utilities in the US widely reported, such as the Houston waste water intrusion by the hacker known as 'pr0f'.	2016	Thousands of computers in Saudi Arabia's civil aviation agency and other Gulf State organisations wiped in a second Shamoon malware attack.
2011	Duqu reconnaissance malware discovered and software components linked to Stuxnet. Duqu was a Trojan target at IACS vendors in Europe in order to gather data and cryptographic keys to authenticate software, for use in future attacks.	2016	Cyber-attackers tripped breakers, in 30 substations, turning off electricity to 225,000 customers in a second attack.
2013	Telvent attacked, allegedly by a highly active Chinese group. Attackers installed malicious software and stole SCADA project files.	2017	APT33: An alleged Iran-linked cyber-espionage group commenced attacks on the aviation and energy sectors.

Source: Adapted from Piggin (2014), and Hemsley and Ronald (2018)

In 2012, malware was discovered at a power plant when an employee was experiencing issues with a Universal Serial Bus (USB) drive in the United States. The USB drive was routinely used for backing up control systems configurations within the control system environment. The employee asked an IT person to check the USB drive. The IT staff inserted the drive into a computer with up-to-date anti-virus software.

The software identified three (3) malware hits. Two (2) were common malware and one was a sophisticated malware. Two engineering workstations were infected with the advanced malware (RISI, 2018).

According to Cardenas et al. (2011), there was a Siberian Pipeline Explosion, in 1982, whereby a Trojan penetrated a SCADA system software, which subsequently led to an explosion. In 2000, hackers seized control of a Russian natural gas pipeline. In that same year, in Maroorch Shire, an ex-employee gained unauthorised access into the SCADA system, of a sewage treatment plant using a wireless Internet device, and triggered some "accidents".

In 2014, the Energetic Bear group was thought to be the mastermind behind a SCADA reconnaissance malware that targeted energy facilities in North America and Europe (Piggin, 2014). New IACSs-attacking malware, exhibits strains of rootkit engineered for control systems.

This software is oftentimes verified and electronically signed by trusted certificate authorities. As a result, it is very difficult to prevent and detect these attacks based solely on ICT information (Cardenas et al., 2011; FortGuard Centre, 2016; Hentea, 2008). Table 4 provides an overview of several documented IACS breaches across the globe.

5. Commercial Off The Shelf (COTS) IACS Solutions

There are several Commercial Off the Shelf (COTS) IACS solutions on the market. The Cyber Exposure Company provides visibility, security and control across operational technology (OT) environments. Tenable is a vulnerability management platform which helps organisations understand and reduce cybersecurity risks (CEA, 2020). Darktrace offers Darktrace Enterprise, an Artificial Intelligence (AI) cyber-defense solution that uses AI and Machine Learning (ML) to protect networks; and Darktrace Industrial, a specially designed tool used to identify threats and vulnerabilities in SCADA systems and IT networks.

The company also has Darktrace Cloud - Darktrace Software as a Solution (SaaS) product. It has adapted innovative mathematical models to IACS data for machines, networks, and users within environments, which spots previously unidentified anomalies in real-time (Darktrace, 2020).

In 2019, Honeywell launched a new industrial IoT analytics platform called Honeywell Forge which collects operational data, analyses that data and provides suggestions for infrastructure optimisation.

Honeywell Forge Cybersecurity Platform is a unified platform that enables consolidated, secure remote access to industrial plants and sites; scalable platform enabling asset discovery, inventory, monitoring, risk monitoring, secure file transfer with threat detection, automated updates (patches and virus signatures), and comprehensive activity logging. Cybersecurity as a service is one of the offerings of Honeywell Forge (Honeywell, 2020; CEA, 2020).

6. Next Generation Firewalls - What are They?

Traditional firewalls alone are not sufficient to protect the enterprise from dangers of the Internet. Next Generation Firewalls (NGFWs) equipped with advanced packet inspection functionality, and advanced reporting features can improve security around the access gateways (Skybakmoen, 2018).

NGFWs have added new features to better enforce policy (application and user) control or detect new threats. These include: additional Intrusion Prevention System (IPS) functionality, sandboxing and threat intelligence (Young and Pescatore, 2010). NGFWs provide more granular control within the firewall rules. They have the ability to allow or block content based on user access credentials or group membership, such as allowing only the Process Engineering team to use YouTube, for work purposes (Thomason, 2012).

Gartner (2020) defines NGFWs as deep-packet inspection firewalls that move beyond port/protocol inspection and blocking. They add application-level inspection, intrusion prevention, and bring intelligence from outside the firewall.

According to Thomason (2012), a minimum of five (5) basic requirements are essential to be classified as a NGFW.

1) It must have deep packet inspection ability and must be able to scan all files for threats, including encrypted files.
2) It must provide application intelligence with the ability to know what applications are traversing on http and https ports, and what each application is doing.
3) As NGFWs perform deeper analysis of packets, performance can become an issue. The system is still expected to perform all its functions at 'wire' speed.
4) A NGFW needs to have good reporting abilities which are easy to understand. It should provide much more than just the source and destination IP addresses and ports.
5) It needs to be manageable: Most system failures are due to human errors and misconfiguration. NGFWs will have sound interfaces which allow them to be managed centrally via a console.

7. Research Framework

The research endeavor reviewed existing literature and was supported by interviews with experts in the application space. The approach was to use real traffic, to monitor the IACS environment and the associated risks. An attempt was made to use that data, to identify markers that provide early indication of malicious behavior or behaviors that *run afoul of the organisation's policies*.

Event logging was enabled from the NGFW appliances to send their logs to a Syslog server. This previously existed on the Corporate LAN and was used for collecting logs from other existing Corporate LAN systems and applications. A new instance of Splunk was created on the Corporate LAN to read data from the Syslog Server, specific to the exercise (see Figure 3).

Rules were created on the PCN NGFW (NGFW_P) to allow its data to be incorporated into Splunk (analytics tool). NGFW_E represents the Corporate LAN perimeter defense appliance set. Initially, consideration for enabling a Mirrored Port on the main PCN switch was considered. The objective was to have a parallel set of PCN traffic copied to a laptop for analysis. However, the PCN solution provider advised against using that method, given the inherent risks.

8. Results and Analysis

The standard NGFW reporting tools were very useful in providing a summary of prospective threats, categorised as low, medium and high risks based on the devices'

Table 5. Firewall Considerations for PCNs

Recommendations	
The base rule set should be Deny All, Permit None. All permit rules should be both IP address and TCP/UDP port specific, if appropriate.	All rules shall restrict traffic to specific IP address or range of addresses.
All traffic on the PCN is typically based on routable IP protocols, either TCP/IP or UDP/IP. Any non-IP protocol should be dropped.	Prevent traffic from transiting directly from the PCN network to enterprise network. All traffic should terminate in the DMZ.
Any protocol allowed between PCN and Demilitarised (DMZ) is explicitly NOT allowed between DMZ and enterprise networks (and *vice versa*).	All outbound traffic from the PCN to the enterprise to be restricted by service and source and destination ports, using static firewall rules.
Allow outbound packets from the PCN or DMZ only if those packets have a correct source IP address assigned to the PCN/ DMZ devices.	All management traffic should be routed either via a secured (separate) management network or over an encrypted network with two-factor authentication. Traffic should also be restricted by IP address to specific management stations.
PCNs shall not be directly connected to the Internet, even if protected via a firewall. Consider deploying a DMZ with Control Zones to reduce the attack surface and increase the layers of PCN protection against attacks, emanating from the Internet.	Ports and services between PCN and an external network should be disabled. Access only granted based on specific business justification.

Source: Adapted from NISCC (2005) and Byres (2018)

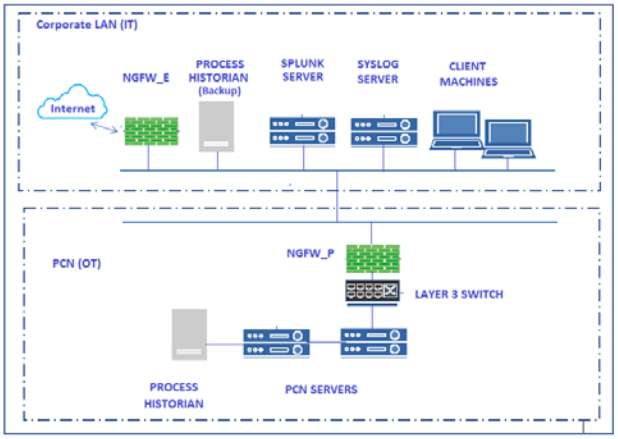

Figure 3. Depiction of Data Collection Architecture

preset criteria. Those datasets were further analysed using Splunk reports and Matlab.

Figure 4 provides a summary of the threats which emanated from the Internet. With the exception of the Bandwidth Consuming Application, the threats were mitigated by the NGFW_E, based on the configuration to restrict traffic based on specific parameters. Bandwidth Consuming Applications were initially considered as low risks based on the attendant rules defined within the (edge) NGFWs. Hence, this category was reviewed periodically and corrective action taken where necessary.

Reports from the NGFW_P, confirmed that no matching log data was available relating to Threat Detection and Data Exfiltration from the Corporate LAN. Therefore, from Top-Down perspective, it can be inferred that no observable malicious traffic needed to be filtered by NGFW_P. It was apparent, however, that the NGFW_P blocked events from within the PCN attempting to access the Internet, to upgrade their system software.

Subsequently, it was recommended that each of those blocked conversations be reviewed to identify the best means of disabling them rather than having the NGFW restrict them. That meant removing or disabling unnecessary services or closing the respective ports. Moreover, with the aid of Wireshark protocol analyser, it was determined that Modbus TCP, Network Time Protocol (NTP) and ARP messages were found to be allowed via the NGFW_P.

Engagement of the PCN vendor confirmed that NTP was allowed for time synchronisation, Modbus TCP traffic as was allowed for inter-device communications. A limited amount of ARP traffic was also allowed for network establishment.

Traffic and protocols which should have been allowed, consistent with the PCN, vendor's procedures and guide were assessed and corroborated against the recommendations in Table 5. Peers within the energy sector were also consulted to discern what levels of security they had to support their IACSs. It was apparent that most had a similar PCN architecture, designed by the same solution provider. However, various Security Information and Event Management (SIEM) tools were in use across the industry.

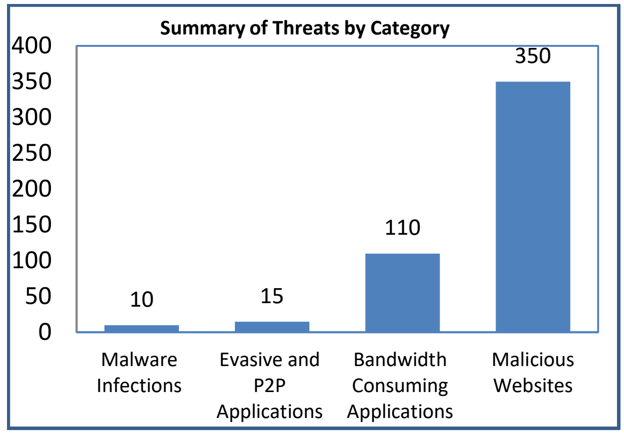

Figure 4. Summary of Threats Emanating at the Edge of the Corporate LAN

9. Conclusion and Future Work

The review of literature, expert feedback and data from a real PCN system corroborated each other. The interconnectivity of corporate networks with PCNs brings potential security threats. Nationally, companies have taken tangible steps to secure their CIs with access controls. The importance of protecting PCNs cannot be overstated, given the potential impact of a malicious attack. Consider the costs highlighted in Figure 1, and the threats mentioned within Section 4. Organisations must conduct the necessary risk assessments and endeavor to use contemporary tools as best as practicable. Naturally, an overarching security framework that assesses and treats with People, Process and Technology must be adopted. Inherent therein will be a critical role for NGFWs, considering the top (boundary protection) risks based on ICT-CERT (2016) study.

NGFW is an essential appliance in the defense against current and future cyber-threats in business networks and PCNs. For firewall considerations for PCN (see Table 5), the tool is not infallible and where possible, it should be used within a tiered architecture to have multiple layers of defense. NGFWs used within PCNs should be industry-grade with fault tolerance and online health monitoring functionality.

It was evident that the tiered NGFWs worked in complementary fashion. They allowed only trusted communication protocols and traffic to communicate across the two interconnected networks. The standard NGFW reports provided invaluable information regarding prospective threats. This was in keeping with the characteristics of NGFW highlighted by Thomason (2012). However, the entire architecture inclusive of the corporate network must continually be assessed. It cannot be overstated that a cybersecurity campaign requires the integration of People, Process and Technology. It is not a one-off process.

Based on the findings, it can be concluded that NGFWs do play an invaluable role in PCN cybersecurity. The hypothesis proved to be true that paired NGFWs do restrict malware by at least 50%. It is noteworthy that the associated literature to date, appears to be predominantly simulation – based data rather than data from production systems. Contrastingly, this research utilised actual data from a PCN in operation. A prospective next step is to engage in an in-depth assessment for a period of at least six (6) months. Additionally, using AI to support cybersecurity – end-user behaviour analytics across PCNs is currently being considered.

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Authors' Biographical Notes:

Eddison Jaggernauth *received his BSc (Hons) in Computing and Information Systems from The University of London, MBA from Heriot-Watt University, and MASc degree in Electrical and Computer Engineering, with a major in Communication Systems, from The University of the West Indies (UWI), St. Augustine. He is currently a PhD Candidate in Electrical and Computer Engineering at The UWI. He is also a Chartered IT Professional certified by the British Computer Society and a Project Management Institute certified Project Management Professional. His interest includes: IACS Cybersecurity, Deep Learning and Management Information Systems (MISs).*

Sean Rocke *received his BSc in Electrical and Computer Engineering from The University of the West Indies in 2002, his Masters in Communications Management and Operational Communications from Coventry University in 2004, and his PhD in Electrical and Computer Engineering from Worcester Polytechnic Institute in 2013. His areas of interest include signal processing and optimisation techniques relating to wireless communications management application and biosensor development and biological data mining, as well as and emergency communication systems.* ■

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Barbados towards 100% Renewable Energy: Case Scenarios for 2030 National Energy Target Plans

Sheldon Marshall [a] and Randy Koon Koon [b,Ψ]

Department of Physics, University of the West Indies, Mona Campus, Jamaica, West Indies;
[a]Email: sheldon.marshall@mymona.uwi.edu
[b]Email: randy.koonkoon@uwimona.edu.jm

[Ψ] *Corresponding Author*

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Abstract: *The integration of renewable energy (RE) into the overall energy mix of Caribbean nations has been increasing in recent times. The volatile nature of the carbon-based industry through fluctuations in prices of fossil fuel based-products renders it necessary to promote an aggressive energy profile transition to renewable energy, as this is crucial to energy security in these vulnerable Small Island Developing States (SIDS). The nation of Barbados has notably understood this reality and, as such, its government has endorsed the approach of 100% RE implementation by 2030. This paper explores three distinctive annual growth rate (AGR) scenarios to assess the impact on the expected power generation, economic and environmental parameters through the period of 2019-2030. Notable findings at a high case scenario for 2030 (at an AGR of 3%) projects a power generation of 1.343 Tera-watts-hour (TWh), which will displace 790,500 barrels of oil equivalent (boe), resulting in an abatement of approximately 0.95 million tons of carbon dioxide into the atmosphere.*

Keywords: *Barbados, annual growth rate, renewable energy, carbon neutral*

1. Introduction

1.1 Brief history of Barbados

Barbados is a Caribbean island country situated in the Lesser Antilles of the West Indies and sits about 100 km East of the Windward Islands, the most easterly of the Caribbean islands. It is located at 13.1939° N, 59.5432° W. The country is 34 kilometers in length and 23 kilometers in width with a relatively flat area of 432 km^2. Its maximum elevation is just 343 m (BTE, 2019) above sea level, at Mount Hillaby in the parish of St. Andrew. Barbados received independence in 1966, and in 1973 became one of four (4) founding members of the Caribbean Community (CARICOM), which has since grown to fifteen (15) full members. Like most of the CARICOM states, Barbados depends heavily on the importation of fossil fuels for energy generation. This dependence on this finite resource carries with it consistent fluctuations in price due to global oil market volatility, making the island vulnerable to drastic hikes in electricity prices.

The island of Barbados is densely populated, and according to 2018 population data, the country has a population of just over 286,000 with a density of 666 persons per square kilometer (Statistics Times, 2018). According to the United Nations data, this places Barbados at no. 17 for most densely populated countries in the world, and no. 1 of the 15 CARICOM states. Due to the island's political, social and economic stability, Barbados has a high standard of living and a very high Human Development Index (HDI) at no. 58 in the world and 2nd to the Bahamas (54) in the Caribbean (UNDP, 2018). Historically, Barbados' economy was supported by its sugar cane industry which was the island's main source of revenue. However, in more recent years, the tourism and hospitality sectors have taken over as their economic mainstay. These sectors require a great demand for energy and that demand is directly proportional to the influx of tourists to the country.

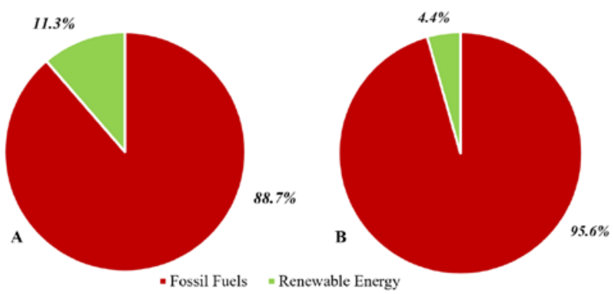
1.2. Barbados' Energy Resources and Energy Market

All CARICOM members are pursuing energy security. Given their dependence on fossil fuel imports, it is necessary to develop cheaper, alternative energy sources. The rate of domestic electricity is USD 0.35/kWh (Energy Chamber, 2017). The Barbados Light and Power Company Limited (BLPCL) supplies electricity to Barbados. According to the Director of Operations at BLPCL (Greaves, 2019), the energy mix at the end of 2018 is composed of:

- Fossil fuel generation plants (256 MW) at three locations--Spring Garden, Garrison and Seawell;
- PV Solar Plant (10 MW) with battery storage (5 MW) at Trent, St. Lucy; and
- Independent Power Producers (20 MW – distributed customer-owned rooftop solar PV and wind).

Additionally, at the end of 2018, renewable energy (RE) stood at 11.3% by capacity and at 4.4% by energy produced, as seen in Figure 1. The fossil fuel generation plants consist of 6 low-speed diesel plants, 6 gas turbines, and 2 steam turbines (BLPCL, n.d.).

According to the Barbados Economic Report Energy Chapter 2017, consumption for the island was 944 GWh for 2017 which was only an 0.04% increase from the figure for 2016. Of the energy consumed in 2017, approximately 36.2 GWh or 3.8% of that energy came from renewable energy sources (Government of Barbados, 2018). However, according to Greaves (BLPCL) 2018 saw 0.15% drop to 942.6 GWh in consumption for the country with 4.4% of that energy coming from RE sources. The Caribbean islands, and more so Barbados, are therefore vulnerable to the ever-changing fluctuations in the price of fossil fuel-based products.



A: Installed Power Capacity of 286 MW,
B: Power Generation of 942.6 GWh

Figure 1. A 2018 Power Profile of Barbados
Source: Based on Greaves (2019)

In 2013, CARICOM ratified a renewable energy policy, providing a framework for increased penetration of renewables in the region. This paper examines three distinctive annual growth rate scenarios to investigate and determine the impact of implementing 100% renewable energy in Barbados. The investigation was informed by a myriad of technical, economic, environmental and social limitations.

1.3 Towards an Enhanced Climate Sensitive Nation

Increasing penetration of renewables across Barbados and a consequent reduction in fossil fuel importation is not only economically prudent but also environmentally friendly and climate-sensitive. The Caribbean has strengthened its stance at the world stage for greater reductions in greenhouse gas emissions globally. Through research published in the Intergovernmental Panel on Climate Change Special Report on the warming of 1.5℃ above pre-industrial levels (IPCC, 2018), over 90 Caribbean and Latin American authors contributed to a body of data for increasing climate security for the vulnerable small island developing states (SIDS). Caribbean nations over the past decade, and more recently, have been devastated by the passage of major hurricanes such as María and Irma in 2017. Barbados is among the Caribbean nations focussed on the reduction of carbon dioxide gas. The goal is to become a carbon-neutral nation through the 100% transition towards renewables.

2. Target – 100% Renewable by 2030

The Barbados Labour Party, in their 2018 Manifesto, stated that they are aiming to transition Barbados to the "first 100% green and carbon-neutral island-state in the world" (Barbados Labour Party, 2018). The phrase "100% green" refers to having all the electricity generation being fueled by renewable sources that are replenishable on a human timescale. This means a transition away from using fossil fuels as a source of fuel for electricity generation. Additionally, for the country to be carbon neutral, the number of carbon emissions eliminated from going 100% green will at least equal the amount emitted from other processes, namely transport (cars, sea vessels, and planes).

2.1. 100% Renewable in Barbados

Hohmeyer (2015) suggested that 100% RE for Barbados is both feasible and affordable. Table 1 lists the capacity for the varying source of renewable sources. Wind and solar photovoltaic (PV) at the stated capacities would supply the energy demands of the country. However, the literature discussed the importance of balancing 100% renewable energy as both wind and solar are intermittent and will not always meet the demand of the system as there is going to be large and fast fluctuations of the residual load. The difference between the power required through the demand load and the power generated results in the residual load. Thus, the residual load must be met to ensure the system is balanced and the energy supply is maintained.

Barbados requires a significant amount of storage to balance the RE sources, as Barbados has only a high potential for wind and solar. An additional alternative energy source can be obtained in the form of biomass from sugar production. Bagasse from the sugar production process is converted into a liquid biofuel that can be used to run combustion engines.

In the case of Barbados, storage must meet the maximum load of the electricity system and must at least supply that demand for 12 hours. When considering the type of storage, the storage generation capacity must be between 150 and 200 MW, with a storage volume of between 1 and 10 GWh.

Moreover, of the different types of storage technologies, pumped hydro storage was determined to be the best option. It is the only type that suits the conditions of the county and meets the required capacity while being a flexible, affordable and already mature technology. Table 1 shows the capacity for the same renewable energy sources to cover full electricity generation and the demand for e-mobility (i.e., the transition from petrol or diesel for transportation to electrical mobility through means of renewable energy). Hence, renewables can supply energy for electricity generation, in addition to significantly impacting the transportation sector (including power cars and buses).

Table 1. Suggested Capacities by Renewable Energy Source for 100% RE for Barbados

Source	Capacity for 100% electricity generation	Capacity for 100% RE + demand for e-mobility
PV	195 MW	376 MW
Wind	200 MW	452 MW
PHS	1 GWh	3 GWh
Biomass	25 GWh	25 GWh

Source: Based on Hohmeyer (2015)

2.2. Power Consumption

The level of consumption for the country is impacted by population size and the number of customers. The growth of these two parameters is dependent not only on the increase in the number of individuals but also on the magnitude of energy usage per individual. Secondary to the magnitude of energy usage is how the energy is being used. This also has an impact on consumption as persons can consume far greater than is required to do tasks that could have been supplied with a lot less energy through proper Demand-Side Management (DSM). With effective DSM, the consumption can be minimised to its lowest requirement. Thus, energy efficiency is crucial to the sustainable development of the island.

2.3. Power Production

The production of electricity for the country is currently primarily generated from fossil fuels and therefore there must first be an increase in RE capacity to supply the demand currently supplied by fossil fuels. This increase in RE capacity must not only be in magnitude, but also by the source as each renewable source comes with its advantages and limitations. The characteristics of the different renewable energy technologies along with their sources of fuels determine the viability for their use in the Barbados energy mix. Of the different renewable energy technologies, wind, solar and biomass would be the best options for the country with pumped hydro storage for storage to cover the demand (Hohmeyer, 2015).

Energy production is not limited to just the utility power provider, Barbados Light and Power Company Limited (BLPCL). This means that private entities, both residential and business, can set up renewable energy systems and feed the power to the grid. This is facilitated by the Electric Light and Power Act 2013 and by policies such as the Government's Barbados National Energy Policy (BNEP). According to the Barbados Economic Report Energy Chapter 2017, under the Electric Light and Power Act 2013, one hundred and thirty-one (131) licences were issued to new applicants since May 2015. Of those 131 licences, 53 (40%) were issued in 2017.

The total renewable energy capacity from those licences stood at 30 MW, of which 27 MW were connected to the grid by the end of 2017. There were also amendments made to the Act making adjustments to the Renewable Energy Rider (RER). The RER now allows applicants to install systems up to 500 kW (up from 150 kW): The adjustment removed the restriction that limited applicants from installing a system that produced more than 1.5 times their consumption. The report states that applicants are now applying for larger licences (Government of Barbados, 2018).

3. Paths to 2030 Targets

Barbados' path to 100% RE by 2030 is going to be heavily dependent on the rate of RE penetration and development per year, as well as the degree to which consumption levels can be maintained or decreased. Below are three (3) case scenarios examining the impact of varying the average energy consumption growth rate. The three cases are a base rate of -0.055%, a low rate of -0.40% and a higher rate of 3.00%.

Table 2 shows the projected data for 2030 and the impact of each of the three scenarios. Each case scenario is outlined. Another factor to consider is the impact of effective DSM. The BNEP suggests a 22% reduction in consumption owing to electricity efficiency programmes and technologies (Ince, 2018). This 22% reduction was accounted for in the case scenarios by first calculating the 22% reduction total according to the 2030 figure based on the specific growth rate for the scenarios.

It then reverses calculating to determine the percentage increase each year from 2018 to reach 2030, 22% reduction value. Each case scenario's 100% RE production target is based on the growth rate set for the scenario and therefore the production targets will vary for the different cases. Figure2 shows the projected annual

Table 2. Three Case Scenarios for 100% RE for Barbados by 2030

Cases	Consumption (GWh)		Barrels of Oil Equivalent ('000 boe)[a]	Cost Avoided at 100% RE (USD $ mil)[b]	CO_2 Emissions avoided (metric tons)[c]
	2019	2030			
Scenario 1	942.1	936.4	550.8	52.9	662,035
Scenario 2	938.8	898.3	528.4	50.7	635,098
Scenario 3	970.9	1,343.9	790.5	75.9	950,137

[a] The metric conversion of 1,700 kWh is equal to 1 boe was utilised (Investopedia, 2019).
[b] Cost of oil was taken at USD 96 for 2030 according to the International Energy Agency World Energy Outlook 2018 (Trends News Agency, 2018).
[c] CO_2 Emissions was given as 7.07E-4 metric tons of CO_2/kWh (USEPA, 2017).

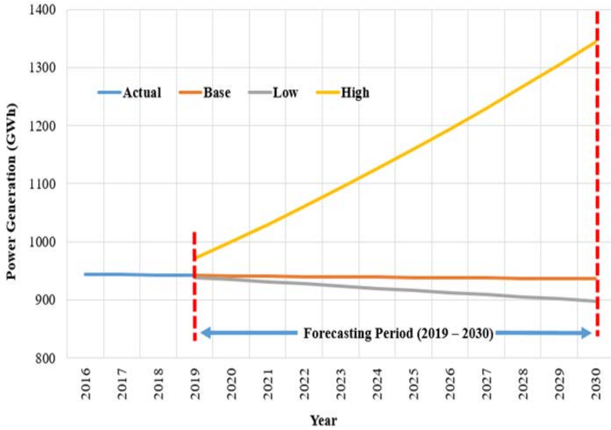


Figure 2. Forecasted System Load at Three Scenarios without DSM

energy consumption trend for the three case scenarios toward 2030.

3.1. Three Case Scenarios

The BLPCL's Integrated Resource Plan (IRP) indicates that the growth in electricity consumption in Barbados is strongly influenced by the country's GDP as there is a significant correlation between the two variables as observed in recent years. Therefore, the likely base case for energy consumption was determined using the forecasted base GDP growth rate of 1.6% (BLPCL, 2012). The average annual growth rates of electricity consumption are identified for the three scenarios, as follows:

- *Scenario I – Base Case: At -0.055%* - The average annual growth rate of -0.055% for the current rate was determined from the average of the 0.04% increase in 2017 and the -0.15% drop in 2018. A rate of -2.10% was determined in the scenario with DSM for a reduction of 22% in 2030.
- *Scenario 2 – Low Case: At -0.40%* - The annual growth rate of -0.40% was used for the low case from the BLPCL IRP 2012 where they also used this rate for their low case (BLPCL, 2012). -2.44% was used for the DSM for consumption reduction of 22% in 2030.
- *Scenario 3 – High Case: At Higher Rate* - An annual growth rate of 3.00% was used for the high case and, like Scenario 2, the rate came from the BLPCL's IRP. For DSM for a reduction in consumption of 22% in 2030, an annual rate of 0.89% was used.

3.2 Considerations towards Energy Targets

Achieving 100% RE for Barbados is going to take quite a bit of work, much of which depends on different factors. Some of the considerations that must be considered to facilitate the process include technical, economic, environmental and social aspects. Each of these is just as important to successfully reach the target.

3.2.1 Technical and Economic Impacts

Technical considerations in the pursuit of 100% RE for a small country like Barbados include, but are not limited to, energy stability, reliability, efficiency, and diversity. Energy stability is increased as there is a greater sense of predictability of long-term energy prices as the cost of electricity will no longer be tied to the global oil market which fluctuates erratically. However, those prices will be tied to energy systems that have a greater measure of control locally. Reliability of the energy is important to consider to move away from fossil fuels, Barbados will need to be able to provide the system load from the RE sources available in the country. This lends itself to greater diversity as it is necessary for Barbados to not rely on any particular RE source but to utilise as many of the options that are both available and viable for the Barbadian context. With each of the sources, it will also be important to ensure high-quality products are used to attain the best results, as well as the most efficient and reliable system possible (Greaves, 2019).

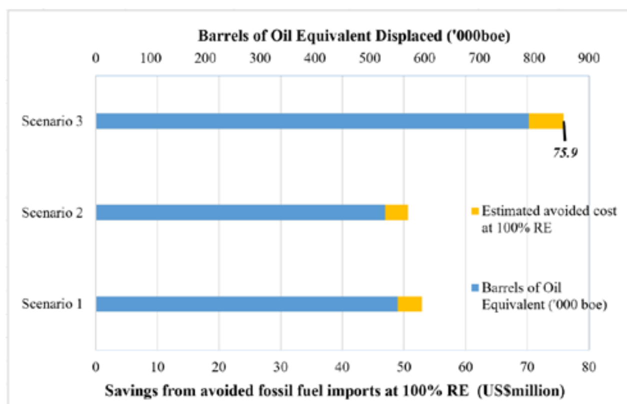


Figure 3. Projected Scenarios of Avoided Barrels of Oil Equivalent and Its Associated Savings through 100% RE Implementation without DSM

An increase in RE capacity and energy production directly relates to a decrease in the use of fossil fuels for energy production. This allows the country to save much of its foreign exchange and the money can be spent in the local economy. A greater supply of funds in the local economy means the Government will be able to retrieve some of that money via taxation. This means that the country can both save money and earn revenue which can all be reinvested into the country's development. Scenario 3 illustrates the case of the greatest annual growth rate, and thus, through the transition to 100% renewables, will displace the greatest number of barrels of oil equivalent resulting in an avoided cost of approximately US$ 75.9 million.

3.2.3 Environmental and Social Impacts

The global environment is impacted by what is done locally. Even though Barbados may be small, because of its high population density and high energy consumption, the impact of burning fossil fuels to produce the power needed to supply the country will be significant on the environment. Increasing to 100% RE will significantly reduce the CO_2 emissions from being released into the atmosphere.

Social considerations are vital to the development of the RE systems within the country. Time must be spent making persons aware of their role in moving Barbados to the 100% RE target, as there must be buy-in by the citizens of the country. In addition, there is the need for citizens to understand what it means for the country to be free of the bond of the global oil market and what benefits are provided because of such a shift in the source of energy.

3.3 Research Limitations

Research into renewable energy development in a small country, like Barbados, aiming for 100% replacement of fossil fuels by RE for electricity generation by 2030, comes with many limitations. This paper does not consider the economic growth forecast for the country which plays a major role in determining Barbados' consumption by 2030. Any major developments in industry and manufacturing over the next decade are not factored in. Tourism is a major economic sector and brings with it a direct link to energy consumption, as growth in that sector directly increases energy demand.

Barbados is limited by space. The utilisation of land for RE technologies can therefore be challenging, with potential competition for land for other purposes. Given the make-up and location of Barbados, the country is limited to just solar PV and wind, along with biomass as sources of energy (Hohmeyer, 2015). Both solar PV and wind require significant amounts of land space for operation.

This paper does not evaluate the space requirement for these technologies and therefore utilises the specified targets identified by Hohmeyer (2015). Additionally, PV and wind are both intermittent sources and therefore not ideal for baseload supply. However, storage and biomass are proposed in the energy mix to mitigate that problem. Factors such as temperature and the weather were also not considered in this paper. Their impact on the efficiencies of the RE technologies, namely PV and wind, as well as the growing of sugar cane for bagasse to be used as a biofuel, is significant. The reserves needed for the demand calculations were not used, as the only factor considered for those calculations was the consumption from 2016, 2017 and 2018.

3.4 Energy Efficiency Approach - Demand-Side Management (DSM)

The three case scenarios, base, low and high, for energy consumption by 2030 indicate what the energy consumption would be like by 2030 and therefore how much energy generation is necessary to cover the demand. The base and low scenarios both have negative annual consumption growth rates of -2.10% and -2.44% respectively. The high scenario shows an annual growth rate of 0.89% which takes the projected consumption to 1,344 GWh in 2030. The base and low scenarios led to significantly fewer values of 936 GWh and 898 GWh, respectively.

Renewable energy currently only accounts for 4.4% of the energy produced in Barbados (Greaves, 2019) and therefore an annual RE growth rate of 29.8% is required, beginning in 2019, to reach 100% RE by 2030. The 29.8% then translates to how much percentage more of the current RE needs to be installed annually as the energy produced is dependent on the capacity, as well as the technologies being used and their efficiencies. The installed capacity needed is dependent on the case scenario path the country decides to go down. Additional to the production is consumption, and this figure can be managed via DSM, which then can reduce the required demand, with scenarios 1, 2 and 3 having a demand of 730.7 GWh, 700.8 GWh and 1,048.3 GWh, respectively, as shown in Table 3.

Table 3. The consumption (GWh) in 2019 and 2030 (100% RE) with DSM Consumption Reduction of 22% in 2030

Case	Power Consumption (GWh)	
	2019	2030
Scenario 1 w/DSM	922.8	730.7
Scenario 2 w/DSM	919.6	700.8
Scenario 3 w/DSM	951.0	1,048.3

The DSM is very important and necessary for planning towards 100% RE supply as it will ensure the lowest possible consumption demand. This is done by introducing energy efficiency measures to minimise wastage and promote energy-saving habits. Figures 4 to 6 show the forecasted power consumption load for 2030 with and without DSM for each scenario. What about the forecasted power consumption load for Scenarios 2 and 3? These graphs would be useful.

4. Conclusion

The average annual growth rate of RE production must remain at a minimum of 29.8% for Barbados to achieve their target of 100 % RE by 2030, given that Barbados continues with the base rate in Scenario I without DSM. Because of the different cases, each with and without a DSM variation, what will be needed in terms of capacity will vary. Therefore, less will be required to be installed each year to remain on track.

If Barbados took the fast-tracked path with scenario III, owing to major development, a far larger RE capacity, and storage would be needed to supply the demand, which comes with a much higher capital cost for commissioning these RE systems. However, the cost and

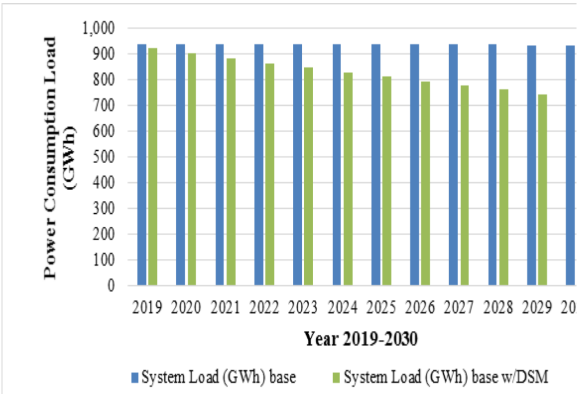


Figure 4. Forecasted Power Consumption Load for Scenario I, with and without DSM

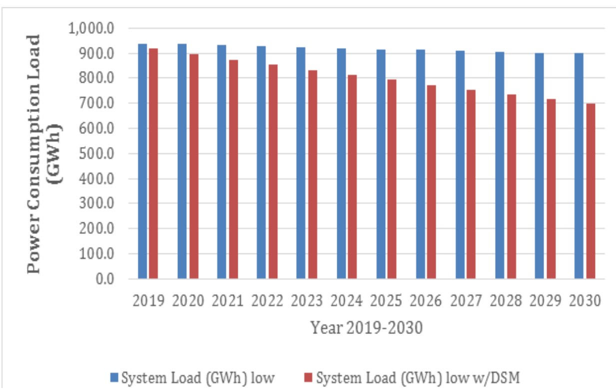


Figure 5. Forecasted Power Consumption Load for Scenario II, with and without DSM

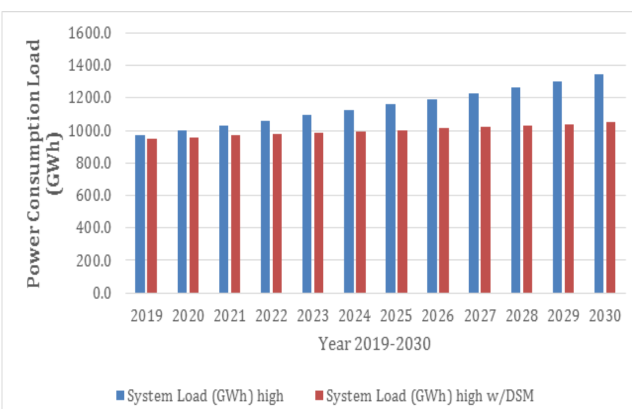


Figure 6. Forecasted Power Consumption Load for Scenario III, with and without DSM

CO_2 emissions avoided will also be much greater, resulting in large savings.

A greater magnitude of annual RE capacity will be required to maintain the annual growth of RE generation needed for 100% coverage by 2030. It is important that in planning to reach 100% RE by 2030, every effort is made by the government and the people of Barbados to manage the consumption end of the system, therefore requiring less energy to maintain a stable and reliable system for clean, affordable energy.

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Authors' Biographical Notes:

Sheldon Marshall *is a postgraduate student pursuing an MSc in Renewable Energy Management with a special interest in renewable energy technologies and solutions, and building as energy systems. He is a certified Photovoltaic Associate through the North America Board of Certified Energy Practitioners, thus solidifying his keen interest in renewables.*

Randy Koon Koon *is currently a lecturer in renewable energy at the Department of Physics, The University of the West Indies, Mona campus. His desire for enhanced renewable energy integration throughout the Caribbean coupled with active research in renewable technologies and energy efficiency methods positions him as an avid renewable energy advocate.* ■

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Assessment of the Emerging Landscape of Unmanned Aerial Systems in Trinidad and Tobago

Raid Al-Tahir [a,Ψ], and Giatri K. Lalla [b]

Department of Geomatics Engineering and Land Management, The University of the West Indies, Trinidad and Tobago, West Indies;

[a]Email: raid.altahir@sta.uwi.edu
[b]Email: giatri.lalla@my.uwi.edu

[Ψ] *Corresponding Author*

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Abstract: *Interest in the civilian applications of Unmanned Aerial Systems (UAS) has been growing worldwide, especially in government and commercial tasks such as surveillance, search and rescue, inspection of infrastructure, agriculture, mining, and mapping. Likewise, Trinidad and Tobago (T&T) has been witnessing a growing interest and application of commercial and non-commercial UAS operations. However, there is little assessment for the growth of the UAS market nor is there characterisation of UAS-based activities since the pertinent regulations established in 2016. This study seeks to formally identify the emerging UAS landscape in T&T during the period 2015 to 2019. As such, this study maps and characterises the spatial and temporal patterns of UAS distribution, then appraises the various categories for the existing operations. To achieve these goals, this study utilised qualitative and quantitative techniques of Geoinformatics. The intent for this study is to provide a perspective on the growth and the implications of the UAS industry in T&T, and to guide strategic planning among organisations with a stake in the emergence of UAS into civil airspace.*

Keywords: *Unmanned Aerial System. Drone. Geoinformatics. Civil Aviation. Trinidad and Tobago*

1. Introduction

Drones refer to aircraft without an on-board human pilot. These aircraft can be remotely controlled by a pilot on the ground or can fly autonomously based on pre-programmed flight plans aided by on board position and navigation sensors (Al-Tahir et al., 2011). While "drone" is the most popular term in the media, the professionally preferred terms are Unmanned Aerial Vehicle (UAV) and Unmanned Aerial System (UAS) (Fombuena, 2017; Granshaw, 2018). "UAS" is used to identify the actual air vehicle in addition to associated components (ground control station and the communication data link) that allow it to operate remotely. In a variation of this term, the letter "A" refers to "aircraft" (Colomina and Molina, 2014; ICAO, 2011; TTCAA, 2016).

Unmanned aerial vehicles have been around since the early 1900s, when they were solely used for military operations. These vehicles were used as targets for anti-aircraft training in the post-World War I era (late 1910's), and then as flying bombs during World War II (1940's). The actual armed use of the UAS started in the early 1990's when they were used for surveillance, and eventually in active combat missions in the beginning of the current century (Colomina and Molina, 2014; González-Jorge et al., 2017; Nguyen 2018).

Over the past two decades, the civilian use of unmanned aircraft has been expanding rapidly to support recreational and commercial applications. The increased demand for UAS is attributable to their low manufacturing and operational costs, as well as the flexibility of the platforms to accommodate the consumer's needs while eliminating the risk to pilots' lives in difficult missions (Al-Tahir and Arthur, 2012). Moreover, the continuous miniaturisation of electronics enabled the production of smaller, cheaper and more efficient UAS capable of being equipped with cameras and other sensors, hence provided greater availability (Floreano and Wood, 2015; Coops, Goodbody and Cao, 2019). The new technology offers the opportunity to replace or augment existing solutions and the expansion into new applications. By 2010, UAS production had more than doubled in 10 years while civilian and research applications had grown threefold and twofold, respectively (Al-Tahir and Arthur, 2012; van Blyenburgh, 2010). Furthermore, the UAS logistics and transportation market was estimated to be valued at US $11.20 billion in 2022 and is projected to reach $29.06 billion by 2027 (Murfin, 2018).

In Trinidad and Tobago (T&T), the public's view of unmanned aircraft has significantly evolved over a number of years. This is due to the technological development, social influences, potential commercial use, and the easy access to the UAS. However, only few anecdotal indications are available for the early appearances of commercial UAS activities in the country prior to 2015. Specifically, there were few published academic research such as Al-Tahir et al. (2011) and Al-Tahir and Arthur (2012), as well as a number of newspaper articles on the use of drones for activities such as police operations (Persad, 2013). Another indication for early public interest is the tender for an UAS issued by the government to provide image products to satisfy the country's needs of spatial data (Colomina and Molina, 2014; GORTT, 2013).

On the other hand, the commercial and non-commercial UAS operations have grown continuously after 2015. For example, the Trinidad and Tobago Police Service (TTPS) was utilising UAS to monitor drug traffickers and other criminal activities (Alexander, 2016; Alonzo, 2018). Another example is the use of UAS for watching the Digity mud volcano (De Silva, 2018). More recently, a project for *Birds Caribbean* conducted UAS-based aerial surveys of specific high shorebird concentration sites in Trinidad to determine shorebird abundance and diversity and provide a base for effective shorebird management (Gebauer and Sorenson, 2020). Additionally, there are a large set of ongoing commercial applications and projects that do not get into the academic publications or the media.

It is clear that UAS are not only increasing in popularity, but are also rapidly being incorporated into different industries for commercial use. Against this backdrop of growing interest, this study aims to analyse the changing landscape of the UAS industry in T&T in the period 2015-2019. The aim is to provide an important baseline for those interested in the UAS applications (academic, commercial, or otherwise) to understand the evolution of this industry in T&T. This study firstly examines the spatial and temporal changes in the distribution of UAS using geoinformatics techniques. It then identifies the various categories, and assesses the spread of UAS users and operations in T&T. Finally, the study concludes with identifying the existing and future implications of the growth of the UAS industry in T&T.

2. Regulations for the UAS Industry in T&T

The year 2015 witnessed a drastic increase in complaints by the citizens to TTPS against the use of UAS. The majority of the complaints revolved around the invasion of privacy and what was considered unfair competition in certain businesses (Alexander 2016). Consequently, Trinidad and Tobago's Civil Aviation Authority (TTCAA) established the Civil Aviation Unmanned Aircraft Systems Regulations (TTCAR No.19). These regulations were intended to address these issues by making it mandatory to register the UAS and obtain permission to operate in certain instances. One set of the regulations ensures the airworthiness of the system for operation, while another set focuses on physical and mental requirements for the operator. Another section provides regulations that disallow operating of a UAS with negligent or in an irresponsible manner that would endanger the life or the property of others.

Of specific interest to this study is a set of changes to the framework for the operation of the UAS that have influenced the growth of the UAS industry in T&T. One of these changes dictates that UAS operators must keep an unaided visual line of sight of the aircraft. While a second observer can be utilised (without the aid of any device apart from corrective lenses), continuous communications must be maintained.

Another set of regulations prohibits the operation of UAS over persons not located under a covered structure that provides reasonable protection in the case of a system malfunction. As such, permission is needed for operating over private property such as land, vehicles, and all public properties. A verbal permission suffices to operate over private property if the aircraft is utilised for non-commercial or recreation purposes. Conversely, the UAS operator must acquire approval by the Civil Aviation Authority for commercial operations (where compensation is received for services provided). Approval for UAS operations in these situations is subject to providing proof of permission from each individual that would be present on the location.

The third subset of regulations that has influenced the growth of the UAS industry in the country is related to operating UAS over restricted areas. Specifically, UAS cannot be flown at an altitude above 121 meters (400 feet). Additionally, no operations are to be conducted within five kilometres (km) from the boundary of any airport, within two km of any helipad, or within no fly zones specified by the Authority. Figure 1 represents the designated no fly zones and the navigation routes over T&T.

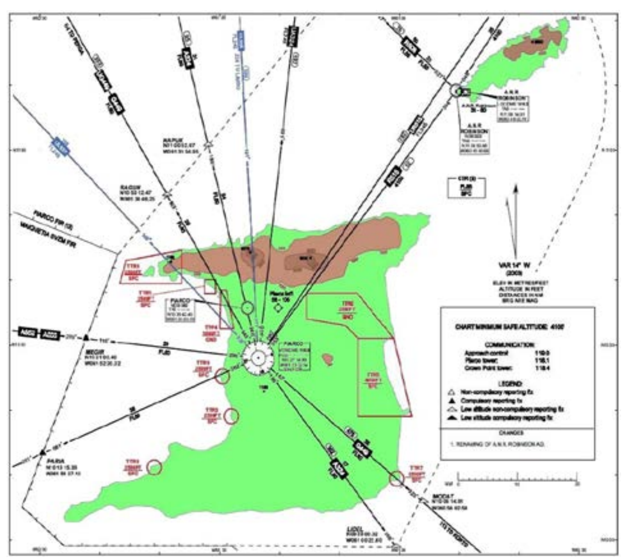

Figure 1. No Fly zones and navigation routes over Trinidad and Tobago (after Piarco FIR, 2020)

3. Data and Methodology

Several datasets were utilised for the purpose of mapping and analysing the growth of the UAS industry in T&T. The main set of data is UAS-specific dataset that was obtained from the Trinidad and Tobago Civil Aviation Authority (TTCAA). Ongoing since 2015, the TTCAA has been collecting data regarding the user operations and the distribution of the registered UAS in the country. Specifically, this dataset includes the following specific subsets:

- Registered UAS, which includes additionally the geographic locations of the UAS owners.
- UAS Characteristics; a non-spatial database describing the technical specifications for the registered UAS.
- UAS Use; a non-spatial database that identifies the type and location of UAS-based operations in the country.

Other ancillary datasets were used in this study to provide the backdrop for the UAS data and to facilitate the intended analysis. These datasets were all GIS-ready and consisted of the following:

- Coastline, Regional Corporation Boundaries, and the Road Network for the country.
- Buildings dataset that depicts the location of all buildings in the country (as of 2007) and their categories (government, commercial, and residential).
- Restrictive Buildings dataset for structures and establishments that UAS flight restrictions may exist to protect them (e.g., Police Stations, and Hospitals, etc.).
- UAS No Fly Zones that delimits areas where UAS flights are restricted unless special approvals are granted as stipulated by the TTCAA Regulations.

Several spatial and statistical analysis tools within Geographic Information System (GIS) were utilised to extract spatial relationships that exist within the data. However, considering that the provided data were simple and limited, basic geoprocessing tools were suitable enough to produce the maps needed for this study. Given that two of the TTCAA datasets are non-spatial database, the first task was to unify and convert them into a spatial database. This was done using the Geocoding tool that would take a text-based address of the registered UAS operators and generate its coordinates within the national mapping coordinate system. Among the many records in this combined dataset, 750 records were then extracted exclusively for users who are citizens of, or residing in T&T.

After combining the UAS datasets with the other ancillary datasets, fundamental GIS tools were used for performing queries, classifications and summarising a number of feature characteristics into attribute tables. Additionally, the Buffer operation was applied to determine which features would lie within the flying range of a UAS (for example, the typical range of a DJI drone is 5 km). These features (structures and establishments) may be potentially exposed to physical harm due to drone operation or malfunction. As a result of this operation, there were many incidents of clustering of points that allowed for multiple buffers to be merged thus creating a larger buffer.

To infer any correlation or relationship, the several pertinent datasets must be overlaid with each other. Hence, the Overlay tool was utilised to perform operations such as point-in-polygon, line-in-polygon and polygon-on-polygon operations. Another tool utilised in this study was the density-based Clustering tool to identify specific areas where UAS points are concentrated and where they sparse. The result indicated the existence of points that clustered into a pattern using a minimum cluster of 25. However, there were some data that did not cluster, these are usually singular events. This was completed by using the technique of unsupervised machine learning algorithm to detect the patterns.

Lastly, the geoprocessing tool known as a Directional Distribution (Standard Deviational Ellipse) was utilised. This tool was ideal for the statistical analysis of the data since it summarises the spatial characteristics of the point data by producing the central tendency, distribution and even the dispersion trends. When the Standard Deviational Ellipse tool is utilised, it creates an output class in the form of an elliptical polygon. The polygon uses the dataset's mean X and Y coordinates for the center, two standard distances (long and short axes), and the orientation of the ellipse.

4. Analysing the Growth of UAS in T&T

4.1 Spatial and Temporal Spread of the UAS in T&T

In order to examine the dynamics of the geographical spread of the UAS in the country, the following paragraphs look at the number, distribution, and type of the UAS devices in each year between 2015 and 2019. In 2015, there were only 39 UAS registered to individuals (personal use) although registration was voluntary. They were clustered around Port of Spain (the country's capital) and the lower Diego Martin, but sparsely scattered along the east-west corridor (see Figure 2). The majority of the UAS in the database consisted of quadcopters (four rotors) while there were three fixed-wing UAS. About 85% of all the UAS were manufactured by DJI technology company such as the Phantom and Inspire series, although there were few UAS manufactured by Yuneec and DragonFly.

With the introduction of TTCAR No.19, the year 2016 witnessed a surge in the number of registered UAS in the country. By the end of the year, the number of registered UAS quadrupled with the addition of 178 devices, three of which registered in Tobago. As for the users, eight organisations and one club registered their UAS devices in that year. Figure 3 clearly indicates that registered UAS were clustered in urban areas on a much

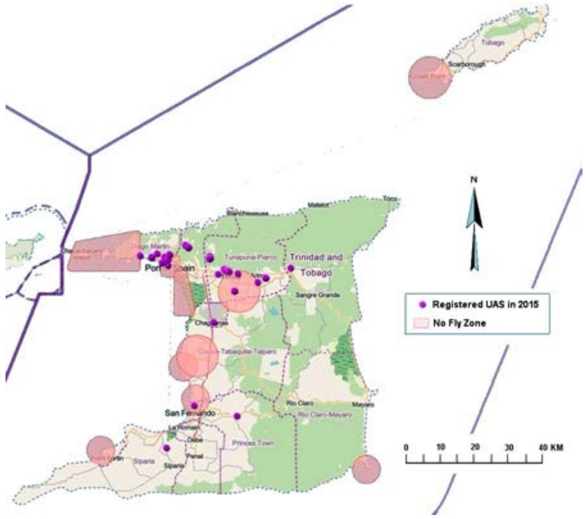

Figure 2. UAS distribution in 2015

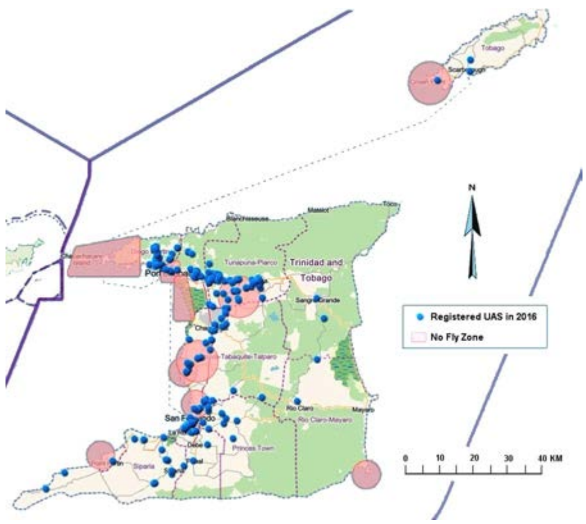

Figure 3. UAS distribution in 2016

larger scale than it had been in 2015. It can be noted that UAS were beginning to spread along the western side of the country. Quadcopters UAS were still dominating the UAS landscape in the year 2016, although there was an increase of four fixed wing UAS. While most of the UAS was still DJI Phantom, the database now included brands from other manufacturers such as Yuneec, Autel Robotics, HTEC, and MUVI.

In the year 2017, 166 registered UAS were added to the database including 22 UAS registered to organisations (nearly tripling the amount of registered organisational UAS). One can notice based on the distribution of the UAS in the country (see Figure 4) that the UAS industry was evolving to be more acceptable by the public. In addition to areas where they were previously existed, these systems expanded into new areas along the east-west corridor and in the cities of Chaguanas and San Fernando which house the country's major industrial and commercial centres. As another noteworthy change in the industry, the DJI Phantom series was no longer the main type of UAS as DJI's Mavic Pro series became the most popular series in 2017.

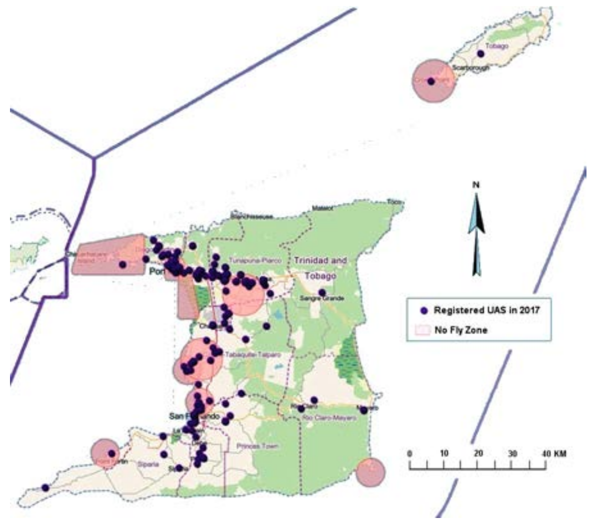

Figure 4. Distribution of UAS in 2017

The growth trend continued in 2018 and 2019 at almost the same pattern of distribution (see Figures 5 and 6) but at slightly declining numbers. There were 193 UAS added to the registry in 2018 and 154 UAS in 2019. These two years also witnessed the relatively significant proliferation of UAS in Tobago around the south-western and the north-eastern sides of the island. The amount of registered organisational UAS steadily grew by 30 and 28 in 2018 and 2019, respectively. The majority of the UAS was still quadcopters, with an increase in the smaller size DJI Mavic series.

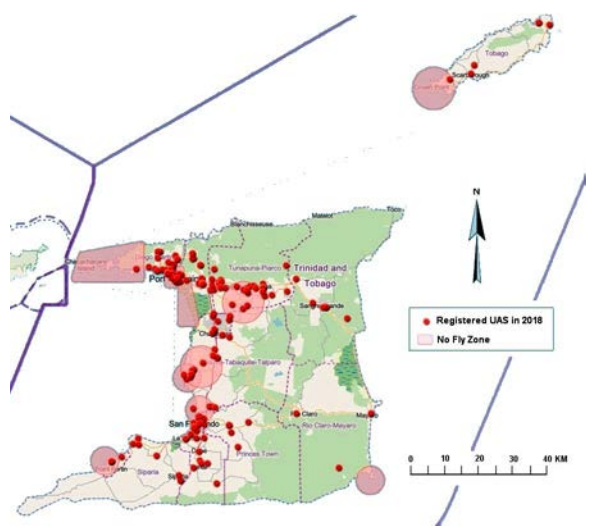

Figure 5. Distribution of UAS in 2018

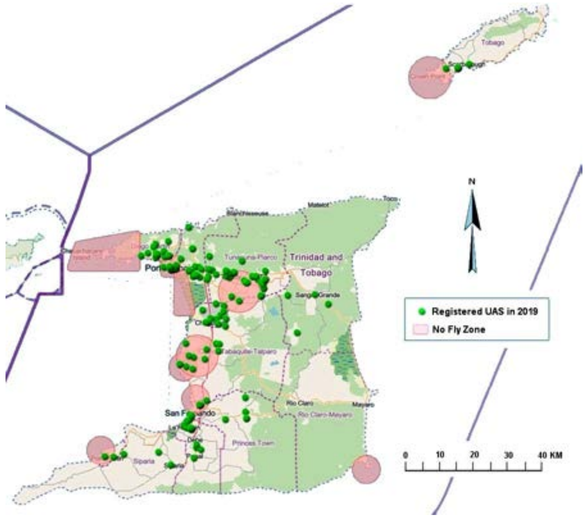

Figure 6. Distribution of UAS in 2019

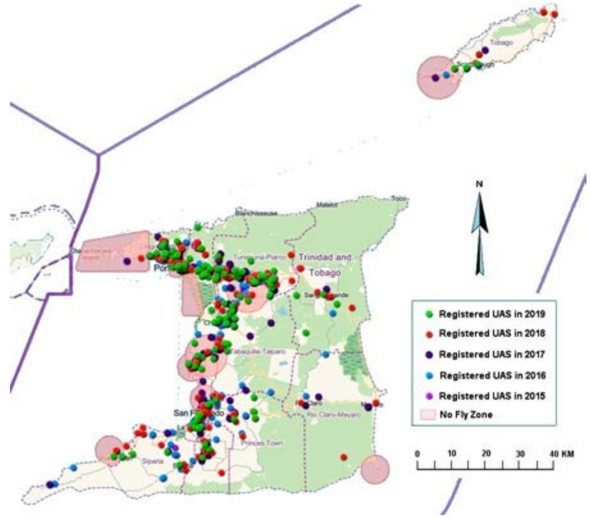

Figure 7. Distribution of all UAS registered in 2015 to 2019

At the same time, few numbers of hexacopters (six rotors) and octocopters (eight rotors) began to emerge in the registry. Table 1 provides a summary for the number of the UAS devices as categorised by the type of operators and by the UAS frame format.

Table 1. Summary characteristics of registered UAS in Trinidad and Tobago 2015-2019

Year	UAS per Type of Operator	UAS per Type of UAS Frame
2015	Personal: 39	Fixed: 3, Quad: 36
2016	Personal: 169, Organization: 8, Club: 1	Fixed: 4, Quad: 174
2017	Personal: 144, Organization: 22	Fixed: 4, Quad: 162
2018	Personal: 163, Organization: 30	Fixed: 4, Quad: 187, Hexa: 1, Octo: 1
2019	Personal: 126, Organization: 28	Fixed: 4, Quad: 149, Hexa: 1

Figure 7 presents an aggregate view of all registered UAS between 2015 and 2019. The figure asserts that most of UAS were clustered within the Port of Spain Regional Corporation, the Diego Martin Regional Corporation, and along the east-west corridor, mostly in Tunapuna Regional Corporation. Other three clusters can be noticed in the populated areas of Chaguanas, Couva, and San Fernando. One can also notice that the majority of the UAS expansion has been around commercial and industrial sites, and along the main road network of the country.

4.2 Assessing UAS Operations in T&T

The TTCAA dataset catalogues all UAS-based operations and includes the type of operations and the number of approvals received against 25 recognised types of operations (see Figure 8). These operations can be further divided into three segments: government/public service, enterprise (commercial/ company/ organisation), and private operations.

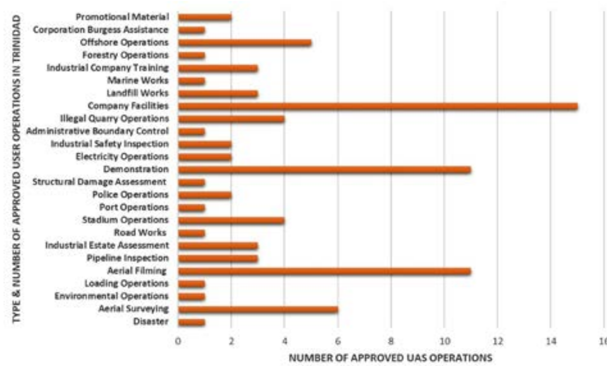

Figure 8. Type and number of approved operations in Trinidad and Tobago 2015-2019

The government/public service segment consisted of 17 approved operations completed by any public sector organisation in T&T. The most prominent activities were related to quarrying and landfill operations. Other applications included disaster management and relief, corporation burgess, forestry, administrative boundary control, electricity works, police operations, and road works. Interestingly to note was that the number of approvals obtained for police operations was only two in total, which may indicate the existence of an arrangement between the Trinidad and Tobago Police Service (TTPS) and the TTCAA allowing the operations to take place without approvals.

The second segment of UAS operations in T&T revolves around enterprise activities. There have been 32 approvals issued for this type of operations. Examples for such users are companies involved in the oil and gas industry as well as industrial facilities and services. The use of UAS is advantageous for the industrial companies (especially those with larger overall facilities) as it facilitates cost-effective, comprehensive, and in-depth levels of reconnaissance for wide areas. For example, 15

UAS operations were specifically approved for the purpose of facilities management that were directed towards inspecting gas and pipeline leaks, roof leaks, building damages, faulty wiring, and similar aspects. The second largest activity in this segment was offshore work that accounted for five approvals. This included operations for safety training videos and offshore rig inspections since UAS is ideal for a quick visual overview and extensive surveying of hard to reach areas.

In the third segment, there were 37 UAS approvals for private UAS operations in T&T since 2015. Aerial filming operations, with 11 approvals, had the lead in this segment. It encompasses a number of trades including movie productions, advertisements, and scientific operations. Equally in the lead in the approved private operations was the use of UAS for demonstration and promotional operations, a business that has seen a growth of UAS role fairly recently. Other activities in this segment included, though on a much smaller scale, operations related to marine, port, stadium, and loading operations.

Apart from the number and types of operations in Trinidad, it is also important to examine the pattern for where these operations took place. It is critical to remember that there are only 86 approvals being examined throughout Trinidad while only very few operations staged in Tobago. Therefore, the following inferences should be considered carefully regarding the spread of the operations throughout the island and offshore. Figure 9 undoubtedly indicates that the majority of the operations appear to be clustered at the south-western end of the Couva/Tabaquite/Talparo regional corporation.

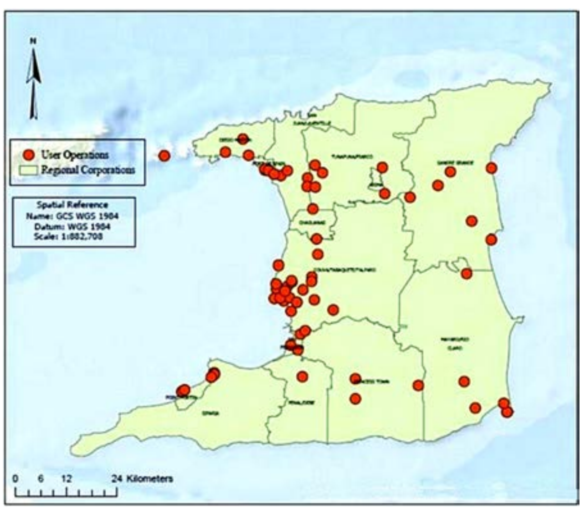

Figure 9. The distribution of UAS operations in Trinidad

This scenario could have been prompted by the nature of the operations in the area that ranges from facilities management to industrial operations, partly related to the activities of Point Lisas Industrial Estate. Similar rationalisation may be the reason for the small number of operations around Point Fortin and Galeota where large oil estates are located. The second largest clustering was in Port of Spain and its vicinity. This can be attributed to the number of parks, buildings, and companies in addition to picturesque nature of the area. There was an interesting spread of individual operations across the east-west corridor and south-west to south-east corridor. This can be attributed to the type of commercial activities and UAS operations related to forestry and monitoring of quarrying operations.

5. Analysis and Implications of the Growth of the UAS Industry in T&T

The previous section provided graphical presentations for the spatial patterns for the spread of the UAS in T&T through the period 2015-2019. Based on that, key traits can be deduced regarding the changes in the UAS landscape over the period.

The registered unmanned aircraft are small or mini-sized devices that weigh less than 20 kilograms. These models are relatively easy to handle but are limited in flight range and time. The increase of the number of registered UAS reflects an increasing acceptance by the public and the users. One important observation is that setting up the Civil Aviation Unmanned Aircraft Systems Regulations had a significant positive impact in these aspects.

The growing number of the UAS and their operations is an indicative of the growing needs for such activities. The government has gradually increased the use of UAS in several of its operations together with the established use in homeland security and policing. For example, UAS were used to identify the affected areas and stranded residents during the floods of 2018 in Trinidad (Philip, 2018). Other examples include the government initiatives for utilising UAS for the mapping project mentioned earlier, and the recent efforts by the Ministry of Energy and Energy Industries for applying UAS technology to the monitoring, surveillance, and enforcement functions of the Minerals Division.

In parallel, the number of the commercial operations by enterprises and individuals can also be quite revealing about the growing operations in T&T. Furthermore, some of the unmanned aircraft were solely registered for a specific use indicating more specialised and focused applications that require the technologically advanced UAS and personnel for the relevant operations.

Judging by the nature and growth of the UAS industry in T&T, one may conclude key positive implications. Firstly, it is encouraging to observe that UAS users in all sectors are becoming more technologically advanced and by extension, the society as a whole. Secondly, the use of UAS will ultimately increase the efficiency and productivity of any project since fewer resources will have to be siphoned into operational costs. One final positive implication is that employing such technology induces further research and development for advancing the discipline and generating new knowledge.

On the other hand, there are also several negative implications. With the exponential increase of UAS in T&T, the possibility for a collision within the airspace or crash on the ground is exacerbated. This is a serious concern judging by the civilian air navigation routes (see Figure 1). While there are set regulations in place to ensure the airspace safety, there is no systematic mechanism for monitoring or policing that would guarantee compliance.

Another negative implication is the looming public safety and privacy concerns. The figures in the previous section clearly indicate that most of the registered UAS are located within urban areas and operate within the range of many public and private properties. Such a condition would most certainly lead to instances where citizens' privacy or safety is jeopardised. While many UAS operators have understood the cause for these concerns, many operators may be less caring while operating the UAS or may not seek permission to fly over a property as required by the regulations.

To address these problems and the negative implications, this study suggests the following recommendations towards the improvement of the regulations.

1. Promoting the use of relevant checklists by the operators to help in pre-flight inspection, as well as promoting the documentation of maintenance logs.
2. Issuing additional set of regulations to mandate reporting, site visits and monitoring the operations as a means of ensuring compliance.
3. Naming the exact operations that are not allowed over persons.
4. Setting up a dedicated entity to process permission requests so that individuals will not be deterred from the process due to its current excessive length.

It is also envisaged that the regulations should be updated to accommodate for the advancements in the unmanned aircraft that aim at improving their efficiency and preparing for their safe integration in the national airspace. Some of these intensely pursued subsystems are the Beyond Visual Line of Sight (BVLOS) that eliminates the need for direct visual monitoring by human, 'Detect and Avoid' that allows UAS to detect and safely steer clear of aircraft or other obstructions, and Geo-fencing for creating virtual fences around areas or points of interest to keep UAS away.

6. Conclusion

Over the last couple of decades, the world has experienced a growing utilisation of unmanned aerial systems to perform a broad spectrum of applications. The rising demand is influenced by the unique range of features that these aircraft offer along with the continuous advances in automation and sensor technologies. The emergence of a robust government and commercial UAS industry in T&T is inevitable following the global trend. It is clear that civilian applications of UAS have been rapidly evolving, matched by their growing affordability and the advancement of the associated hardware and processing software. Scaling up the use of small drones from a niche market to widespread use in civilian applications depends on having appropriate regulatory frameworks in place. To understand the impact of the Civil Aviation Unmanned Aircraft Systems Regulations of 2016 and their future implications, this study analysed the growth of the UAS industry over the period 2015-2019. Geoinformatics tools were employed for this task using user information, the distribution of UAS, and the related operations.

Although there was a limited amount of data available to this study, it can be observed that the number and types of unmanned aircraft are rapidly increasing. As for the spatial patterns, one can recognise that UAS owners and their operations tend to cluster around the south-western end of the Couva/Tabaquite/Talparo corporation and Port of Spain city corporation. This is expected when one considers the concentration of business establishments and industrial opportunities at both locations.

The study identifies positive impacts for the UAS growth on the country manifested by the foreseen technological development, advancement of knowledge and research, and increase in the efficiency of commercial operations. Equally, the study envisages negative implications such as the airspace proliferations, general safety and privacy concerns. While there are set regulations to ameliorate these potential problems, there is a need to maintain, enforce, and update these regulations.

It is evident that large volumes of UAS are expected to be flying in the future, so safe operation is essential for the user and the public in general. As such, before the full potential of this market can be exploited the regulatory framework should respond to such needs and to evolving technological developments. Specifically, in response to the demand for autonomous operational capabilities, two related issues need to be addressed: the full integration of the UAS into the national airspace system and the removal of the legal restriction to fly beyond the operator's visual line of sight (BVLOS). An unmanned aircraft being operated BVLOS no longer has the protection of the pilot or observer to avoid terrain, obstacles or other aircraft.

Finally, the growth and future implications of the UAS industry in T&T despite limitation in the pertinent regulation has potential to speak into policy that will streamline more founded regulations in the future. Other countries experiencing similar landscape may borrow from the experience of the study area. Further, considering the limited human and financial resources in the region, one recommendation might be to encourage more collaboration between Industry and Academia if this is not already the case.

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Authors' Biographical Notes:

Raid Al-Tahir *holds a PhD. degree in Geodetic Sciences from The Ohio State University (USA) and a BSc. Engineering from the University of Baghdad (Iraq). Currently, he is a Senior Lecturer at the Department of Geomatics Engineering and Land Management, The University of the West Indies (Trinidad and Tobago). He is also an Adjunct Professor at the Department of Geodesy and Geomatics Engineering, the University of New Brunswick (Canada). His research interests include spatial data collection, quantitative analysis, and modelling using geo-spatial images and Geographic Information System to address issues related to land cover dynamics with implications for environmental degradation and natural resource management.*

Giatri K. Lalla *obtained a BSc degree in Geomatics and is pursuing a MSc degree in Geoinformatics from The University of the West Indies (Trinidad and Tobago). She has been employed within the Trinidad and Tobago Civil Aviation Authority for 3 years and it is where she specialised in Unmanned Aircraft Systems thus in 2020, she was appointed as the organization's Unmanned Aircraft Systems Officer. Ms. Lalla holds a Federal Aviation Administration Part 107 Remote Pilot's License. She has obtained professional education on the subject of Unmanned Aircraft Systems from Embry-Riddle Aeronautical University (USA). She continues to expand her knowledge on Unmanned Aircraft Systems, general aviation and geographic information systems.*

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Spatio-temporal Kriging of Lower Caribbean Wind Data

Neil Ramsamooj

Faculty of Engineering, The University of the West Indies, Trinidad and Tobago, West Indies;
Email: Neil.Ramsamooj@sta.uwi.edu

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Abstract: *Planning of a wind farm location requires significant data. However, wind speed data sets in the lower Caribbean are usually incomplete. This paper considers imputation by spatio-temporal kriging using data from neighbouring locations. Temporal basis functions with spatial covariates are used to model diurnal wind speed cyclicity. The residual set of our spatio-temporal model is modelled as a Gaussian spatial random field. Fitted models may be used for spatial prediction as well as imputation. Examples of predictions are illustrated using two months of hourly data from eight Caribbean locations with prediction accuracy being assessed by cross validation and residuals.*

Keywords: *Spatio-temporal modelling, wind speed, unbalanced data, imputation, temporal basis functions, kriging*

1. Introduction

Renewable energy (RE) sources are potential means of mitigating the reliance on petroleum and natural gas in the Caribbean. Wind energy has been identified regionally (Elliott *et al.*, 1987; Renewable Energy Committee, 2011) as a particularly viable RE source. The development of wind farms requires significant expenditure and therefore it is crucial to identify suitable wind farm locations in order to optimise energy production and reliability while minimising capital and working costs. Prediction methods for wind characteristics at a target wind farm location with minimal data from one or more reference locations are known in the wind engineering literature as measure-correlate-predict (MCP) algorithms (Carta, Velázquez and Cabrera, 2013). Initial MCP methods employed linear or quadratic regression techniques with data from a single reference location. Later MCP algorithms utilised multiple or vector regression methods with data from several reference locations.

Wind data is typically non-stationary and auto-correlated which implies that differencing or co-integration adjustments are required in multiple regression MCP algorithms. (Hunt and Nason, 2001) used a wavelet packet transform method to construct an MCP algorithm which accounts for non-stationarity; this method was only applied to a single reference location but may be extended to multiple reference locations. The above methods do not account for spatial correlation among multiple locations and do not provide a transparent method of trend removal. In this paper, we use the spatio-temporal model.

$$y(s,t) = \sum_{i=1}^{m} \beta_i(s) f_i(t) + \nu(s,t) \qquad (1)$$

where $y(s,t)$ is wind speed at location $s \in \mathrm{R}^2$ specified by longitude and latitude coordinates and time $t \in \mathrm{R}$. Temporal basis functions $\{f_i(t): i = 1, \ldots, m\}$ are used to capture the nonstationarity of wind data. The theory of spatial temporal basis functions is discussed in (Fuentes, Guttorp and Sampson, 2006) and (Wikle, Zammit-Mangion and Cressie, 2019). Hunt and Nason also use basis functions but our method is clearer as it does not rely on wavelet theory. The spatial fields $\beta_i(s)$ of our model (1) are readily tuned (by choosing latitude and longitude as geographical covariates) to allow for varying seasonality among the reference locations.

Similarly, there is flexibility in the choice of the covariance structure of the spatial random field in order to improve model fit. Furthermore, this model can be extended to include exogenous covariates (such as temperature and air pressure) in order to improve wind prediction accuracy (see Section 4). The model (1) is defined in Section 2.3. A case study illustrating spatio-temporal prediction of wind speeds using two months of hourly data from eight reference locations (shown in Figure 1) is given in Section 3. The prediction accuracy for this case study is assessed in Section 3.3 by the use of cross-validation groups. The R code for the case study is shown in Appendix A. A similar model was used by (Lindström *et al.*, 2013) in a pollution study of NO_x concentrations in metropolitan areas in the United States. Some code segments used in our case study are due to Lindström *et al.* (2013).

2. Problem Formulation

2.1 Data Sets

The wind speed data sets used in this paper were obtained as CSV files from the Iowa Environmental Mesonet (2021) and the National Oceanic and

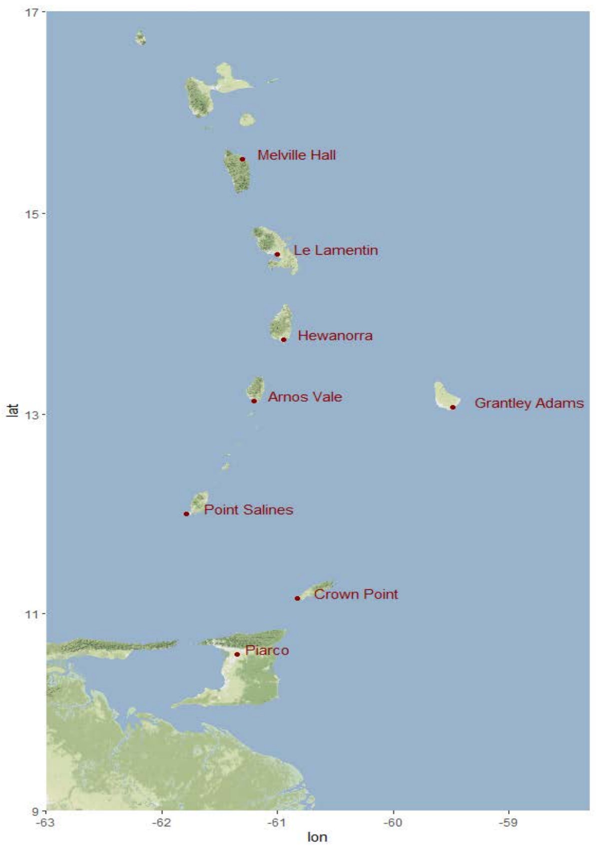

Figure 1. Eight reference locations for case study

Atmospheric Administration (NOAA, 2021) and originated from Meteorological Terminal Aviation Routine Weather Report (METAR) (National Weather Service, 1998) hourly records from January to February 2015. The web addresses of the download interfaces of the Iowa Mesonet and NOAA are given in the references above. Iowa Mesonet data may also be accessed within R using the package riem (Salmon, 2016) and NOAA data may similarly be obtained from the R package rnoaa (Chamberlain, 2021). A code example using rnoaa is given in Appendix A.1. Note that the METAR wind speed measurements have a resolution of only knot.

Observations from eight weather stations (located at airports) in the lower Caribbean were used in our analysis. Boxplots were used to remove outliers from each weather station data set. Figure 2 shows time series plots of hourly wind speed observations for five days from the three of these locations: Piarco (Trinidad), Crown Point (Tobago) and Point Salines (Grenada). Note that these plots only show a small subset of our entire data set which consists of two months of hourly data from eight locations. A plot of this larger data set is given in Appendix A.1.

From Figure 2, we may observe that Point Salines and Piarco wind speeds are correlated. Note also that there is more available data at Point Salines than at Piarco (see Figure 3). The kriging method of this paper allows (as an example) for the imputation of missing Piarco data by the use of data from Point Salines and other nearby weather stations. Furthermore, kriging allows for wind speed prediction at any location within the lower Caribbean region.

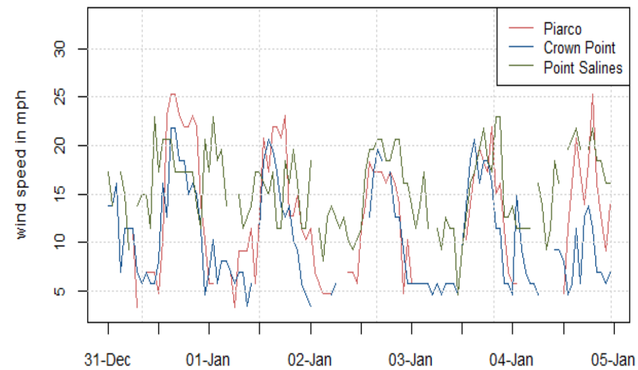

Figure 2. Five day subset of hourly wind speed observations (from a two month data set)

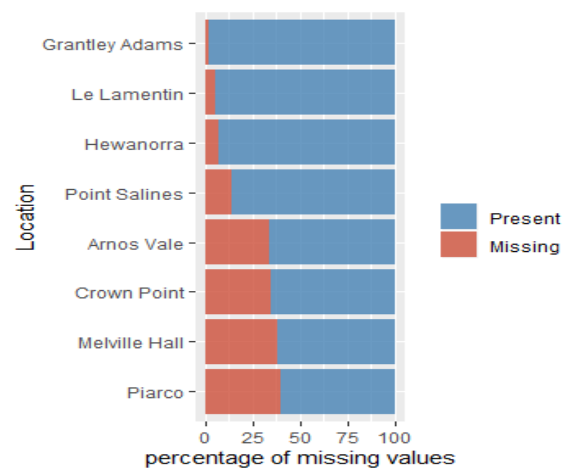

Figure 3. Percentages of missing values

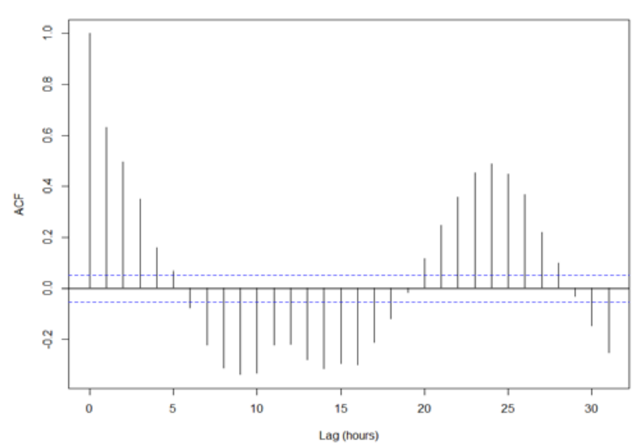

Figure 4. Sample autocorrelation function of Piarco wind speed data

The wind speeds illustrated in Figure 2 show a common diurnal cyclicity which is modelled by the use of temporal basis functions discussed in Section 2.3. A multivariate ARCH test (see (Tsay, 2013)) confirms that our wind speed data is heteroskedastic and so the data was log transformed in order to stabilise the variances; see (Paciorek *et al.*, 2009; Sampson *et al.*, 2011) for applications of spatio-temporal modelling with log transformed data.

2.2 Kriging

Let $D \subseteq \mathbb{R}^2$ be a domain in the plane and let $s \in D$ be a generic location. A *spatial random field* is a family of random variables which is indexed by the locations s in the domain D, see (Cressie, 1992). As an example, $Z(s)$ may model wind speeds at varying locations s at some fixed time.

$$\{Z(s): s \in D\} \quad (2)$$

The *expected value* $\mu(s) = E(Z(s))$ of the random field $Z(s)$ may vary with location s. The *covariance function* $C(s_i, s_j)$ of the random field $Z(s)$ is defined as

$$C(s_i, s_j) = E\left((Z(s_i) - \mu(s_i))(Z(s_j) - \mu(s_j))\right) \quad (3)$$

and measures the dependence of Z between different spatial locations s_i and s_j.

Consider the case for which Z may only be sampled at known locations $s_1, s_2, \ldots, s_n$ (for example, wind data will usually only be available at a few weather stations in a given region). *Kriging* is the determination of a best unbiased linear estimator of Z at an unknown location s_0 in terms of random variables $Z(s_i)$ at known locations. In the case of *simple kriging* (when the random field $Z(s)$ is second order stationary with known constant mean $\mu(s) = \mu$) then the estimator at an unknown location s_0 is

$$Z(s_0) = \sum_{i=1}^{n} \lambda_i Z(s_i) + \left(1 - \sum_{i=1}^{n} \lambda_i\right)\mu \quad (4)$$

where the *kriging weights* λ_i are obtained (see (Montero, Fernández-Avilés and Mateu, 2015)) by solving a linear system of n equations

$$\sum_{j=1}^{n} \lambda_j C(s_i, s_j) = C(s_i, s_0) \qquad i = 1, \ldots, n \quad (5)$$

with covariance coefficients. In the case of *universal kriging*, the mean $E(Z(s))$ is not assumed to be constant but is a linear combination of spatial functions $f_i(s)$. The kriging weights are again obtained from a linear system; see (Cressie, 1992). As an example, the functions $\beta_i(s)$ (used in our spatio-temporal model for wind speed given in Equation (1)) are spatial random fields with universal kriging structure in which the nonconstant means are assumed to be linear combinations of longitude and latitude.

A *spatio-temporal random field*

$$\{Z(s,t): s \in D, t \in T\} \quad (6)$$

is a family of random variables indexed by locations s in a spatial domain D and by times t in a time interval T. The development of spatio-temporal kriging is similar to the cases of (spatial) kriging above where time may be regarded as a spatial dimension with the caveat that the spatio-temporal covariance functions (used to determine kriging weights) consist of distinct spatial and temporal components; see (Wikle, Zammit-Mangion and Cressie, 2019) for further details. The determination of a suitable covariance structure of a spatio-temporal random field is first approached by calculating the *sample spatio-temporal semivariogram*

$$\hat{\gamma}(h,\tau) = \frac{1}{2|N(h,\tau)|} \sum_{N(h,\tau)} \left(Z(s_i,t_i) - Z(s_j,t_j)\right)^2 \quad (7)$$

where $N(h,\tau)$ is the set of pairs of spatio-temporal locations (s_i,t_i), (s_j,t_j) that satisfy $s_i - s_j = h$ and $t_i - t_j = \tau$; see (Montero, Fernández-Avilés and Mateu, 2015; Wikle, Zammit-Mangion and Cressie, 2019). The calculated semivariogram is then fitted to a suitable covariance model. A wire plot of a sample semivariogram of hourly wind speeds from the Caribbean wind data set is shown in Figure 5. The R code for obtaining the semivariogram and directional spatial semivariogram (discussed below) is shown in Appendix A.1. Note that the cyclicity along the time axis corresponds to alternating positive and negative correlation with varying time lags (Pyrcz and Deutsch, 2014); this is supported by the cyclic sample autocorrelation function shown in Figure 4.

The variability of wind speeds in the north/south and east/west directions may be examined with the use of a *directional* spatial semivariogram

$$\hat{\gamma}(h) = \frac{1}{2|N(h)|} \sum_{N(h)} \left(Z(s_i) - Z(s_j)\right)^2 \quad (8)$$

where $N(h)$ is the set of pairs of spatial locations that satisfy $s_i - s_j = h$ where the separation vectors h are partitioned into direction subsets; see (Pebesma, 2021). We first randomly sample 400 time instances from our spatio-temporal wind speed data frame and merge these into a single spatial data frame (with a time index) using the procedure from (Pebesma and Gräler, 2021). The directional spatial semivariogram shown in Figure 6 is formed by partitioning the direction vectors $h = s_i - s_j$ (for pairs of locations s_i, s_j) according to the directions of 0°, 45°, 90° and 135° that are measured clockwise from north. The direction h of a pair of locations is associated to the nearest of these four directions and so each point in the 45° panel in Figure 6 corresponds to a pair of locations with a relative direction that lies between 22.5° and 67.5°.

The variability shown in the 45° panel indicates that our wind data set contains information required to model variations in the northeast direction (each point in the

45° panel has a time resolution of 1391 hours). Variability in the east/west direction may also be examined by considering the variation of trend components with longitude as shown in Figure 9. This longitudinal trend is considered further in Section 2.3.

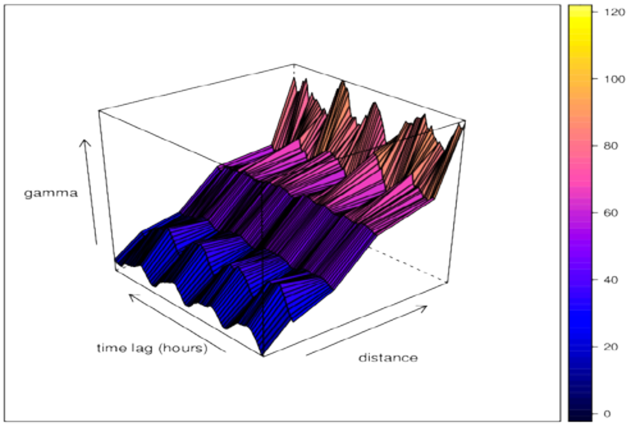

Figure 5. Sample semivariogram of hourly wind speeds from lower Caribbean data set during January and February 2015

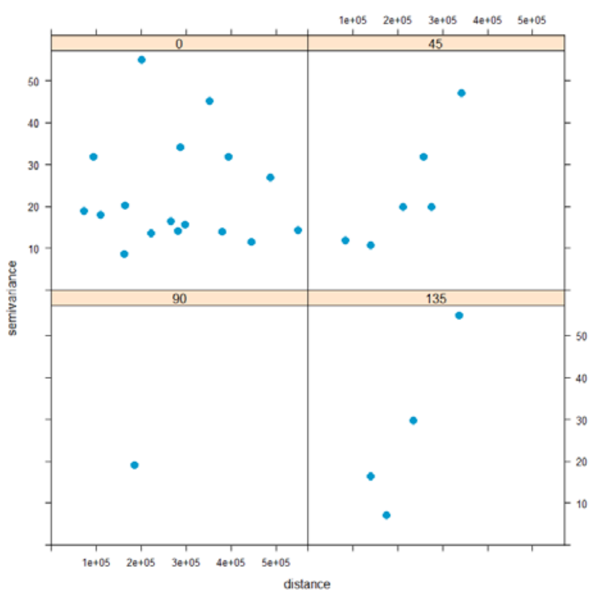

Figure 6. Directional spatial semivariogram of hourly wind speeds during January and February 2015

2.3 A Spatio-temporal Model

Wind speed $y(s,t)$ at location $s \in \mathbb{R}^2$ specified by longitude and latitude coordinates and time $t \in R$ is modelled as

$$y(s,t) = \sum_{i=1}^{m} \beta_i(s) f_i(t) + \nu(s,t) \qquad (9)$$

where $\{f_i(t)\colon i = 1, \ldots, m\}$ is a set of temporal basis functions with $f_1(t) \equiv 1$ and where $f_i(t)$ $(2 \le i \le m)$ are used to model non-stationary seasonal temporal behaviour. The basis functions $f_i(t)$ used in this paper are computed from incomplete data by using a singular value decomposition (Fuentes, Guttorp and Sampson, 2006; Lindström *et al.*, 2013). Other basis functions (Fourier, wavelet or Wendland) may be used (Wikle, Zammit-Mangion and Cressie, 2019). The number m of basis functions required to model temporal seasonality are determined by cross validation using the statistics AIC (Akaike information criterion), BIC (Bayesian information criterion), MSE (mean squared error) and R^2. A plot of these statistics (in the case of our Caribbean wind data) for an increasing number of basis functions is shown in Figure 7.

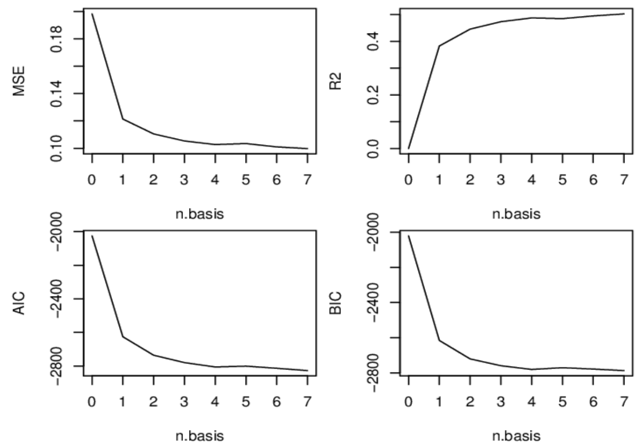

Figure 7. Facet plot of cross validation statistics for number of basis functions

In our case of strongly autocorrelated wind data together with persistent diurnal cyclicity (see the sample autocorrelation function in Figure 3), $m = 5$ temporal basis functions are used. A large number of basis functions is computationally impractical (particularly during cross validation) as parameter estimates are obtained by discrete optimisation routines. The basis functions are shown in Figure 8.

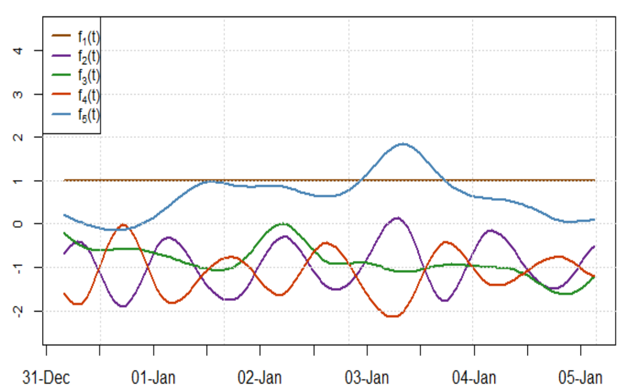

Figure 8. Temporal basis functions

The coefficients $\beta_i(s)$ in Equation (1) are spatial fields which allow for varying seasonal behaviour among sites. A plot of $\beta_1(s)$ versus latitude (at observed locations) together with a line of best fit is shown in Figure 8; these values are mean wind speeds as the corresponding temporal basis function $f_1(t) \equiv 1$. A similar plot of $\beta_1(s)$ versus longitude is shown in Figure 9. Figure 10 indicates a small latitudinal trend (which physically corresponds to a small decrease in wind speed with distance from the South American coast). It illustrates a significant longitudinal trend which corresponds to a nontrivial increase in mean wind speed in the eastern direction. This longitudinal trend is present in the wind speed predictions shown in Figure 12.

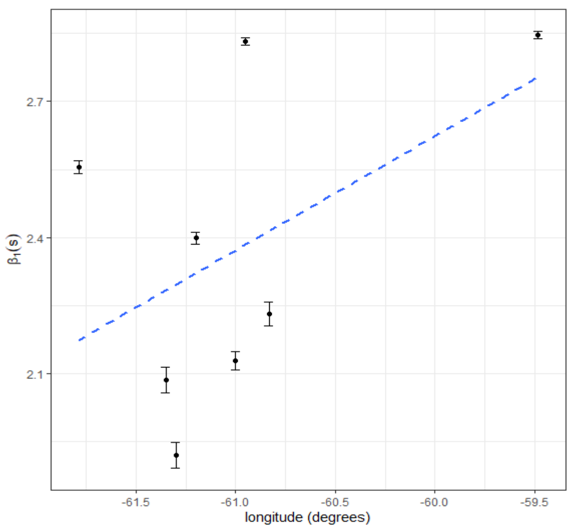

Figure 9. Longitudinal trend of spatial field   estimates at station locations (with   confidence intervals) together with a line of best fit

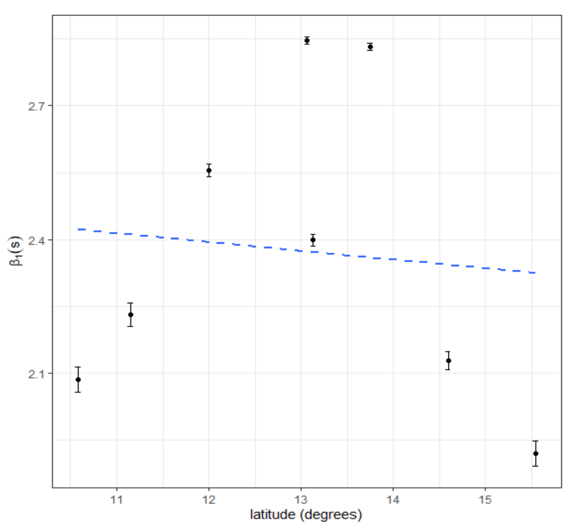

Figure 10. Latitudinal trend of spatial field estimates at station locations (with confidence intervals) together with a line of best fit

A covariate structure of the form

$$\beta_1(s) = a_1 + b_1 x + c_1 y + \eta(s) \tag{10}$$

where $s = (x,y)$ and x,y represent longitude and latitude indicates that the trend component of the spatial field $\beta_1(s)$ is modelled as a linear function. Similar plots of $\beta_i(s)$ ($i = 2 \ldots 5$) versus both latitude and longitude are used to determine suitable covariate structures of the $\beta_i(s)$. The use of geographic covariates is called land use regression; see (Lindström et al., 2013). In this way, values of $\beta_i(s)$ at unobserved locations may be determined by universal kriging with longitude and latitude as spatial covariates and where the covariance functions $\mathrm{cov}(\beta_i(s), \beta_i(s + h))$ are exponential. In our case, a nugget effect is assumed for the covariance models of $\beta_i(s)$.

Initial parameter estimates for these covariance functions are required for an optimisation procedure which determines the parameters of the spatio-temporal model (1). A fitted spatio-temporal model may be used to either predict wind speeds at unobserved locations or to interpolate missing data at observed locations. The former necessitates an initial grid which specifies the space and time coordinates for which we require wind speed predictions.

The spatio-temporal random field in the model (1) is assumed to be a zero mean Gaussian field which is spatially correlated but independent in time. It is used to model short-term random effects (not captured by the temporal basis functions) which affect medium to large spatial regions; see (Lindström et al., 2013).

$$v(s,t) \sim N\left(\underline{0}, \begin{bmatrix} \sum_{v}^{1} & \underline{0} & \underline{0} \\ \underline{0} & \ddots & \underline{0} \\ \underline{0} & \underline{0} & \sum_{v}^{T} \end{bmatrix}\right) \tag{11}$$

In this paper, the covariance function $c(h,\tau)$ of $v(s,t)$ is assumed to be exponential with a nugget effect, that is

$$c(h,\tau) = c_0(1 - \delta(h)) + b\exp\left\{-\frac{\|h\|}{a}\right\} \tag{12}$$

where $h \equiv s' - s$, $\tau \equiv t' - t$, c_0 is the magnitude of the discontinuity at the origin, δ is the Dirac delta function, $b > 0$ is a variance parameter and $a > 0$ is a scale parameter (Wikle, Zammit-Mangion and Cressie, 2019; Hristopulos, 2020). Note that right of Equation (12) is independent of τ as $v(s,t)$ is assumed to be temporally uncorrelated.

2.4 Implementation

We briefly discuss the implementation of the model (1) to our data set in the programming language R. The CSV data for each weather station was converted to an xts time series with POSIXct indices. xts objects are particularly useful and allow for the manipulation of irregularly spaced time series, interpolation of missing data, conversion of time zones, aggregation and merging of time series (Zhang, 2016). In our case, data from the various stations are collectively stored in a space-wide (Bivand *et al.*, 2008) xts object which has some missing data (see Figure 3). This data was used to form a STdata object with longitude and latitude covariates originating from the weather station locations. The temporal basis functions $f_i(t)$ and corresponding spatial fields $\beta_i(s)$ were then determined from this STdata object. Plots of these spatial fields (see Figure 8 for example) were used to specify their spatial covariates. A STmodel was then initialised from the wind STdata object, the covariance functions for the residual field $v(s,t)$ and spatial fields $\beta_i(s)$ together with their spatial covariates.

Initial values were then provided for the estimation of the parameters of the STmodel via optimisation. The fitted spatio-temporal model was used to predict wind speed on a three dimensional (two spatial and one temporal) grid which was constructed as a STdata object. In order to display these predictions, raster map tiles for the lower Caribbean were obtained from (Stamen Maps, 2021) via the R package ggmap. The predictions are then superimposed as a contour plot on the Caribbean map using the geom_point and geom_contour functions. A flowchart of our procedure is shown in Figure 11.

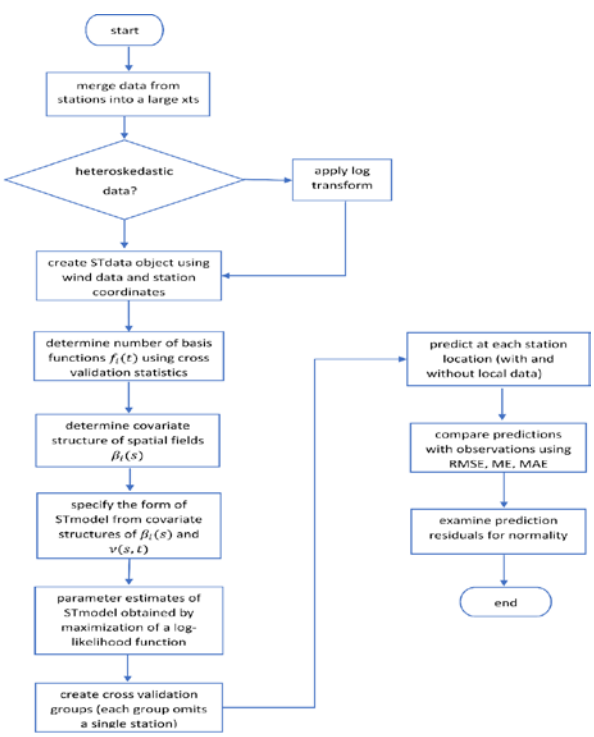

Figure 11. Procedure for predicting and validating wind speeds using the model (1)

3. Results

3.1 Spatial Prediction

Once the structure of the spatio-temporal model (1) is specified (see Section 2.3), its parameters are determined by likelihood estimation by calling the R function optim. The fitted model may then be used for spatial prediction, that is, the model may be used to predict at locations which have no measurement data. A 100 x 100 spatial grid of points was constructed within a bounding box between W57°, W67.2°, N5.8° and N15.7°. An hourly temporal sequence was also specified between midnight and noon of January 1 2015; note however that we may spatially predict at any time within the window of our measurement data. These spatial and temporal objects were combined into a STdata object (Lindström *et al.*, 2013) and the fitted model was used to predict wind speed at each point on this spatio-temporal grid. Contour plots of these predicted wind speeds at midnight and noon respectively are shown in Figure 12. The larger wind speeds at midnight are consistent with the diurnal cyclicity exhibited in Figure 2.

The contour topology also agrees with the direction of the north east trade winds which decrease as they move over the South American continent.

3.2 Imputation

Classical imputation methods only use temporal information (Yang *et al.*, 2018) to construct a time series model (such as ARIMA, support vector regression or hidden Markov models) which is then used to estimate missing values. Kriging utilises additional spatial information by taking a linear combination of nearby observations which is weighted according to covariance values (which depend on distance). Recall that our Caribbean wind observations have substantial missing data. As an example, we consider the Crown Point data set in late February 2015. These incomplete observations are plotted in red in Figure 13.

Recall from Figure 3 that more data is available at nearby Point Salines and Grantley Adams. The estimation of the spatio-temporal model (1) determines a collection of daily temporal trends $\{f_i(t)$: $i = 1,\ldots 5\}$ using data from all locations. These temporal trends are then weighted by the spatial fields $\{\beta_i(s)$: $i = 1,\ldots 5\}$. The evaluation of these spatial fields at the Crown Point location $s = s_0 = (x_0, y_0)$ determines the trend component of the predicted wind speed at Crown Point. The trend component for our Crown Point example is shown in green in Figure 13.

The component $v(s,t)$ of spatio-temporal model (1) interpolates the variation of wind speed observations from the trend component. The addition of the component $v(s,t)$ to the trend component results in the imputed (i.e. predicted) wind speeds illustrated in black in Figure 13. The variances of these predictions are used to form a confidence band for the predictions; this is

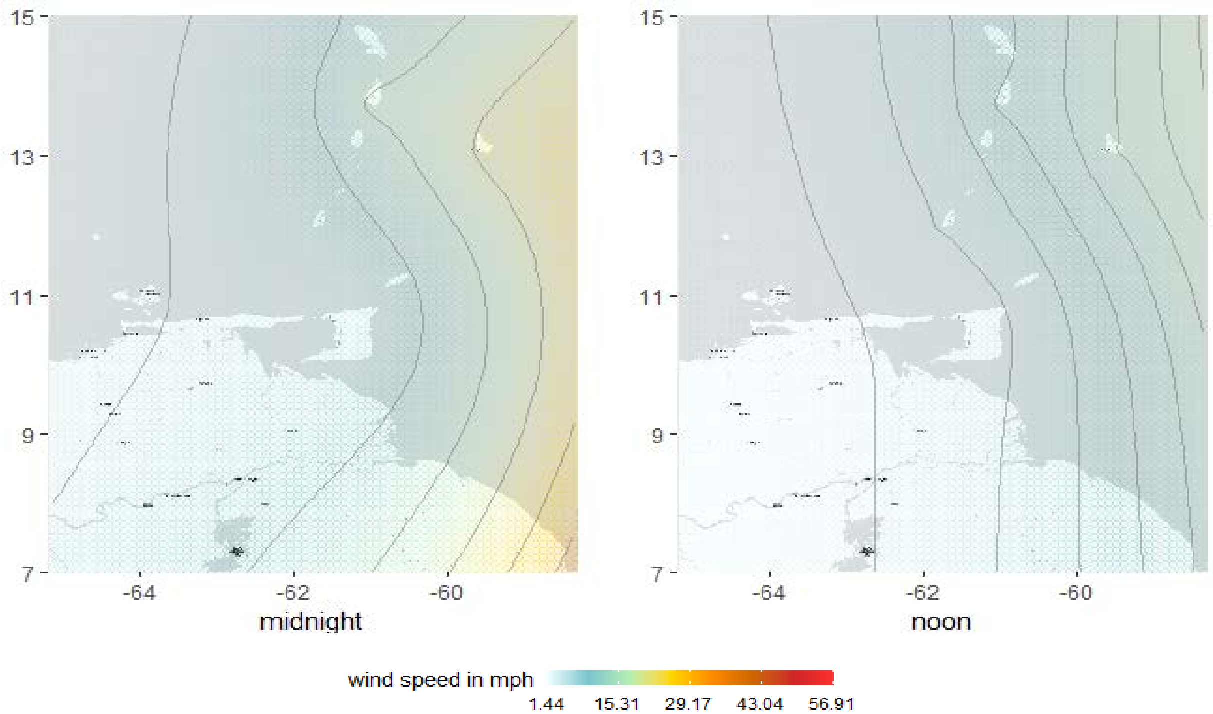

Figure 12. Facet plot of wind speeds in the lower Caribbean on January 1 2015. The left and right panes show wind speeds at midnight and noon respectively.

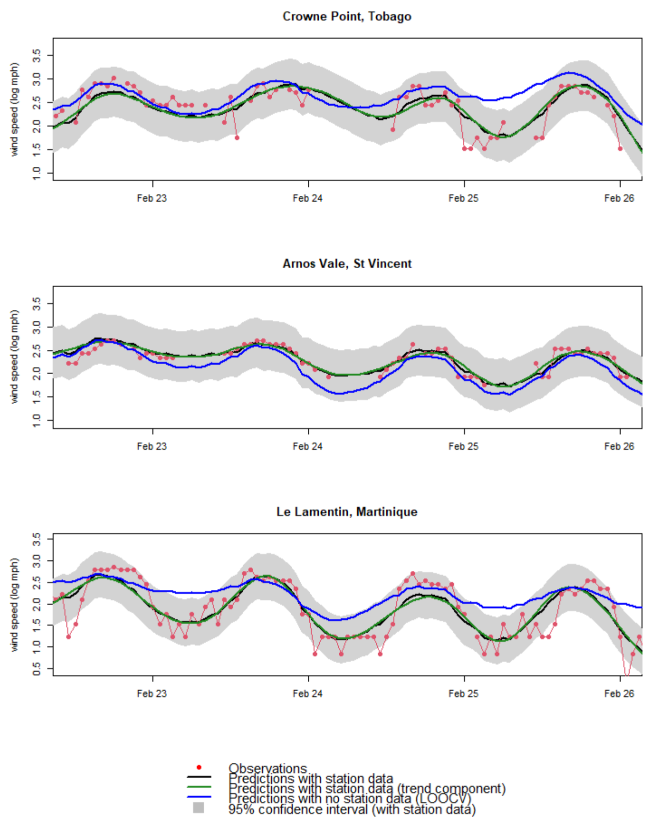

Figure 13. Imputation with validation of Crown Point logarithmic wind speed observations in late February 2015

illustrated as the grey areas in Figure 13.

3.3 Validation

Cross-validation is a method of assessing the predictive ability of a model by partitioning the available observations into *training sets* (used to estimate the parameters of the model) and *test sets*. The estimated model is used to form predictions at the locations of the test sets and so predictions may be compared with actual observations. Our case study is assessed by the use of eight cross-validation groups where the i^{th} group consists of all reference locations except location i. The spatio-temporal model (1) is estimated using training data from the seven locations in the i^{th} group and then used to predict wind speeds at location i. These predictions are then compared to the known test data at location i. Figure 13 shows results from three of the eight cross-validation groups. As an example, the blue plot in the Crown Point panel indicates predictions using data from all locations except Crown Point.

The red plot shows actual observations at Crown Point. As may be seen from this panel, the blue predictions are reasonable estimates which capture the cyclicity of the actual observations in red. However, there is a small bias caused by inaccurate estimation of the spatial coefficients $\beta_i(s)$ of the trend component.

Let $y_t, \hat{y}_t$ denote the observed and predicted values of wind speed at a fixed location and time t. The residuals

$$e_t = y_t - \hat{y}_t \tag{13}$$

are used to form accuracy measures of prediction models (Hyndman and Athanasopoulos, 2018). One such measure is the root mean squared error RMSE which is defined as

$$RMSE = \sqrt{\frac{\sum_{t=1}^{N} e_t^2}{N}} \tag{14}$$

where N is the number of observations. Other accuracy measures include the mean error (ME), mean absolute error (MAE), Pearson correlation coefficient and percent bias (Zambrano-Bigiarini, 2014). The accuracy measures in Table 1 show (as expected) that the predictions at Crown Point are improved when local data is available. Note that these measures indicate that predictions at Crown Point are meaningful even if no local data is used.

Table 1. Comparison of predictions with/without Crown Point (CP) data using goodness of fit measures

Measures	with CP data	without CP data
ME	0.0003	0.3155
MAE	0.2513	0.3654
RMSE	0.3302	0.4886
Pearson	0.7301	0.6505
Percent bias	0	13.4

The validity of our wind speed predictions is dependent on the assumption that the residual field $v(s,t)$ of our spatio-temporal model (1) is normally distributed. A check for normality of residuals may be done via a quantile-quantile (Q-Q) scatter plot which is obtained by plotting sample quantiles against theoretical quantiles of a normal distribution. For normal residuals, these points are expected to lie along a straight line. From the Q-Q plots in Figures 14 and 15, we see that the assumption of normal residuals is reasonable with or without the use of local Crown point data.

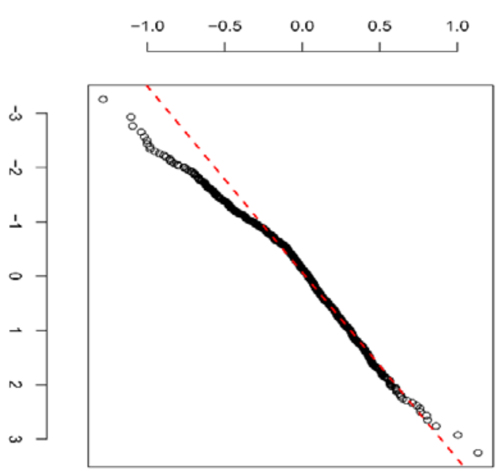

Figure 14. Q-Q plot of residuals of prediction with Crown Point data

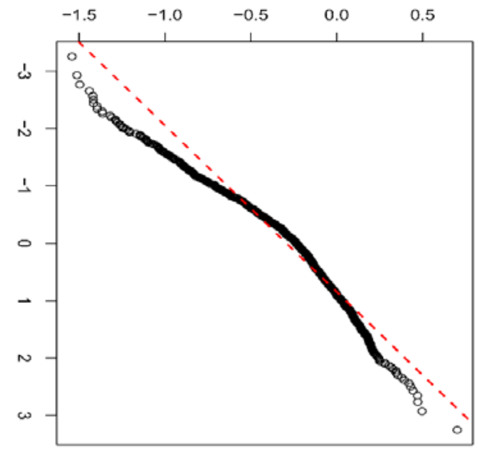

Figure 15. Q-Q plot of residuals of prediction without Crown Point data

4. Conclusion and Future Work

The particular kriging method used in this paper is suitable for imbalanced, trending data. Predictions are more accurate at locations which have some data points as these allow for better estimates of the local trend function. However, we have seen that estimates are still meaningful at locations with no data.

Predictions obtained from our spatio-temporal model given in equation (1) may be possibly improved by the use of a more general model.

$$y(s,t) = \sum_{l=1}^{L} \gamma_l M_l(s,t) + \sum_{i=1}^{m} \beta_i(s) f_i(t) + v(s,t) \tag{15}$$

which now includes exogenous spatio-temporal covariates $M_l(s,t)$ (see Lindström *et al.*, 2013). It is feasible that pressure and temperature covariates may improve our wind speed predictions (Şen, 1997); note also that pressure and temperature data are typically available in METAR records. Surface roughness and elevation are other (non-temporal) covariates which may be used although roughness data is less readily available (Wever and Groen, 2009). The use of roughness and elevation data may necessitate the use of bridges between R and geographic information software (GIS) (Lovelace, Nowosad and Muenchow, 2019).

Furthermore, the METAR data used in the paper may be supplemented with the ERA5-Land hourly dataset (CDS, 2021) which has a spatial horizontal resolution of 9 km. Finally, as direction may be numerically specified in degrees, our kriging method may also estimate wind directions which can then be combined with wind speed estimates to obtain velocity predictions.

.

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Appendix A: R code for case study

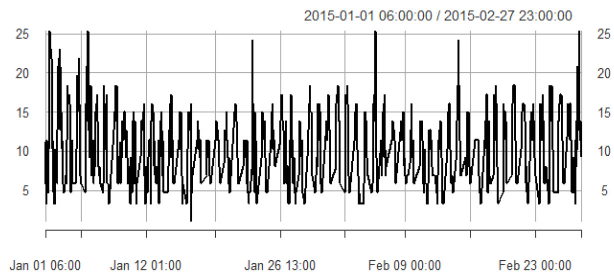
A.1 Data acquisition, processing and preliminary analysis

```
Sys.setenv(TZ='UTC')
library(pacman)
pacman::p_load("rnoaa","readxl","dplyr","lubridate","stringr","xts","zoo","tidyr","knitr")
stations_near_Trinidad = isd_stations_search(lat = 10.6918, lon = -61.2225, radius = 600, bbox = NULL)
knitr::kable(head(select(stations_near_Trinidad,usaf,wban,station_name,icao,lat,lon)))
```

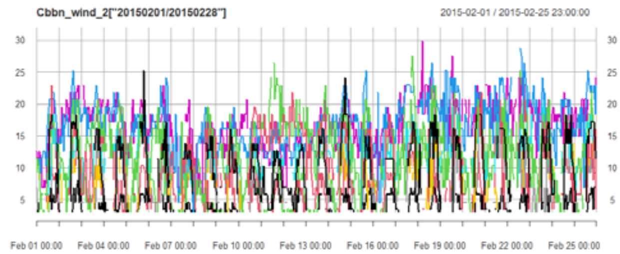
usaf	wban	station_name	icao	lat	lon
999999	11610	WALLER BWI		10.617	-61.217
789700	99999	PIARCO	TTPP	10.595	-61.337
789700	11634	PIARCO INTL AP	TTPP	10.583	-61.350
749040	99999	TOCO		10.833	-60.933
749041	99999	CHICKLAND		10.400	-61.400
999999	11621	TRINIDAD BWI	MCGU	10.683	-61.617

```
#first six rows of data frame of weather stations within 600 km of Trinidad
#contains usaf and wban numbers for each station

Piarco_noaa <- isd(usaf="789700", wban="11634", year=2015)
# download Piarco weather data (for year 2015) from NOAA site
write.csv(Piarco_noaa, file="Piarco1.csv")
Piarco <- read.csv("Piarco1.csv", stringsAsFactors = FALSE,colClasses=c("NULL", "NULL", "NULL", "NULL",NA,NA,"NULL", "NULL","NULL", "NULL", "NULL", "NULL","NULL", NA,NA,NA,NA,NA,NA))
Piarco <- Piarco[c(1,2,3,4,6,7)]
Piarco$time <- formatC(Piarco$time, flag = 0, width = 4)
Piarco$date <- formatC(Piarco$date)
```

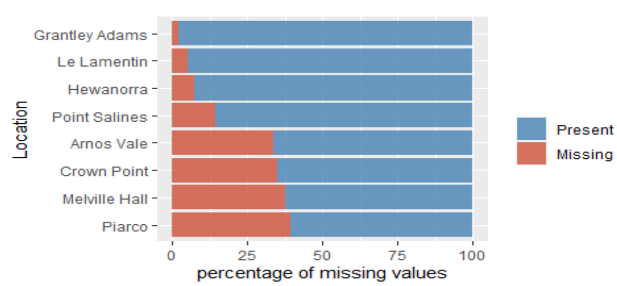
```
Piarco<-unite(Piarco, date_time, c(date,time), sep=":")
Piarco$date_time<-as.POSIXct(strptime(Piarco$date_time,for
mat = "%Y%m%d:%H%M",tz="UTC"))
Piarco$wind_direction[ Piarco$wind_direction == 999] <-NA
# 999 represents NAs
Piarco<-drop_na(Piarco)
Piarco$wind_speed<-as.numeric(Piarco$wind_speed)*(2.237/1
0)
# noaa wind speed is in m/s and scaled by 10
Piarco_speed<-Piarco[c(1,4)]
boxplot(Piarco_speed$wind_speed)$out
outliers <- boxplot(Piarco_speed$wind_speed, plot=FALSE)$o
ut outliers<-outliers[outliers >30]
# remove outliers
Piarco_speed <- Piarco_speed[-which(Piarco_speed$wind_spe
ed  %in% outliers),]
# convert Piarco_Speed from data frame to xts
Piarco_speed_xts<-xts(Piarco_speed[,-1], order.by = as.POSIX
ct(Piarco_speed$date_time))
plot(Piarco_speed_xts["20150101/20150227"],main=NULL)
```



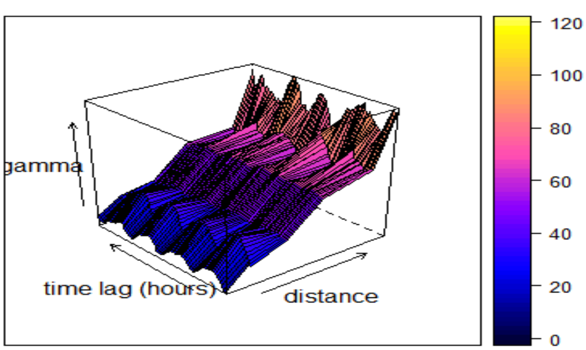

```
 # plot of Piarco wind speeds for Jan 1 2015 to Feb 27 2015
#similar data processing done for other stations and data from
Iowa Mesonet

# merge data from all stations into a single xts
All_stations<-merge(Piarco_speed_xts,Crown_point_Tobago_
xts,Point_Salines_Grenada_xts,Grantley_Adams_Barbados_xts
,Arnos_Vale_St_Vincent_xts,Hewanorra_St_Lucia_xts,Maturi
n_VZ_xts,Cheddi_Jagan_xts,
Simon_Bolivar_xts,Melville_Hall_xts,Le_Lamentin_xts,join="
outer")
#remove the rows with duplicated indices
All_stations<-All_stations[!duplicated(index(All_stations))]
#remove rows with all NAs
All_stations<-All_stations[rowSums(is.na(All_stations)) != nco
l(All_stations),]
# saveRDS(All_stations, file = 'All_stations.Rds')
Cbbn_wind <- readRDS('All_stations.Rds')
Cbstart="2015-01-01 00:00:00";Cbend="2015-02-25 23:00:00"
Cbbn_wind<-Cbbn_wind[paste(Cbstart,"/",Cbend,sep="")]
#truncate dataset to first two months
Cbbn_wind_2<-Cbbn_wind[seq(from=as.POSIXct(Cbstart, tz=
"UTC"),
to=as.POSIXct(Cbend, tz="UTC"),by="hour" )]
# remove observations that occurred at half hours as such obse
rvations
# only occurred at Le Lamentin
plot(Cbbn_wind_2["20150201/20150228"],ylim=c(3,32))
```



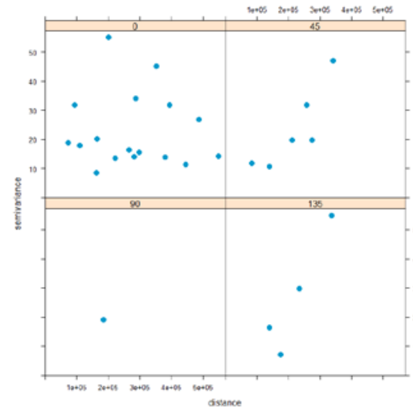

```
# plot of wind speeds from 11 stations from Feb 1 2015 to Feb
28 2015

# MISSING VALUES DIAGRAM
Cbbn_wind<-Cbbn_wind[,c(1:6,10,11)]
names(Cbbn_wind)<-c("Piarco", "Crown Point","Point Salines
","Grantley Adams",
   "Arnos Vale","Hewanorra", "Melville Hall", "Le Lamentin")
 Cbstart="2015-01-01 00:00:00";Cbend="2015-02-26 23:00:00
"
 Cbbn_wind_2<-Cbbn_wind[seq(from=as.POSIXct(Cbstart, tz
="UTC"),
                 to=as.POSIXct(Cbend, tz="UTC"),by="hour" )]
 Cbbn_wind_3<-as.data.frame(Cbbn_wind_2)

 mvals <- Cbbn_wind_3 %>%
   gather(key = "key", value = "val") %>%
   mutate(isna = is.na(val)) %>%
   group_by(key) %>%
   mutate(total = n()) %>%
   group_by(key, total, isna) %>%
   summarise(num.isna = n()) %>%
   mutate(pct = num.isna / total * 100)

 levels <-
   (mvals  %>% filter(isna == T) %>% arrange(desc(pct)))$key

  pplot<- mvals %>%
   ggplot() +
   geom_bar(aes(x = reorder(key, desc(pct)),
              y = pct, fill=isna),
          stat = 'identity', alpha=0.8) +
    scale_x_discrete(limits = levels) +    scale_fill_manual(name
 = "",
           values = c('steelblue', 'tomato3'), labels = c("Present", "
Missing")) +
   coord_flip() +
   labs(title = "", x =
         'Location', y = "percentage of missing values")
 pplot
```



```
# test for Heteroskedasticity  (Tsay page 406)
MarchTest(as.matrix(na.spline(Cbbn_wind_2)))
## Q(m) of squared series(LM test):
## Test statistic:  593.7194  p-value:  0
## Rank-based Test:
## Test statistic:  1403.636  p-value:  0
## Q_k(m) of squared series:
## Test statistic:  21008  p-value:  0
## Robust Test(5%) :  19562.9  p-value:  0

# sample variogram
Cbbn_wind <- readRDS('All_stations.Rds')
Cbstart="2015-01-01 00:00:00";Cbend="2015-12-31 23:00:00"
Cbbn_wind<-Cbbn_wind[seq(from=as.POSIXct(Cbstart, tz="
UTC"),
     to=as.POSIXct(Cbend, tz="UTC"),by="hour" )]
Cbbn_wind <- Cbbn_wind[,1:7]
Cbbn_df<- data.frame(time=index(Cbbn_wind), coredata(Cbbn
_wind))
stations <- c("Piarco", "Crown Point","Point Salines","Grantley
 Adams",           "Arnos Vale","Hewanorra","Maturin")
lat<-c(10.583,11.150,12.004,13.067, 13.133,13.750,9.749)
lon<-c(-61.350,-60.833,-61.786,-59.483,-61.200, -60.950, -63.1
53)
Ccrds<-data.frame(stations,lon,lat)
coordinates(Ccrds) = ~lon+lat
proj4string(Ccrds) = "+proj=longlat +datum=WGS84"
Cpts = coordinates(Ccrds)
rownames(Cpts) = Ccrds$stations
Cpts = SpatialPoints(Cpts, CRS("+proj=longlat +datum=WGS
84 +ellps=WGS84"))
utm20 = CRS("+proj=utm +zone=20,21 +datum=WGS84 +ellp
s=WGS84")
Cpts = spTransform(Cpts, utm20)
Cwind.data = stConstruct(as.matrix(Cbbn_df[,2:8]), space = lis
t(values = 1:ncol(Cbbn_wind)),
        time = Cbbn_df[,1], SpatialObj = Cpts, interval = TRUE)
vargmCbbn<-variogramST(values~1,Cwind.data[, "20150101/
20150107"],tlags=0:100, cutoff=2000000,na.omit=TRUE)
plot(vargmCbbn,wireframe=TRUE)
```

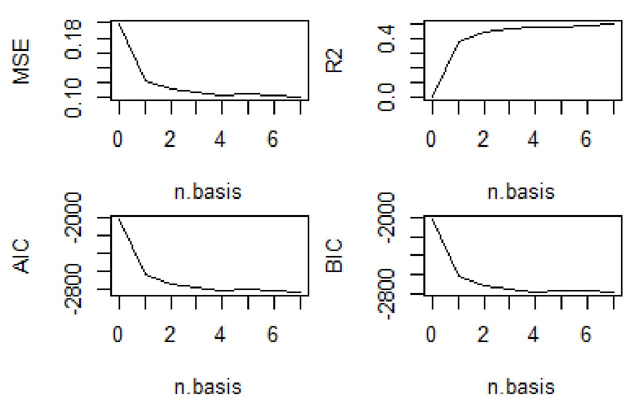



```
# directional variogram
time_samples = sample(dim(Cwind.data)[2], 400)
lst2 = lapply(time_samples, function(i) { x = Cwind.data[,i]; x
$ti = i; rownames(x@coords) = NULL; x} )
pts2 = do.call(rbind, lst2)
v1.dir = variogram(values~ti, pts2[!is.na(pts2$values),], dX=0,
width=50,cutoff=2000000,alpha = c(0, 45, 90, 135))
plot(v1.dir,as.table = TRUE,pch=19, col="deepskyblue3", cex=
1.3)
```

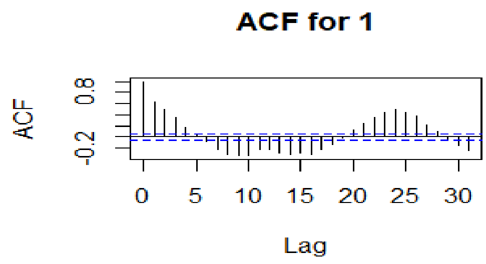


A.2 Estimation, prediction and validation

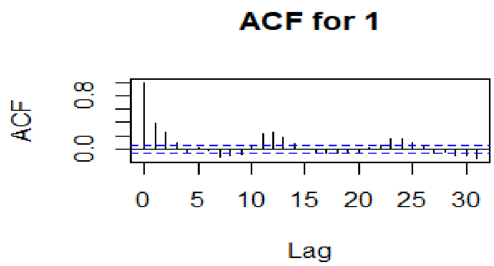
```
# use logs because of heteroskedasticity
Cbbn_wind<-log(Cbbn_wind)
# use two months of hourly data
Cbstart="2015-01-01 00:00:00";Cbend="2015-02-25 23:00:00"

Cbbn_wind<-Cbbn_wind[paste(Cbstart,"/",Cbend,sep="")]
#truncate dataset

Cbbn_wind_2<-Cbbn_wind[seq(from=as.POSIXct(Cbstart, tz=
"UTC"), to=as.POSIXct(Cbend, tz="UTC"),by="hour" )]
# remove observations that occurred at half hours as such obse
rvations
# only occured at Le Lamentin

Cbbn_wind_2_core <-coredata(Cbbn_wind_2)
Cbbn_wind_daily_xts <- xts(Cbbn_wind_2_core,seq(as.Date("
2015-01-01"), length=nrow(Cbbn_wind_2), by="days"))
Cbbn_wind_matrix2<-as.matrix(Cbbn_wind_daily_xts)
Cbbn_STdata<- createSTdata(Cbbn_wind_matrix2, covars = C
crds)

# facet plot of change in AIC, MSE, BIC, R^2 with n.basis
D <- createDataMatrix(Cbbn_STdata)
CV_facet<- SVDsmoothCV(D, 0:7)
plot(CV_facet)
```



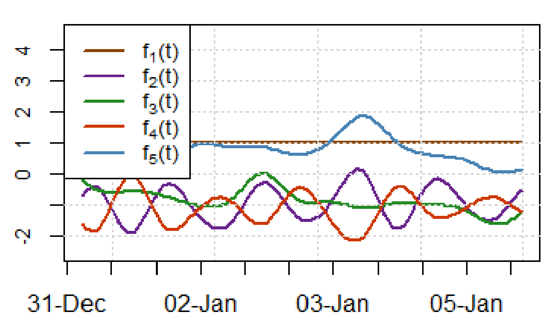

```
# Piarco acf before trend removal
plot(Cbbn_STdata, "acf", ID = "1")
```



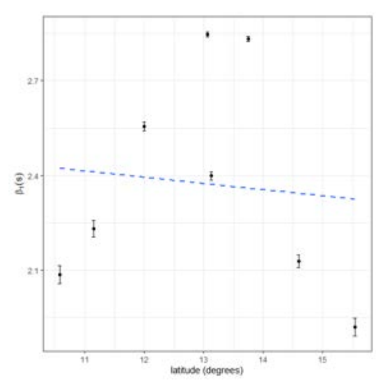

```
Cbbn_STdata <- updateTrend(Cbbn_STdata, n.basis = 4)

# Piarco acf after trend removal
plot(Cbbn_STdata, "acf", ID = "1")
```




```
#plot of five basis functions
Cbbn_STdata_trend_xts <- xts(Cbbn_STdata$trend,seq(as.POS
IXct("2014-12-31 20:00:00"), length=nrow(Cbbn_STdata$tren
d), by="hour"))
col_ones_xts<-xts(rep(1, nrow(Cbbn_STdata$trend)),seq(as.P
OSIXct("2014-12-31 20:00:00"), length=nrow(Cbbn_STdata$t
rend), by="hour"))
Cbbn_STdata_trend_xts<-cbind(col_ones_xts,Cbbn_STdata_tr
end_xts)
tt <- time(Cbbn_STdata_trend_xts)[seq(1, length(Cbbn_STdata
_trend_xts), by = 12)]
cols <- c( "darkorange4" ,"darkorchid4","forestgreen","oranger
ed3","steelblue")
plot(as.zoo(Cbbn_STdata_trend_xts["20150101/20150105",c(1
:5)]),col = cols,
    screens = 1,ylim=c(-2.5,4.5),ylab="",xlab="",cex.axis=0.8,c
ex.lab=0.85,cex.main=0.95,
    main="",xaxt="n",lwd=2 ,font.main = 1 )
grid()
legend(x = "topleft", legend = c(TeX('$f_1(t)$'),TeX('$f_2(t)$')
, TeX('$f_3(t)$'),TeX('$f_4(t)$'), TeX('$f_5(t)$')),lty = 1,col =
cols,pt.cex = 1,cex=0.9,bg="white",lwd=2 )
axis(1, tt,format(tt, '%d-%b'),las=1)
```

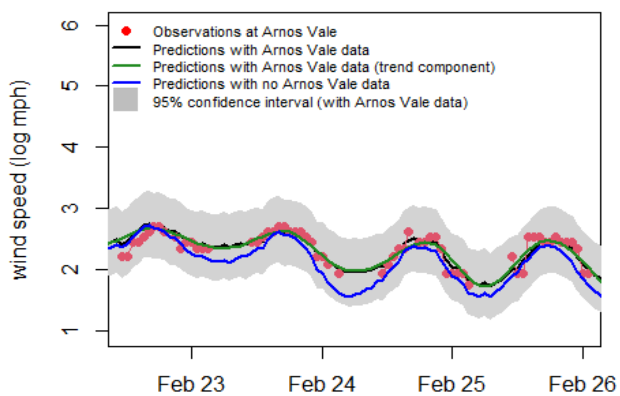



```
beta_fields <- estimateBetaFields(Cbbn_STdata)
row.names(beta_fields$beta)
beta_fields$beta <- data.frame(beta_fields$beta)
beta_fields$beta.sd <- data.frame(beta_fields$beta.sd)
beta_fields$beta$ID <- row.names(beta_fields$beta)

# using five basis funtions
merged_beta <- cbind(beta_fields$beta[,1:5], beta_fields$beta$
ID,beta_fields$beta.sd[,1:5])
#using first 4 columns of merged_beta etc
colnames(merged_beta) <- c("alpha1", "alpha2", "alpha3", "alp
ha4",
          "alpha5", "ID",
          "alpha1_CI", "alpha2_CI", "alpha3_CI", "alpha4_CI",
          "alpha5_CI" )
merged_beta <- left_join(merged_beta, Ccrds, by = "ID")


ggplot(merged_beta) + geom_point(aes(x = lat, y = alpha1)) +
    geom_smooth(aes(x = lat, y = alpha1),method = "lm", se =
FALSE, linetype=2)+
  geom_errorbar(aes(x = lat,
          ymin = alpha1 - 1.96*alpha1_CI,
          ymax = alpha1 + 1.96*alpha1_CI)) +
  ylab(expression(beta[1](s))) +
  xlab("latitude (degrees)") + theme_bw()
```

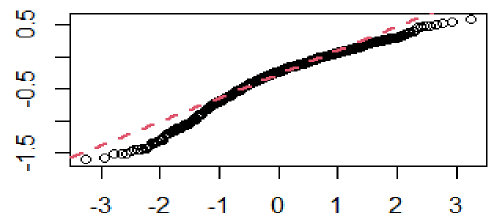



```
# beta1 essentially shows mean wind speed at each station
lcbeta <- list(covf = "exp", nugget = TRUE)
c_nu <- list(covf = "exp",nugget = ~1,random.effect = FALSE)

locations <- list(coords = c("lon", "lat"))

# land_use in the case of four basis function (well five when co
nstant is included)
land_use <- list(~lat + lon, ~lat, ~lat , ~1 , ~1)
STmodel <- createSTmodel(Cbbn_STdata, LUR = land_use, co
v.beta = lcbeta,
            cov.nu = c_nu, locations = locations)
# init_ in the case of four basis functions
init_ <- matrix(1, 18, 1)
SpatioTemporalfit1 <- estimate(STmodel, init_)
pred_Cbbn <- predict(STmodel, SpatioTemporalfit1, pred.var=
TRUE)
# LOOCV cross validation
CV_groups <- createCV(STmodel, groups=8)   # this will crea
te 8 groups each omitting a single station
init_ <- coef(SpatioTemporalfit1, pars="cov")[,c("init")]
est.cv.STmodel <- estimateCV(STmodel, init_, CV_groups)
pred.cv.STmodel <- predictCV(STmodel, est.cv.STmodel, LT
A=TRUE)
```

```
par(mfrow=c(1,1))
plot(pred_Cbbn, ID=5, main="", font.main=1,
    xlab="", ylab="wind speed (log mph)", xaxt="n",
    xlim=as.Date(c("2016-10-20","2017-01-12")),
    ylim=c(0.95,6), pch=NA, pred.var=TRUE,STmodel=STmo
del,
    lty=NA, col=c(1,1,"lightgrey"))
plot(pred_Cbbn, ID=5, STmodel=STmodel, add=TRUE,
    lty=c(1,1),lwd=c(2,1), pch=c(NA,16),  cex=c(1.2,1),col=c(1
,2,NA))
axis.Date(1, at=rev(seq(as.Date("2017-01-12"), length=4, by="
-24 days")),labels=c("Feb 23","Feb 24","Feb 25","Feb 26"))
plot(pred_Cbbn, ID=5, STmodel=STmodel, add=TRUE,
    pred.type = "EX.mu.beta", lwd=2, col="forestgreen")
legend("topleft", c("Observations at Arnos Vale",
           "Predictions with Arnos Vale data",
           "Predictions with Arnos Vale data (trend component)",
           "Predictions with no Arnos Vale data",
           "95% confidence interval (with Arnos Vale data)"), bt
y="n",
      lty=c(NA,1,1,1, NA), lwd=c(NA,2,2,2, NA),
      pch=c(16,NA,NA,NA,15), pt.cex=c(1,1,NA,NA,2.5),
      col=c("red", 1,"forestgreen","blue", "grey"),cex=0.7)
plot(pred.cv.STmodel, ID="5",add=TRUE,col="blue",lwd=2)
# blue curve obtained from LOOCV
```

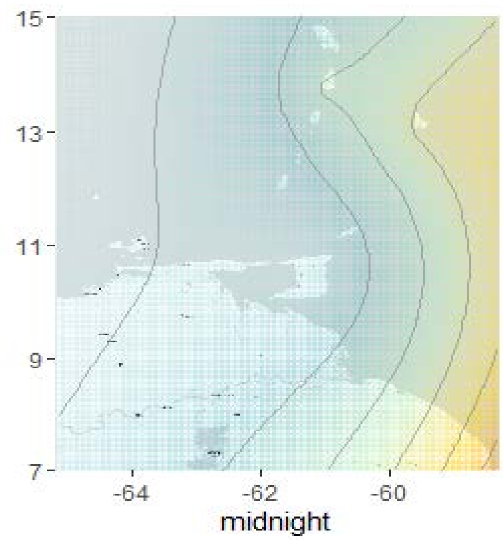



```
rmse(as.vector(pred_Cbbn[["EX"]][,2]),as.vector(Cbbn_wind_
daily_xts[,2]),na.rm=TRUE)
#    package:  hydroGOF
## [1] 0.3335035
TEMP<- pred.cv.STmodel[["pred.obs"]][pred.cv.STmodel[["pr
ed.obs"]]$ID=="2",]  #restrict to ID=2
rmse(as.vector(TEMP$EX),as.vector(TEMP$obs),na.rm=TRU
E)
# actually no need for na.rm here as STDF stripped missing val
ues
## [1] 0.4986291
mae(as.vector(pred_Cbbn[["EX"]][,2]),as.vector(Cbbn_wind_d
aily_xts[,2]),na.rm=TRUE)
mae(as.vector(TEMP$EX),as.vector(TEMP$obs),na.rm=TRUE
)

me(as.vector(pred_Cbbn[["EX"]][,2]),as.vector(Cbbn_wind_da
ily_xts[,2]),na.rm=TRUE)
me(as.vector(TEMP$EX),as.vector(TEMP$obs),na.rm=TRUE)
 rPearson(as.vector(pred_Cbbn[["EX"]][,2]),as.vector(Cbbn_wi
nd_daily_xts[,2]),na.rm=TRUE)
rPearson(as.vector(TEMP$EX),as.vector(TEMP$obs),na.rm=T
RUE)

# QQ plots for residuals

qqnorm(TEMP$res,main="",cex.main=1.5,cex.lab=1.5,xlab=""
, ylab="")  #without Crown Point data
qqline(TEMP$res, col = 2,lwd=2,lty=2)
```




```
## Define space-time grid
spat_pred_grid <- expand.grid(lon = seq(-67.2, -57, length = 10
0),
                lat = seq(5.8, 15.7, length = 100))
spat_pred_grid$id <- 1:nrow(spat_pred_grid)
# spat_pred_grid is simply a data frame with lat lon coords.

temp_pred_grid <- as.Date("2017-01-12") + seq(-11, 0, length
= 12)
#temp_pred_grid

## Initialise data matrix
obs_pred_wide <- matrix(0, nrow = 12, ncol = 10000)

## Set row names and column names
rownames(obs_pred_wide) <- as.character(temp_pred_grid)
colnames(obs_pred_wide) <- spat_pred_grid$id
covars_pred <- spat_pred_grid # covariates
STdata_pred <- createSTdata(obs = obs_pred_wide, # ST objec
t
              covars = covars_pred)
x.final <- coef(SpatioTemporalfit1, pars = "cov")$par
# predict on a grid
E <- predict(STmodel, x.final, STdata = STdata_pred)
library(sp)
library(spacetime)
spat <- as.matrix(spat_pred_grid[,1:2])
colnames(spat) <- NULL
spat <- SpatialPoints(spat)
proj4string(spat) <- CRS("+proj=longlat +datum=WGS84")
times <- as.Date(temp_pred_grid)
ESX <-t(as.matrix(E$EX))
colnames(ESX) <- NULL
pred.st <- STFDF(spat, times, data.frame(vals = as.vector(as.m
atrix(ESX))))
day1<-as.data.frame(pred.st[,1,1] )
#extract day1 data from STFDF
day12<-as.data.frame(pred.st[,12,1] )  # 12 hours later

# exponentiate the logs
day1$vals <- exp(day1$vals)
day12$vals <- exp(day12$vals)
vals <- attr(pred.st[,1,'vals'],'data')
```

```
library(rworldmap)
library(rworldxtra)
library(ggmap)
library(scales)
cbbn_stamen_toner <- get_stamenmap(bbox = cbbn_bb,mapty
pe = "toner-lite", zoom = 9)
breaks <- seq(min(day1$vals, na.rm = TRUE) * 0.95, max(day
1$vals, na.rm = TRUE) * 1.05, length = 21)
require('RColorBrewer')
ColorScale <-c("azure","cadetblue3","darkseagreen2","gold1",
"darkorange","darkorange3","firebrick3",
"firebrick1")

Labs <- round(breaks, 2)
iLabs <- floor(seq(1, length(Labs), length.out = 5))
iLabs[length(iLabs)] <- length(Labs)
Labs <- as.character(Labs[iLabs])
Labs[Labs == "0"] <- " 0.00 "

P <- ggmap(cbbn_stamen_toner)
P <- P + geom_point(aes(x = coords.x1, y = coords.x2, col = va
ls), alpha = 0.15,
        data = day1, na.rm = TRUE)
P <- P + geom_contour(data = day1, aes(x = coords.x1,
             y = coords.x2, z = vals), alpha = 0.5, colour = " gray4
8")
P <- P + scale_colour_gradientn(name = "wind speed in mph",
 colours =ColorScale ,
              breaks = breaks[iLabs], limits = range(breaks), labels
 = Labs)
P <- P + theme(legend.position = "none")
P <- P + labs(x = "midnight", y="")
P
```



Author’s Biographical Notes:

Neil Ramsamooj *is a Lecturer at the Faculty of Engineering, The University of the West Indies, St Augustine. He has a Ph.D. in Mathematics from the University of Wisconsin-Madison.*

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Advancing the Ultra High Frequency RFID in Industrial Applications: A Review

Tracy Aleong [a,Ψ], and Kit Fai Pun[b]

Department of Mechanical & Manufacturing Engineering, Faculty of Engineering, The University of the West Indies, Trinidad and Tobago, West Indies;

[a]Email: tracy.aleong1@gmail.com
[b]E-mail: KitFai.Pun@sta.uwi.edu

[Ψ] *Corresponding Author*

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Abstract: *Radio Frequency Identification (RFID) technology transmits data wirelessly and falls under the broad classification of Automatic Identification and Data Capture (AIDC). The advances in RFID technology continue to be accepted worldwide for various tracking and monitoring type applications. This paper reviews the principle of RFID system operation using an extensive search of relevant articles from technology management and related journals, over the past two decades. It 1) explores the RFID tags operating in the ultra-high frequency (UHF) band, 2) analyses some of the major advancements of this technology in the field of sensor tagging solutions in the past two decades, and 3) discusses industry-based applications utilising UHF RFID sensor tagging solutions for process measurement data acquisition. The main challenges identified are privacy and security concerns on their applications in industry. The paper contributes to amalgamating a list of UHF RFID industry-based applications. It is expected that the findings from this review exercise would shed light on critical areas of the UHF RFID Technology.*

Keywords: *RFID technology, UHF, automatic identification, industrial applications*

1. Introduction

Radio Frequency Identification (RFID) is a wireless technology that allows for automated remote identification of objects, animals or persons (Ahmadian et al. 2005). Traditionally, RFID tags were used in applications such as tracking of inventory, assets, personnel, and manufacturing of goods and materials. While the adoption rate of RFID technology is increasing yearly, mass-market adoption is less likely unless some of the system challenges are addressed through the work of researchers and engineers in the associated fields of study.

In recent years, RFID system has combined the technology of smart sensors and the capability of global positioning system (GPS), which allows the possibility of acquiring sensor data including resistance measurement, temperature, vibration, pressure, movement and location to be wirelessly transmitted through such mediums as the internet of things (IoT). RFID like most other wireless technology has a lot of potential with continuous fast pace growth in some areas and at the same time can be considered provocative, with little to no progress in other areas. The integration of RFID technology with sensor technology opens the doors to developing other types of sensor RFID tags for monitoring process conditions, collecting valuable data for industry users.

This paper comprises five sections. Following the introduction section, it provides a brief overview of the RFID technology and the principle of operation for each of the components. It then describes the methodology used for the literature search and review and provides the quantitative analysis of literature along with the industry applications, recent advancements and limitations for use in the field of RFID Technology. The paper concludes with recommendations for future work, with a focus on UHF tags development and integration with Sensor tag technology.

2. RFID Technology and Systems

2.1 A Brief History of RFID

The early 20th century can be considered the birth of radar, a technology used to send out radio waves for detecting and locating an object by the reflection of the radio waves. One form of RFID is the combination of radio broadcast technology and radar. It is not unexpected that the convergence of these two radio disciplines and the thoughts of RFID occurred on the heels of the development of radar (Landt 2005). During World War II, the concept of the long-range transponder systems for “identification, friend, or foe” (IFF) used in aircraft was developed by the British and employed by the allies as a means to identify their fighter planes from the enemy. It relied on passive radar reflectors, tuned to the home radar frequency, which made a friendly aircraft much brighter to a home radar than an enemy aircraft (Chawla and Ha, 2007). The year 1948 earmarks a significant RFID technology paper published by Harry Stockman, "Communication utilising Reflected Power". This helped pave the way for further research and development within the field of study. Table 1 gives a summarised breakdown of the development of RFID technology over the decades starting from the 1940s to the twenty-first century.

Table 1: Historical breakdown of RFID Technology since the 1940s to date

Decades of RFID	
Decade	**Event**
1940-1950	• Radar refined and used major World War II development efforts. RFID invented in 1948
1950-1960	• Early Exploration of RFID technology, lab experiments
1960-1970	• Development of the theory of RFID. Field application trials began • In 1964, R.F. Harrington examines the electromagnetic theory related to RFID in his paper ''*Theory of Loaded Scatterers"* • The late 1960s saw the start-up of 2 companies called Sensormatic and Checkpoint, working with another company called Knogo, developing the Electronic Article Surveillance (EAS) equipment to face the theft of merchandise, an RFID based solution
1970-1980	• An explosion of RFID Development. Testing accelerated with early adopter implementation of RFID • Between 1973 to 1975, large organisations Raytheon and RCA developed electronic identification systems • The 1970s showed RFID research being done by laboratories and universities, such as the Los Alamos Scientific Laboratory and Northwestern University • In 1978, R.J. King published a book on microwave homodyne techniques which would later be one of the bases for the development of the theory and practice which are used in backscatter RFID systems
1980-1990	• Commercial applications of RFID enter the mainstream • 1987 produced the first commercial application of RFID, developed in Norway and later followed by the Dallas North Turnpike in the United States in 1989
1990-2000	• The emergence of standards, RFID widely deployed, used in everyday life applications • In the '90s, a few American states such as Kansas and Georgia implemented a traffic management system that was based on the use of readers that could detect protocol tags. Texas Instruments developed the TIRIS system, which was used in applications related to vehicle access. European companies, such as Alcatel, Bosch and Phillips spin-off companies, such as Combitech, Tagmaster and Baumer were involved in the development of a pan-European standard for tolling applications. These companies helped develop a common standard for electronic tolling
2000-Present	• RFID continues to grow rapidly with increases in R&D.

Sources: Landt (2005) and Domdouzis, Kumar, and Anumba (2007)

RFID belongs to a group of technologies referred to as Automatic Identification and Data Collection (AIDC). AIDC methods automatically identify objects, collect data about them, and enter those data directly into computer systems with little or no human intervention (Patil and Patil 2018). Similar to RFID, traditional bar-coding technology provides an economical solution for AIDC industry applications. However, this technology has a primary limitation: each barcoded item must be scanned individually, thus limiting the scanning speed. Extra costs are incurred through the use of manual labour or automating the scanning process. When scanning is manually performed, there is the added possibility of human error.

Because of these limitations, RFID technology is making inroads in AIDC applications worldwide. RFID offers greater flexibility, higher data storage capacities, increased data collection throughput, along greater immediacy and accuracy of data collection.

2.2 The RFID System Architecture

The RFID system architecture comprises of two main components; these are 1) the tag or transponder, which is usually attached to an object, and 2) a reader or interrogator. The reader is typically connected to a host computer where data is transferred and stored. Both components have an antenna; for the tag's antenna, it is internally installed within the tag encapsulation and for the reader, it can either be integrally mounted (a part of the device) or remote mounted (separate but connected via cable). The reader emits a radio signal at a fixed frequency, which is used to power up the tag, and communicates with it using a technique called backscattering (Chawla and Ha 2007; Tedjini and Perret 2009; Kaur et al. 2011). Figure 1 shows the core components of RFID, and the key components are elaborated on below.

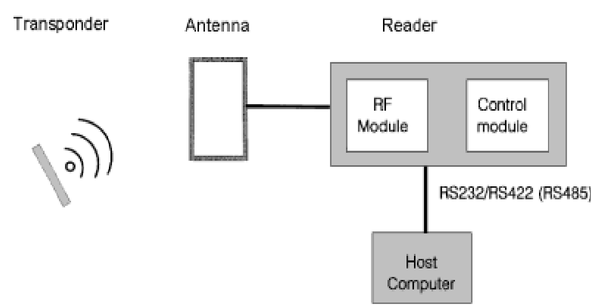

Figure 1. Components of RFID

2.2.1 The RFID Tag

An RFID tag in its most simplistic form comprises of three parts; an antenna for transmitting and receiving signals; an RFID chip (or integrated circuit, IC) which stores the tag's ID and other information; and lastly, some form of encapsulation (Hossain and Karmakar 2006; Want 2006). The tag encapsulation or housing composed of protective material maintains the tag's integrity and protects the antenna and chip from environmental conditions or reagents. The protective material used is mainly plastic and sometimes glass depending on the application requirements. The plastic housing was developed for applications involving particularly high mechanical demands where the tag is embedded between the layers of plastic.

RFID tags transmit data about an item through a specific radio frequency on the electromagnetic spectrum of waves to the antenna/reader combination. Within this spectrum, there are three (3) primary frequency ranges for RFID transmission - Low Frequency (LF), High Frequency (HF), and Ultra-High Frequency (UHF). Recently a 4th range has been added that exceeds the UHF range and it is commonly referred to as the Microwave range. Each frequency has different characteristics such as operating frequency range, read range (distance) and application suitability (appendix 1). The signal received by the reader is in the form of radio waves which is then converted to a usable form of data. Information collected from the tags can be transferred through a communications interface onto a host computer system, where the data can be stored and further analysed. RFID tags come in a variety of shapes and sizes and classified as either Active tags (battery-powered) or Passive tags (no internal power source). Passive tags are used more since they are smaller, thinner and less expensive to implement. These tags also have an indefinite operational life and are small enough to fit into a practical adhesive label (Want 2006).

An Active RFID tag has an on-board power supply (e.g., a battery) to broadcast data, either as a transponder replying to a signal or as a beacon, actively sending out its information. Active tags are mainly used in the UHF tag version since the battery affords long read ranges and large memory in exchange for a large form factor and a shorter lifespan. The battery can also power internal sensors designed to detect process parameters such as moisture, temperature and other environmental changes. In comparison, Active tags are more expensive than Passive tags due to battery maintenance and replacement. For this reason, the low cost of Passive tags makes them an ideal option for disposable and limited use applications. With the integration of sensor technology with RFID technology, a cross between active and passive tags was developed and it is commonly referred to as Battery-Assisted Passive (BAP) RFID tag. These BAP tags use an internal battery to power a sensor monitor and record the data periodically. They do not actively send a signal, instead only send it when requested by an RFID reader. Compared to Active tags, they are less costly and smaller in design since the battery has a smaller footprint.

Unlike Active tags, Passive tags do not have internal power sources and must rely on an external source to be "powered up". This is achieved by the electromagnetic field (EMF) created by the RFID reader. When the tag receives the transmission from the reader/antenna, the tag's antenna captures coupled energy from the EMF and transfers the tag's ID (the tag's IC coordinates this process). The coupled energy is rectified and the voltage multiplied via a multistage Greinacher half-wave rectifier to power up the IC. The energised chip modulates the energy with the desired information and then transmits a signal back towards the antenna of the reader (Kaur et al. 2011). For the energy coupling, there are two (2) different techniques used in passive tags; near-field and far-field coupling (Chawla and Ha, 2007; Kaur et al., 2011).

Because the inductive coupling or backscattered radio waves in RF identification is used to detect the physical parameters of tagged objects, it can be used to deal with sophisticated problems, for instance, to discriminate the variation of materials as a transmission medium of the radio waves. Therefore, RFID tags are also innovatively used as electromagnetic sensors for different measurement purposes, such as strain detection, material corrosion analysis, crack detection and food quality evaluation (Meng and Li 2016). In the case of the Passive RFID sensor tag, RF energy is harvested from the RF radiation to power the circuit and complete the sensing.

Due to their relatively low cost and large distance of communication, passive UHF tags are very promising, Tedjini et al. (2010) contend that UHF RFID technology is generating much interest in industrial and academic institutions owing to its immense potential in tracking. This is why the design of UHF RFID tags with high performances, low cost and interoperability is a very active field of research. Interoperability is needed since there are variations in the frequency bands worldwide (Finkenzeller, 2003; Weis, 2007). In practice, the emission limit is imposed as the equivalent isotropically radiated power (EIRP), defined as the product of the power accepted by the transmit antenna and its maximum gain over all the spatial angles within the regulated frequency band. For passive tags, the read range is dependent on the amount of power received in the transmission and for passive tags, it is important to refer the achieved read range to a specific EIRP value. Table 2 shows a list of the EIRP regulations for UHF RFID systems in different regions.

Table 2. EIRP Regulations for UHF RFID Systems in Different Countries

Countries/ Regions	Frequency Band [MHz]	Effective Isotropic Radiated Power, EIRP [W]
Europe	865.6 - 867.6	3.28
China	840.5 - 844.5 920.5 – 924.5	3.28
Republic of Korea	817 – 920.8 917 – 923.5	4 0.2
Japan	852 – 956.4	4
Canada	902 - 828	4
United States	902 - 828	4
Australia	820 – 926 918 - 926	4 1

Source: https://rfid4u.com/rfid-regulations/

The two options for powering the tags can be through an internal supply such as a battery or power derived from an electromagnetic field provided by the appropriate frequency reader. Simultaneously the way the tag is powered classes it as either an Active tag (battery-powered) or Passive tag (no internal power). The tag has within it, an IC and an antenna surrounded by the encapsulation for protecting the internal parts. Because tags come in different operating frequencies (such as LF, HF, UHF, Microwave), the tag must be chosen to meet the application's requirements. The second component in any RFID system is the reader, and its main purposes are to communicate with the field tag, provide power through electromagnetic induction and retrieve its stored data. This data is then transferred to a host system such as a computer where it can be stored for future processing.

2.2.2 Readers

The reader plays a crucial role as it can be considered the brain of the RFID system, managing the communication through synchronisation of transfers and other system functions. A Reader also referred to as an interrogator or transceiver device is used to transmit and receive radio waves to communicate with RFID tags. The main function of a reader is to collect the data stored in the tag (Tedjini and Perret, 2009). The reader emits radio waves in ranges of one (1) inch to one hundred (100) feet or more, depending upon its power output and the radio frequency. When an RFID tag passes through the electromagnetic zone, it detects the reader’s activation signal. The reader decodes the data encrypted in the tag’s IC (silicon chip) and the data is passed to the host computer for storage or processing (Elmorshidy 2010). The second main function of the reader is to write information into the tag. In addition to this ability to code and decode the information between the tag, the reader ensures the link to middleware that is specific to the application and its physical environment (Tedjini and Perret, 2009).

There are two (2) types of readers available, namely, Fixed RFID Readers and Mobile RFID Readers. Fixed readers usually stay in one location (such as mounted onto a wall), while mobile readers are usually handheld devices that are easily transported around and capable of maintaining wireless communication with a host computer or smart device. Fixed RFID Readers have a lot of flexibility when coupled with a multiplexer allowing additional ports for more antennas, thereby allowing larger coverage or read area. Simple applications may require just one antenna such as scanning in and out of a building, while other applications in the field of inventory and asset tracking in a large warehouse would need a bigger read zone (atlasRFIDstore 2019). In environments with many tags, a reader may have to perform an anti-collision protocol to ensure that communication conflicts do not occur. Anti-collision protocols permit readers to rapidly communicate with many tags in serial order (Weis, 2007).

2.2.3 RFID Antenna

In an RFID system, the antenna plays a pivotal role in both the tag and the reader (Hossain and Karmakar 2006). Infinite varieties of antenna design are possible that provide optimal performance such as the covered slot antenna design presented by Chen and Hsu (2004) and the circular patch antenna analysis by Padhi et al. (2003) and Penttilä et al. (2006). Some of the others identified are Marrocco (2003) meander antenna optimisation, Hirvonen et al. (2004) planar inverted F-antenna, and Qing and Yang (2004) folded dipole antenna design. In each case, the designs were well presented but lacked an overview of criteria for RFID tag antenna design and analysis of practical application aspects. This was not the case of Nikitin and Rao (2009) who was able to cover the antenna design for passive UHF RFID tags, as well as providing a potential generic design process that covers range measurement techniques and then applied it to a practical application, i.e. RFID tag for box tracking in the warehouse.

In the simplest form, an RFID system has two main elements; the tag and the reader Figure 2 shows the Antenna Downtilt and Coverage Calculator (aka Antenna Tilt Angle Calculator) that is used to determine the approximate downward angle, measured in degrees, which the transmitting antenna is to be positioned for optimal signal strength and coverage. It also provides, given a beamwidth, the inner and outer radii of beam's coverage (https://www.microwavejournal.com).

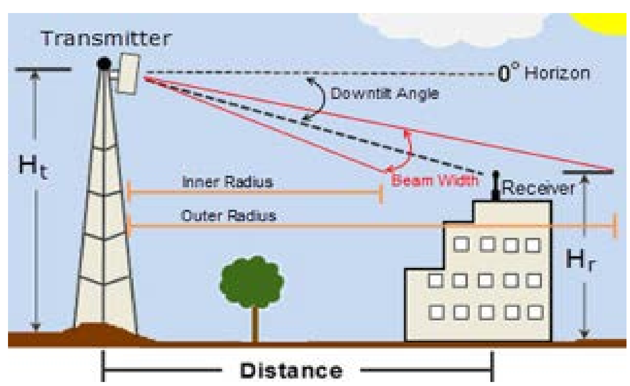

Figure 2. Antenna Downtilt and Coverage Calculator
Source: https://www.microwavejournal.com/articles/29437-antenna-design-analysis-and-simulation

For readers, antennas are either integrated or built into the device or can be standalone and mounted separately from the reader. The reader provides power to the antennas, which then generates an RF field and synchronously, an RF signal is transmitted to the tags within the read range. The antenna's gains refer to the specific direction and strength in which waves are generated. Therefore, the higher the gain, the more powerful and further-reaching RF field an antenna would have. These generated waves are given off along a horizontal or vertical plane, which is considered the antenna's polarity. For passive tags, the tag antenna should receive the EM signal from the reader at a right angle to optimise performance since generally the tag antenna is omnidirectional (Hossain and Karmakar 2006).

Similar to the gain, the antenna's polarity affects the read range since a difference in polarities between the antenna of the reader and the RFID tag would significantly reduce the read range. If the polarities align, then the user can achieve the maximum read range. There is a circularly polarised antenna, which transmits waves in continuous rotation between horizontal and vertical planes, allowing an application enhanced flexibility, so RFID tags can be read in multiple orientations. The drawback of this type is still a shorter read range versus a similar gain linear antenna since the energy is divided between two planes (atlasRFIDstore, 2019).

2.3 Principles of RFID Technology and Operations

Kaur et al. (2011) offer a brief introduction to the principles of the technology, major current applications and challenges of deploying this technology. In terms of applications and usage, RFID has been widely applied for access control and information tracking in logistics and industrial processes (Meng and Li 2016). It is also considered as emerging and disruptive compact wireless and eminent enabling technology for the realisation of ubiquitous monitoring in ad hoc wireless networks especially if fused with other networks (Lakafosis et al. 2010). Since the inductive coupling or backscattered radio waves in RF identification can be used to detect the physical parameters of tagged objects (temperature, gas, moisture, etc.), the technology is also a potential solution for structural-health monitoring systems to detect the strains and cracks in aerospace, civil, or architectural structures, as well as in precision agriculture (Dey, Saha, and Karmakar 2015).

RFID has its list of limitations where security and privacy concerns top the list. Juels (2006) offers a general survey of the security and privacy issues related to RFID, while Mutigwe, Aghdasi, and Kinyua (2013) propose a solution of authenticated readers used to achieve RF silence thereby addressing the concerns raised by privacy advocates. Likewise, Engberg et al. (2004) proposed a "zero-knowledge" RFID security and privacy protocol where the tag only speaks to authenticated readers but did not provide adequate details on how the protocol would be managed. Every year, researchers and engineers have been finding new and useful applications for RFID systems (Finkenzeller, 2003). An increasing number of companies in a variety of markets worldwide are embracing RFID technology to increase the quality and quantity of data collection expeditiously.

3. Literature Searches and Identification

For this study, the data was acquired via searches conducted through Google Scholar. Material published between the years 2000 to 2019 was collected and stored for further analysis.

An advanced search criterion was performed with the terms "RFID" and "Radio Frequency Identification" located within the Title of the article that produced 2,073 various articles. With such a wide selection of articles under the main topic, subcategories of search phrases were used to narrow the selection process. These were:

1) RFID system principle of operation,
2) Ultra-High Frequency RFID,
3) Advancements in UHF RFID sensor tags technology, and
4) UHF RFID sensor tag in industrial applications.

4. Findings and Analysis

4.1 RFID by Publication Date and Type

Of 2,073 publications acquired for the period 2000-2019, 145 were of journal sourced, 2 of magazine sourced, 4 book sourced, 877 fell under reports/dissertation/working paper/other and 1,045 were patents and citations. Appendix 1 presents results by year for each category except citations and patents. Besides, Figure 3 depicts the results of the advanced search and it is well noted that in the period 2000 to 2003, it shows very little published on the topic of RFID. However, from 2004 there is a sudden increase in published articles with steady growth in numbers every 2 to 3 years. Although the numbers fluctuate most years, the overall trend is increasing publications, with the highest seen for the year 2014. The information recorded for the year 2019 shows a reduction from the previous year.

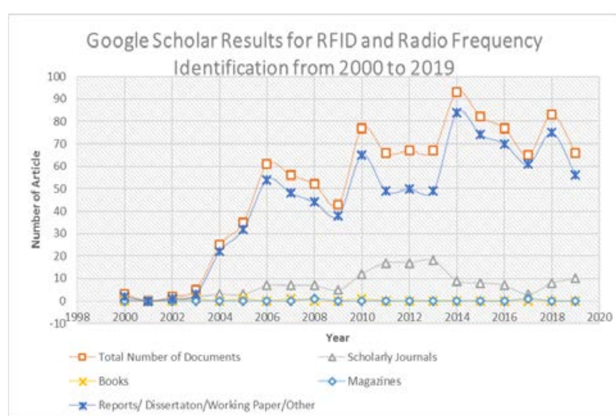

Figure 3. Google Scholar Results for RFID for the period 2000-2019

4.2. RFID Data by Sub-topic Areas

To develop the data required to build the sections within this report, Sub-topic areas were researched. Tables 3-6 depict the organisation and analysis of four (4) sub-topic fields towards building the literature concepts and themes. These are:

1) RFID principle of operations,
2) Recent advancements in UHF RFID technology integrated with sensor tags,
3) Industrial applications for UHF RFID sensor tags, and
4) Major limitations in the field of RFID sensor tag technology.

4.3 Recent Advancements on UHF RFID Tag Systems

In recent times, researchers and engineers have integrated RFID tags with sensors capable of measuring environmental factors such as temperature and pressure. Dey, Saha, and Karmakar (2015) propose these sensor tags are smart sensing since they operate with wireless data-capturing technique that utilises RF energy to automatically extract the identity of remotely placed objects.

Table 3. Understanding of RFID Systems

Concept	**Notes**	**Author/Source**	**Interpretation of Viewpoint**
Overview of RFID	A most comprehensive overview of the topic.	Finkenzeller (2003).	Delivers a general understanding of the working RFID System.
History of RFID	It is not unexpected that the convergence of these two radio disciplines and the thoughts of RFID occurred on the heels of the development of radar	Landt (2005)	Talks about the 1st published paper
History of RFID	Summaries main event in the past century for RFID Technology	Domdouzis, Kumar, and Anumba (2007)	Use to build a history of RFID
Tag Design	An RFID tag in its most simplistic form comprises of three parts; an antenna for transmitting and receiving signals, and an RFID chip (or integrated circuit, IC) which stores the tag's ID and other information and some form of encapsulation	Want (2006)	Identifies the tag components
Tag Design	The tag encapsulation composed of a protective material maintains the tag's integrity and protects the antenna and chip from environmental conditions or reagents. The protective material depends on the application. For example, employee ID badges containing RFID tags are typically made from durable plastic, and the tag is embedded between the layers of plastic	Hunt, Puglia, and Puglia (2007); Finkenzeller (2010)	Identifies the tag components. Same as Want (2006)
Tag Design	Its most simplistic form comprises of three parts: an antenna for transmitting and receiving signals, and an RFID chip. The tag antenna is generally omnidirectional	Hossain and Karmakar (2006)	Identifies the tag components. Same as Want (2006)
Antenna	The tag's antenna plays a pivotal role in both the tag and the reader	Hossain and Karmakar (2006)	Talks about the antenna's role
RFID Readers	Fixed RFID Readers have a lot of flexibility with the use of a multiplexer to allow additional antenna ports, additional antennas can be installed giving larger coverage or read area.	atlasRFIDstore (2019)	Discusses the Reader
Principle of Operation	It relied on passive radar reflectors, tuned to the home radar frequency, which made a friendly aircraft much brighter to a home radar than an enemy aircraft	Chawla and Ha (2007)	*Working principles of the RFID system*
Principle of Operation	AIDC methods automatically identify objects, collect data about them, and enter those data directly into computer systems with little or no human intervention	Maruthaveni and Kathiresan (2018)	*Working principles of the RFID system*
Principle of Operation	The main function of an RFID reader is to collect the data stored in the tag	Tedjini and Perret (2009)	*Working principles of the RFID system*
Principle of Operation	*How the system works*	Kaur et al. (2011)	

Table 4. Major Advancements of the UHF RFID System within the Past 2 Decades in the Field of Sensor Tagging Solutions

Concept	*Notes*	*Author/Source*	*Interpretation of Viewpoint*
Updates on RFID Technology	One of the largest independent online forums providing the latest news, case studies and insights on RFID technology business applications	RFID Journal (2002)	*Can find many articles on applications, industry users, suppliers, advancements in the field*
Applications	Discusses major current applications and challenges of deploying this technology	Kaur et al. (2011)	*The changes to RFID over time is highlighted*
Advancement	Considered as emerging and disruptive compact wireless and eminent enabling technology for the realisation of ubiquitous monitoring in ad hoc wireless networks especially if fused with other networks	Lakafosis et al. (2010)	*Talks about potential uses*

Table 4. Major Advancements of the UHF RFID System *(continued)*

Concept	*Notes*	*Author/Source*	*Interpretation of Viewpoint*
Advancement	Since the inductive coupling or backscattered radio waves in RF identification can be used to detect the physical parameters of tagged objects, RFID technology is also a potential solution for smart sensing to deal with some sophisticated problems	Dey, Saha, and Karmakar (2015)	*Talks about research in the field of smart sensing*
Design / Advancements	The design of UHF RFID tags with high performances and low cost is a very active field of research	Tedjini et al. (2010)	*Improvements to design*
Operating Frequency	Three frequency bands worldwide for UHF RFID Tags	Finkenzeller (2003)	*A few articles on this topic. Information is similar.*
Standard for UHF	Communication protocols for RFID are also being standardised and currently, there is ISO 18000-6 standard that defines specifications for RFID tags operating at UHF frequencies.	ISO (2004)	Recent additions
Standard for UHF	EPC Global standard defining the air interface protocol for RFID. In addition, the most widely used tags follow the EPC global UHF Class 1 Generation 2 standard which defines the physical and logical requirements of the tags.	EPCglobal (2013)	Recent additions

Table 5. Industry-Based Applications Utilising UHF RFID Sensor Tagging Solutions for Process Measurement Data Acquisition

Concept	*Notes*	*Author/Source*	*Interpretation of Viewpoint*
Application	RFID has been widely applied for access control and information tracking in logistics and industrial processes	Meng and Li (2016)	In terms of applications and usage
Application	proposes these sensor tags are smart sensing since they operate with wireless data-capturing technique that utilises RF energy to automatically extract the identity of remotely placed objects	Dey, Saha, and Karmakar (2015)	*Potential Application*
New applications	RFID-enabled sensing platforms for cognitive intelligence applications are introduced	Kim et al. (2013)	*Advancements*
New applications	Paper on the area of autonomous RFID-enabled wireless sensors, focusing on low-power sensor nodes for use in temperature sensing applications	Dowling, Tentzeris, and Beckett (2009)	*Advancement*

Table 6. Limitation of Using UHF RFID Systems

Concept	*Notes*	*Author/Source*	*Interpretation of Viewpoint*
Security and Privacy	A general survey of the security and privacy issues related to RFID	Juels (2006)	*Talks about concerns with security and privacy for using this technology*
Solution to Issue	Proposes a solution of authenticated readers used to achieve RF silence thereby addressing the concerns raised by privacy advocates	Mutigwe, Aghdasi, and Kinyua (2013)	*Proposal for a fix of privacy concerns*
Solution to Issue	Proposed a “zero-knowledge” RFID security and privacy protocol where the tag only speaks to authenticated readers but did not provide adequate details on how the protocol works and managed	Engberg, Harning, and Jensen (2004)	*Proposal for a fix of privacy concerns*
Security and Privacy	Limited privacy protection in current RFID systems is a major concern for individuals. further emphasises that RFID systems have become synonymous with “insecure” systems, a situation that must be thoroughly addressed before it severely limits the widespread deployment of RFID systems	Zappone (2007)	*Biggest concern*
Other Challenges	Challenge of designing and developing communication protocols consisting of a multi-layer authentication and encryption process for data transfer between tag and reader	Mutigwe, Aghdasi, and Kinyua (2013)	
Solutions to limitations	Proposes a design to meet this operation. Some researchers have gone further and proposed custom RFID cryptographic processors for this task.	Tuyls and Batina (2006)	
Operation Challenge	UHF readers may also interfere with sensitive electronics like medical equipment	Weis (2007)	

4.4 RFID-Enabled Sensor Tags and Industry Applications

Traditionally, RFID sensors have been largely used in the field of asset tracking and inventory management type applications. The usages have grown into a multitude of applications covering a variety of domains (see Figure 4). In the case of inventory management, RFID rapidly replaced the barcode system as the need for scanning where line of sight proved to be time-consuming as opposed to RFID. For instance, applications of RFID systems are found in postal services to track packages and shipment locations; in manufacturing, to track parts delivery; tagging livestock, particularly cattle; retail item management; as a form of payment such as road tolls; security access and control to prevent unauthorised personnel from entering buildings or room without a swipe card.

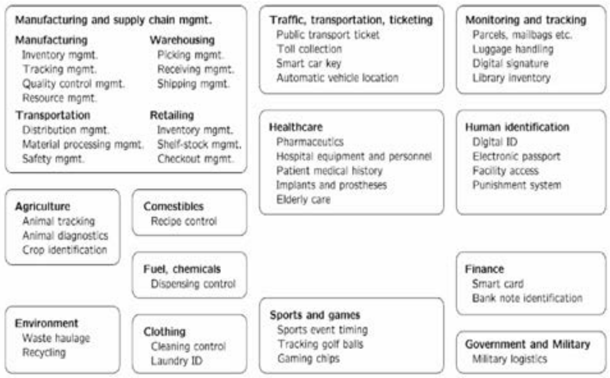

Figure 4. Applications of RFID Technology

Most recently, RFID tags have been integrated with electronic components, such as sensory material, Analogue-to-Digital Converter (ADC), and Micro-Controller Unit (MCU) to make an integrated sensor module as in the case of pressure and temperature sensing tags (Meng and Li, 2016). Moreover, RFID sensors achieve measurement tasks in different ways and based on operating fundamentals, the related methods of RFID measurement can be classified into four categories: RFID electromagnetic sensor, RFID tag integrated sensor, RFID tag array, and RFID sensor networks. Table 7 presents the fundaments of measurement for each category.

Over the last decade, applications using RFID-enabled sensors have been investigated, with much-published work produced by various authors worldwide. Meng and Li (2016) summarise the application of RFID sensors and the measurable physical parameter as depicted in Figure 5.

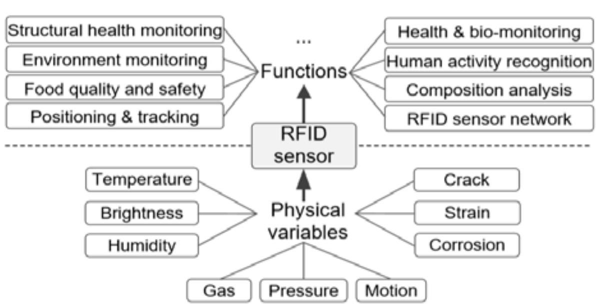

Figure 5. Applications of RFID Sensors
Source: Abstracted from Meng and Li (2016)

Girbau et al. (2012) proposed an RF identification sensor system for temperature measurement comprising of passive resistive sensor and an ultra-wideband (UWB) reader. Similarly, Dowling et al. (2009) present a paper on the area of autonomous RFID-enabled wireless sensors, focusing on low-power sensor nodes for use in temperature sensing applications. Low-power chipless RFID sensors operating in the 2.4 GHz band are utilised. The sensors are required to be completely autonomous, energy-independent, inexpensive, and easy to install. For gas measurement, Potyrailo et al. (2009) investigate the combination of selective vapour sensors using organic electronic sensing materials with diverse response mechanisms to different vapours and passive RFID sensors with multivariable signal transduction. Another application looked at is the measurement of strain in different material compositions (Occhiuzzi, Paggi, and Marrocco 2011). Papers on using Ink-jet Printed RFID Sensor technology has also been published, for example, in monitoring water quality (Cook et al. 2013) and humidity (Virtanen et al. 2011).

Kim et al. (2013) discuss a variety of ink-jet-printed RFID-enabled sensor prototypes and perpetual RFID-enabled sensing platforms for cognitive intelligence applications introduction. Some clarity on the integration of RFID sensors with selected sensing materials such as water-absorbing materials for humidity sensors or carbon nanostructures for gas sensors to detect a parameter change is also given. The chemical, physical, or electrical reaction of the sensing materials in the presence of the sensed parameters would modify the electrical properties (permittivity, conductivity) resulting in easy-to-observe electrical metrics, such as a shift of the resonant frequency of the RFID tag antenna as shown in Figure 6, verifying the simplicity and power efficiency of RFID-enabled sensors.

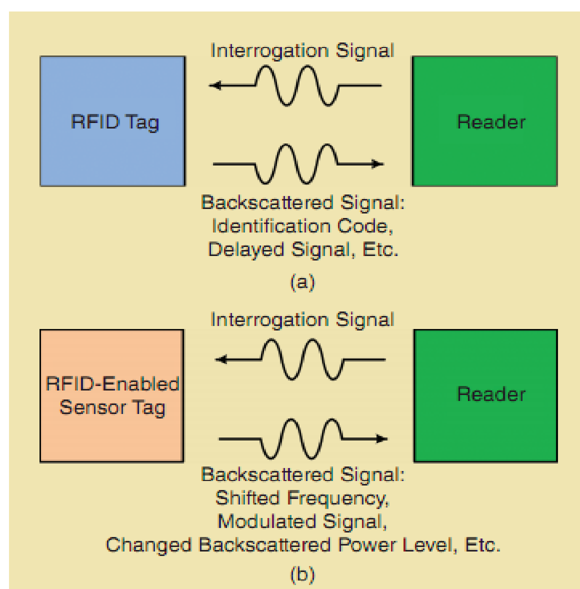

Figure 6. (a) RFID Tag and (b) RFID-enabled Sensor Tag

4.5 Limitations of RFID Technology

Although the uses of RFID systems have continuously grown over the past decades, the technology has been facing areas of concern limiting extensive diffusion into

Table 7. Categories of RFID Sensor Measurement

Categories	Fundamental of Measurement
RFID electromagnetic sensor	The normal passive RFID tag or chipless RFID, for which measurement is based on the analysis of its spectral or phase characteristics
RFID tag integrated sensor	Integrated with a sensor module, RFID is used for energy harvesting and data transmission
RFID tag array	RFID array for expanding measurement space or for localisation and tracking
RFID sensor networks	Batteryless and low-cost solution for wireless sensor networks monitoring

the wireless technology arena and practical adoption. A major hurdle is simply getting RFID systems to work in real-world environments. Systems that work perfectly in a laboratory setting may encounter problems when faced with environmental noise, interference, or human elements (Weis 2007). For example, simply repositioning or re-aligning readers would often address performance issues. Security and privacy issues are major areas of concern expressed for determining the suitability of this technology in different applications.

Zappone (2007) contends that limited privacy protection in current RFID systems is a major concern for individuals. He further emphasises that RFID systems have become synonymous with "insecure" systems, a situation that must be thoroughly addressed before it limits the widespread deployment of RFID systems. The problem lies within the radio-based mode of communication through detectable wireless channels. Therefore, some designs allow tags to promiscuously surrender their identity when queried by any reader operating at the appropriate frequency.

Traditional applications, like large-asset tracking, were typically closed systems and tags did not contain sensitive information. Tags on railway cars contained the same information painted on the side of the cars themselves. However, as more consumer applications emerged, so is the need for greater security and privacy protocols for using those systems. For the corporate executive, this privacy protection issue can leave the entire supply chain exposed to industrial espionage, while the security vulnerabilities can lead to counterfeiting and other acts of economic sabotage. In the last decade, many researchers have taken on the challenge of designing and developing communication security protocols in a bid to address these major concerns such as multilayer authentication and encryption for data transfer. One such study presented by Mutigwe, Aghdasi, and Kinyua (2013) proposes a design to meet this operation. Tuyls and Batina (2006) amongst others have gone further and proposed custom RFID cryptographic processors for this task. Avoine (2006) maintains a comprehensive bibliography of RFID security and privacy papers published by various researchers.

Several areas that pose challenges are indicated below:

1. *Standardisation of Frequencies* – Within the market exists different versions of RFID, operating at different frequencies. There is a need for interoperability agreements between manufacturers, retailers, and distributors and requires specific software and reader to work. This would reduce conflicts, such as, communication protocols, signal modulation types, data transmission rates, and data encoding for companies with closed-loop systems that want to promote their offerings.
2. *Cost* – The cost of Active tags is more than the cost of Passive tags due to the battery requirements. Consumers can opt to implement an alternative solution that might be more feasible for their operation. For instance, in the supply chain sector, barcoding of inventory is still the lower cost option for tagging goods as opposed to RFID tags.
3. *Frequency* – Choosing the optimal frequency depends on various factors, such as transmission mode and behaviour of tagged goods, read/receive distances, and the environment. Properties of some materials such as goods containing water or metal surface may be an obstacle to RFID application with the risk of signal absorption or reflections respectively at a given frequency, potentially leading to corrupted data transmission. Some materials have been developed that may shield UHF tags from metal-related distortion, but these may be cost-prohibitive to use in practice. UHF readers may also interfere with sensitive electronics like medical equipment (Weis 2007). Signal failure because of absorption and reflection can have possible solutions; failure at one frequency does not rule out applicability at other frequencies.
4. *Social and legal issues* – certain countries have restrictions on the allocation of the electromagnetic spectrum and may prohibit the use of these systems. There may be concerns about the health implications of continuous exposure to electromagnetic waves.
5. *Data Collision* - Attempting to read several tags at a time may result in a signal collision and ultimately to data loss. To prevent this, anti-collision algorithms (most of them are patented or patent-pending) can be applied but comes with a cost adder.
   - *RFID Data Cleansing* - Despite the improvement of the accuracy of RFID readers, there are still erroneous readings such as missed reads and ghost reads, due to interference, temporary or permanent malfunction of system components. In addition, RFID data may contain significant redundant information due to duplicated readings. RFID data cleansing is therefore widely

considered as a principal challenge and has been an important research topic in the last few years (Sheng et al. 2010).

- *Global Standards* – Similar to the concern of different existing frequencies, so is the concern here. Several standards of RFID systems are currently in use with the 2 most relevant being the International Organisation for Standardisation's ISO/IEC 18000 standard (ISO, 2004) and EPC Global standards (EPCglobal, 2013).

5.1 Discussion

5.1.1 Findings for the research on RFID

At present, the field of RFID research has abundant resources and published data for any researcher working in this area. Navigating the resource pool was at times, very tedious but eventually, a data pattern emerged from reviewing the various published articles. Within each piece, there was to some extent a simple introduction to the system and its associated components. RFID is considered a cost-effective option for wireless tracking and inventory management systems, as some of the tags are usually inexpensive.

The rate at which RFID is being accepted for different applications is constantly growing and associated with published data. Tracking and monitoring are traditional applications for this technology. While the greatest development pertains to the integration of RFID tags and sensor technology to create the sensor tag. These tags have great potential as industries can employ them in many applications. However, as many of the referenced authors mentioned, quite a few limitations prohibit the worldwide adoption of this system. With privacy and security topping the list of concerns, the implementation into many applications has to wait for an economical and viable fix to this issue.

5.1.2 Significant Advancements in the Field of RFID Technology

Process monitoring is an essential requirement of many industrial sites and the cost for specialised instrumentation can be expensive to implement. Instead, companies would limit the number of physical parameters monitored, such as temperature, pressure, strain, vapour emissions, and other process parameters. RFID sensor tag offers the world a cost-effective and simple architecture option for customers. In fact, with the wireless design and capabilities, many more application doors are opened which may have not been explored previously due to restrictions of having wired instruments. For instance, rotating equipment (such as fan blades) can be equipped with temperature and vibration tags. This would allow the maintenance team to acquire information from the moving parts of their equipment which was not possible with wired instruments.

The developments in tag, antenna, and reader designs have been noteworthy advancements. While improvements are important, researchers also have to continue keeping the cost down for the system to have a competitive edge over other existing wireless systems of similar performance. Within the past two decades, global standards have been created and implemented for RFID systems with the two most relevant and discussed being ISO 18000 and EPC Global standards. These standards would help streamline the processes used by the different manufacturers of RFID components to ensure product quality and assurances are met.

5.1.3 Potentials for Implementing UHF RFID Sensor Tags in Industry

To implement RFID systems into any application, it is advisable to have at least a basic understanding of how the RFID system works, specifically the principle of operations for the individual components. The feasibility of the application is another important factor, simple meaning if the application is suitable for using an RFID system. Noting the limitations such as security concerns, read range limits and asset material composition are just a few of the different aspects that can severely affect how effective an RFID system functions if installed. The Application Feasibility process should entail scoping of the project and the project's environment as a starting point, and then determining if RFID (or another technology) is the right fit for the application. Some simple questions to ask regarding the application to identify the most suitable tag design would be:

- What item is being tagged?
- How far would the tagged device be from the readers?
- How many tagged items or tags required?
- Does the tag require power or would the reader be able to provide the power source?
- What data needs to be collected from the tag? In other words, what are the data packets size and speed requirements between tag and reader?
- Are metal objects/surfaces near the tagged item?
- What are the size requirements for a tag?

Cost is another factor to consider when selecting RFID for an application. Cost for initial start-up (fixed cost) includes labour, training, and recurring costs such as maintenance of system, tag lifespan. In the case of Active tags, changing batteries periodically would be a recurring cost as opposed to Passive tags. In addition, considerations of other systems that may be more reliable and secure might outweigh the cost factor of RFID.

6. Conclusion

Today, RFID has become one established and applied technology with major advances in the field of smart sensing for everyday industry base process applications such as temperature and vibration. This significant development has attracted attention from researchers and engineers to the field as two of the major advantages of employing this system are Low-cost and Wireless Communications. In this paper, the principle of operations was discussed, as well as individual components and their associated roles. It is quite evident that many researchers would continue to push the bar by proposing new designs for various smart sensing applications. This is surely an imperative area for continued future developments and research (R&D). As long as developments continue, this technology has the potential to become an integral part of people's daily lives.

Despite the obvious potential, several fundamental research and development issues persist. As long as privacy and security concerns are not addressed properly, the worldwide adoption of this technology would be affected. R&D works continue in these and other areas such as passive tags, particularly the UHF tags. This is to ensure interoperability, low-cost maintenance requirements, and data security. An in-depth look into this area of concern will be conducted, analysed and submitted for review in a future study.

Of all the classes of tags, the UHF tag can meet most application requirements because it is considered to have a balance performance of range and readability as compared to the other frequency ranges of tags. However, there are disadvantages in using these tags such as susceptibility to interferences caused by environmental idiosyncrasies like metal distortion. When that happens, the signals might be absorbed or reflected if the tag is near metal. This would result in unreliable data transmission and can affect the future developments of the UHF passive tags in the smart sensory integration drive.

In other situations of interferences, the best way to address those issues would be by trial and error, and practical experience to recognise what is causing the problem. For example, simply repositioning or re-aligning readers would often address performance issues in some situations. It would be meaningful to conduct different tests and record the performance of UHF passive tags under varying environmental conditions especially in the tropical climate of sun, rain, and windy conditions.

One area for future research would be to extend the range and utility of wireless sensors especially the ones that are designed with passive tags. Other possible areas of research include energy harvesting and power scavenging of ambient energy sources, such as light, vibration, RF, and heat. The introduction of printed circuits also plays a promising role in future developments of tag design. If field application testing is successful, this advancement has the potential to greatly lower manufacturing costs and to produce RFID tags built out of flexible plastic materials, instead of other materials like silicon. This technology might be years away from being economic and there are many hurdles to overcome.

As the market continues to grow, certain aspects of the RFID system's costs would drop and new applications would become more economical. The prosperity of different kinds of RFID smart sensing technology is simple enough for this researcher and others alike to continue research within the field, which can one day lead to the worldwide technological adoption of this simple, yet practical solution.

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Appendix 1: Characteristics for Tags Operating on the Different Frequencies (LF, HF, UHF, Microwave)

Frequency Range	**125 KHz** Low Frequency (LF)	**13.56 MHz** High Frequency (HF)	**868 - 956 MHz** Ultra-High Frequency (UHF)	**2.45 GHz & 5.8 GHz** Microwave
Typical Max Read Range (Passive Tags)	< 0.5 m	~ 1 m	~3m to ~10m	~ 1 m
General Characteristics	Relatively expensive, even at high volumes. Low frequency requires a longer more expensive copper antenna. Additionally, inductive tags are more expensive than a capacitive tag. Least susceptible to performance degradations from metal and liquids	Less expensive than inductive low frequency tags. Relatively short read range and slower data rates when compared to higher frequencies. Best suited for application that do not require long range reading of multiple tags	In large volumes, UHF tags have the potential for being cheaper than LF and HF tags due to recent advances in IC design. Offers good balance between range and performance; capable of reading multiple tags quickly	Similar characteristics to the UHF tag but with faster read rates. A drawback to this band is that microwave transmissions are the most susceptible to performance degradations due to metal and liquids, among other materials
Tag Power Source	Generally passive tags only, using inductive coupling	Generally passive tags only, using inductive or capacitive coupling	Active tags with integral battery or passive tags using capacitive, E-field coupling	Active tags with integral battery or passive tags using capacitive, E-field coupling
Typical Applications Today	Access control, animal tracking, vehicle immobilizers, POS application including SpeedPass	Smart Cards, Item-level tracking including baggage handling (Non-US), libraries	Pallet tracking, electric toll collection, baggage handling (US)	SCM, electronic toll collection
Notes	Largest install base due to the mature nature of low frequency, inductive transponders	Currently the most widely available frequency worldwide due mainly to the relatively wide adoption of smart cards; common frequency worldwide	Different frequencies and power levels are used worldwide: Europe allows 868 MHz @ .5 to 2watts whereas the US permits operation at 915MHz @ 4w; Japan does not allow transmissions in this band at this time.	
Data Rate	Slowest	←------t---------	-------t-------→	Fastest
Ability to read near metal or wet surfaces	Best	←------t---------	-------t-------→	Worst
Passive Tag Size	Largest	←------t---------	-------t-------→	Smallest

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Authors' Biographical Notes:

Tracy Aleong *is a Director of Smart Technical Process Solutions Limited, Trinidad. She has substantial work experience in process plant instrumentation engineering, controls and automation. Ms. Aleong received her B.A.Sc. in Electrical Engineering from the University of Trinidad and Tobago, Trinidad and Tobago and her MBA specialised in Innovation and Leadership from Anglia Ruskin University, United Kingdom. She is currently pursuing an MPhil in Industrial Engineering at The University of the West Indies, Trinidad and Tobago. Her research interest and activities include industrial engineering, smart instrumentation technology, mass local manufacturing and graphical designs.*

Kit Fai Pun *is presently Professor of Industrial Engineering of the Faculty of Engineering at The University of the West Indies, St Augustine Campus, Trinidad and Tobago. He is a Registered Professional Engineer in Australia, Europe, Hong Kong, and The Republic of Trinidad and Tobago. His research interests and activities include industrial engineering, engineering management, quality systems, and performance measurement.*

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