SMART FARMING IRRIGATION SYSTEMS USING INTERNET OF THINGS

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DECLARATION

I declare that this project report is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed this 22nd day of September 2021

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Kudzayi Matekaire

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ABSTRACT

The global population growth rate is greater than the exponential increase in food production. The agricultural economic sector is challenged to cater for the increased demand for agricultural products. Agricultural irrigation plays a very important role in sustaining increased food production. Older irrigation methods used in earlier years are less efficient in managing resources. The advent of IoT technological realm brings various opportunities for redesigning almost all sectors of the economy. Irrigation systems are no exception to this technological manifestation. IoT is challenging existing irrigation methods. Agricultural irrigation can leverage IoT to monitor environmental sensors that detect soil moisture content, humidity, temperature, and irrigation infrastructure.

This study made use of Delphi survey technique to gather insights from a panel of experts in the domain of IoT and irrigation systems. The primary purpose of this study sought to determine in what ways can IoT be useful in improving the overall performance of smart irrigation systems. The study further evaluates the usefulness of IoT-based smart farming irrigation systems on reducing the overall cost of crop production.

An IoT architectural framework assists in conceptualising how various components of an IoT based smart farming irrigation system integrate. How well IoT architectural frameworks integrate with legacy irrigation systems is a key success factor to improving their overall performance. The lack of standards and well-established best practices negatively impacts on the potential use of IoT. Various architectural framework proposals were examined in this study and a consensus was reached on the best suited IoT architectural framework for smart farming irrigation systems.

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LIST OF ACRONYMS

Artificial Intelligence	AI
Confidentiality Integrity Availability	CIA
Denial of Service	DOS
Distributed Denial of Service	DDOS
Food Agricultural Organisation	FAO
Global Systems for Mobile Communication	GSMA
Internet of Things	IoT
Internet Protocol	IP
Local Area Network	LAN
Megabits per Second	Mbps
Operating System	OS
Open System Interconnect	OSI
Potential of Hydrogen	PH
ZAR (South African Rand)	R
Technology Acceptance Model	TAM
Transmission Control Protocol /Internet Protocol	TCP/IP
United Nations	UN
United Nations International Children’s Emergency Fund	UNICEF
Uniplexed Information and Computing System	UNIX
Wireless Fidelity	Wi-Fi
Wireless Local Area Network	WLAN

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Internet of things (IoT) refers to the use of interconnected devices, embedded sensors, digital machines, objects, people, and systems to gather data over a telecommunication network with no human interaction (Burhan *et al.*, 2018; Kurmar and Mallick, 2018). IoT has evolved due to the synthesis of various technologies that include machine learning, wireless sensors, and embedded systems. One of the most important applications of IoT is in smart farming irrigation systems. Smart farming irrigation is a concept that emphasis on the use of information and communication technology in the farming environment for the provision of irrigation water for crops to ensure optimal utilisation of water resource (Wolfert *et al*., 2017).

IoT brings a paradigm shift in the field of smart farming. By making use of technology driven irrigation systems and gadgets, farmers can be able to enhance and gain more control of irrigation process (Goap *et al*., 2018). The South African agricultural sector has lost considerable revenue and jobs as a result of a series of drought crisis and unpredictable rainfall patterns. About 60 per cent of water that is supposed to be used for irrigation purposes is wasted owing to poor and inefficient systems used in the irrigation process (Anila *et al.*, 2017). This draws attention on the usefulness of IoT in smart farming to better manage irrigation processes (Gondchawar and Kawitkar, 2016) . It is evident that the application of IoT in smart farming irrigation systems will open various opportunities which include storage of soil moisture data, water predictions, early-warnings, agricultural processes and trace management (Anila *et al.*, 2017). IoT is a novel technological idea which is an extension of the more developed computer networking domain. Its inception allows irrigation systems to monitor and control various variables in the irrigation field.

IoT based irrigation systems have the potential to significantly improve utilisation of scarce water resources. This subsequently results in the reduction of irrigation operational costs namely the cost of energy to run motor pumps and labour attributable towards the operation of irrigation infrastructure (Pernapati, 2018). Integrating older traditional irrigation system models such as drip irrigation, sprinkler, and centre pivot with intelligent IoT technologies will greatly enhance plant germination and shorten the average crop life cycle due to precise water application thereby reducing the overall costs of crop production (Debauche *et al.*, 2018).

Despite the value added by embracing IoT technologies, the attitudes and un-willingness of farmers to forgo traditional irrigations practices is challenged (Chuang *et al.*, 2020). The Technology Acceptance Model (TAM) as reviewed by Mortenson and Vidgen (2016), seeks to explain the behaviours, attitudes, and willingness of end-users to adopt new novel technologies. Since its inception, the model has been applied in numerous studies on user acceptance and usage. Furthermore, the model states that the perception of users on the usefulness and user-friendliness of the technology will greatly influence user acceptance. The success of IoT-based smart farming irrigation systems is heavily dependent on the attitudes and willingness of farmers to accept this novel technology. The rate of adoption of an innovation technology system is a useful metric in measuring the overall successful adoption of a technology (Rogers, 2010).

The agricultural irrigation sector operates in a complex interaction between water resources and the technological environment. It is essential that irrigation systems are designed taking into cognisance the external technological environmental factors that largely impact the overall performance of irrigation systems (Dhakal *et al.*, 2018). Due to the diversity of external environmental factors which influence the implementation of various new irrigation technologies, stakeholders and farmers are challenged with the problem of selecting the most appropriate irrigation technology among various alternatives. There is a positive correlation between various variables that include age, technological acumen, level of education, and perception of need with the rate of adoption of a new innovative technology (Chuang, 2020). The rate of adoption of a new irrigation technology is heavily dependent on other factors that include social-economic characteristics stage of development of technology, financial characteristics, and human factors (Chuang, 2020).

1.2 PROBLEM STATEMENT/ MOTIVATION

1.2.1 Reasons for Research

The complexity of IoT use in smart farming irrigation systems presents new challenges for research and innovation studies. IoT use in smart farming irrigation systems plays a vital role in assisting irrigation schemes to eliminate waste of precious water resource, keeping crops healthy and cutting costs (Anila *et al.*, 2017).The primary purpose of the study is to investigate how IoT can be used to enhance smart farming irrigation systems to solve the water scarcity problem thereby improving agricultural crop production. There is an increased number of irrigation technologies that users are challenged to embrace, these technologies include irrigation software used for developing IoT based irrigation systems from concept through to completion as well as accessing irrigation information

(Hydrawise, 2021). Popular examples of irrigation systems applications include Hydrawise Control, Sprinkl, Irrigation Business Software and Rain Bird. Often, these IoT irrigation systems application software's mentioned above are complicated and are developed using different IoT architectural reference frameworks (Hydrawise, 2021). This results in interoperability issues as there is no agreed framework to follow among different software vendors (Palattella *et al.*, 2016; Tawalbeh *et al., 2020*). IoT device sensors generate voluminous unstructured data beyond the capabilities of current database management systems. Most database management systems are designed to handle structured data. The sheer volume of data generated must be stored, sorted, and analysed for presentation to the end-user, it becomes difficult to analyse such type of data as it often contains inconsistences and duplicates in many different formats (Cai *et al., 2016*). This research seeks to establish whether a consensus can be reached on a de facto IoT architectural reference framework and explore challenges encountered by integrating IoT technologies with traditional irrigation systems as well as to investigate the usefulness of IoT in reducing the overall cost of irrigation.

The concept of IoT has been successfully adopted in several economic sectors such as manufacturing, mining, agriculture, and transportation (Nasiri and Objanen, 2017). The agricultural sector can potentially benefit from IoT implementation especially in smart farming irrigation systems. IoT is set to transform the future of irrigation systems implementation by enabling process improvement (Misra *et al., 2015).* Thus, IoT use in smart farming irrigation systems allows farmers to remotely manage irrigation processes more efficiently.

1.2.2 Problem Statement

Water is a precious resource required for crop production. As water becomes more scare, it is vital to tackle the problem of inefficient use of water by irrigation systems (Goap *et al.*, 2018). The problem is particularly greater in bigger multi-crop fields where they are multiple growing seasons. Irrigation performance data collection is low, slow and disintegrated (Nayyar and Puri, 2016). The onus is on irrigation schemes to develop sustainable integrated cost-efficient solutions. Emerging IoT innovative technology devices include sensor networks, which are network connected. These technologies include stations, cameras and smart phone applications which can be used to collect and integrate irrigation performance data to support good decision making (Vineela *et al.*, 2018). One of the most prevalent problems associated with traditional farming irrigation systems is configuring an efficient irrigation schedule. Determining the correct volume of water required for irrigation is critical to avoid over irrigating or under irrigating. Both scenarios will result in water and nitrogen lost to leaching as well as increased energy consumption costs (Vorster, 2015).

Therefore, the research problem statement is: Inefficient utilization of the precious water resource by irrigation systems resulting in increased costs of production and decreased economic benefits from farming. This presents an opportunity for IoT to make irrigation systems smart, effective, and efficient in utilizing resources and thereby enabling larger areas to be irrigated.

1.3 RESEARCH QUESTION

Recently, most small scale and commercial farmers practice irrigation farming (Vorster, 2015). Traditional irrigation systems such as sprinkler irrigation, drip irrigation and open gravity canals have been widely adopted by individual, small and large scale irrigation schemes (Vineela *et al.*, 2018). IoT has the potential to play an important role in enhancing irrigation systems. Integrating IoT with traditional irrigation systems through the use various smart sensors placed in the irrigation field to collect and transmit real-time data enables farmers to analyse the data gathered and make better informed decisions on irrigation scheduling and accurate application of water (Nayyar and Puri, 2017).

Despite the perception farmers might have regarding IoT technology use in irrigation systems, recent trends show an increased adoption of IoT technologies in other domains such as health care, connected homes, smart cities, and education. GSMA (2014) survey estimates that the total number of IoT devices in use will reach 25,5 billion by 2020. There is mounting pressure for irrigation schemes to follow similar trends. This is further aggravated by pressure coming from organisations such as Food Agricultural Organisation (FAO) and government initiatives to promote maximum utilisation of water resources and increased food production (Alvarez *et al.*, 2014).

The central research question is as follows:

> *In what ways can IoT be useful in improving the overall performance of smart farming irrigation systems?*

1.4 RESEARCH OBJECTIVES

1.4.1 Main Research Objective

The primary objective of this research study is to determine in what ways can IoT be useful in improving the overall performance of smart farming irrigation systems.

1.4.2 Sub-Objectives

The sub-objectives of this research are to:

a) Determine how existing IoT-based architectural frameworks can be integrated with smart farming irrigation models.
b) Evaluate the usefulness of IoT-based smart farming irrigation systems on reducing the overall cost of crop production.

1.5 IMPORTANCE OF THE STUDY

The global population growth rate is greater than the exponential increase in food production. The world population in mid-2019 was estimated to be approximately 7,7 billion having increased by one billion people in the last decade (Desa, 2019). The agricultural economic sector is facing various challenges to produce more yields with a few scare resources available to cater for the population expansion (Goap *et al*., 2018). It is imperative that there is need for smart farming irrigation systems to assist farmers to lower the economic cost of water usage thus increasing mass food production. Presently smart farming irrigation systems' implementation is growing due to the increased integration of IoT with smart farming irrigation management systems. The usefulness of IoT in other economic sectors such as health, city management and connected homes can be seen by its wide adoption and success (GSMA, 2014). It is therefore important to better understand the success of IoT models in other economic sectors and how these successes can be applied into smart farming irrigation systems.

Interoperability is the ability of information technology system components to integrate without needing additional special functionalities configured (Palattella *et al., 2016*). IoT is a novel technological realm that extends the typical computer networking model to a heterogenous framework of connected devices (Cheung *et al*.,2020). It is vital to identify which IoT technologies integrate well with traditional irrigation systems so as to improve utilisation and data transmission from various IoT equipment connected to an internetwork.

1.6 LIMITATIONS AND SCOPE OF THE STUDY

The limitations of the study are as follows:

1. The scope of the study focuses on IoT as the underlying technology used to improve smart farming irrigation systems. IoT primarily uses the internet as a point of convergence to

connect various devices or things using limited computational resources. The study does not focus on the use of robotics, artificial intelligence, and machine learning techniques to improve smart farming irrigation systems.

2. The findings of this study are limited to the South African context. Irrigation farms selected under the study are situated in Brits an agricultural town that lies in North-West province of South Africa irrigated by waters of the popular Harbeersport Dam. Expert participants are chosen from IoT solutions consultancy firms, farming communities and academic institutions based only in South Africa.
3. Purposive sampling is used in this study, it relies on the researcher's own judgment and prior experience to select participants that meet the required profile. This could potentially lead to bias as there is a tendency for the researcher to make subjective judgments based on personal opinions.

1.7 ASSUMPTIONS

The following assumptions are made regarding this study:

1. All participants are experts capable of interpreting and evaluating the topic on smart farming irrigation systems. Therefore, a higher cognitive questioning style is applied in the questionnaire.
2. It is assumed that all participants provided accurate information on job titles, work responsibilities, level of education and skill set during the initial recruitment of the panel of experts.
3. All participants will provide honest, reliable and elicit responses in the Delphi survey exercise.

1.8 CHAPTER SUMMARIES

The structure of this research paper is summarised in the following five chapters.

1.8.1 Chapter 1

The first chapter of this research paper establishes the context of the study on Smart farming irrigation systems using IoT. It describes key concepts about the topic under study. In this chapter the researcher motivates the reasons and importance of conducting the study. An outline of the objectives and critical research question to be handled is highlighted. Additionally, limitations and scope of the study is established specifying the demarcation line for the study.

1.8.2 Chapter 2

This chapter presents a critical review of existing literature on the phenomenon of interest on smart farming irrigation systems using IoT. The literature gathered from cited publications is organised in a spread sheet matrix using themes and keywords to filter unimportant literature not relevant to the study. Keywords, outcomes, and themes used in the literature review search strategy include IoT, impact of IoT in smart farming, IoT architecture, interoperability, benefits and barriers to IoT implementation.

1.8.3 Chapter 3

In this chapter, a description of the research methodology process is given specifying the procedures used to collect and analyse the data. The chapter provides justification on why the researcher chooses qualitative research approach together with the Delphi survey. The sampling technique used, and selection criteria of participants is explained. This chapter critically evaluates how the researcher intends to validate the reliability and credibility of the study using triangulation and respondent validation. Lastly ethical considerations are discussed.

1.8.4 Chapter 4

This chapter presents research findings based on the data obtained from the Delphi survey applied. The approach adopted to write up qualitative research data findings is to report the findings using themes and outcomes of each section using narratives that include text tables, diagrams and paraphrased summarised statements to demonstrate key relationships between IoT systems and irrigation systems under study.

1.8.5 Chapter 5

The last chapter of this research paper summarises the conclusions and recommendations derived from this study on IoT’ s usefulness in irrigation systems implementation. The Chapter further discusses outcomes of the study based on the critical research question and purpose. Lessons learnt together with recommendations for further studies are outlined in this section.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

To effectively gather literature in a study on a phenomenon of interest, it is imperative to compile a list of key concepts, ideas, and problems to be investigated to set guidelines for the literature review (Denzin *and* Linchon, 2017). Several studies have been previously conducted on how to improve smart farming irrigation systems using IoT. There are a total of 160 published papers as from the year 2014 to 2019 (García *et al.*, 2020). Most of these studies investigated on the use of various IoT techniques for water management in irrigation systems using sensors to collect data on various environmental parameters. The literature obtained from the cited publications is organised in a literature review matrix using Microsoft Excel spreadsheet application software. The literature review matrix compiled details about sources, fundamental theories, framework models and dates, highlighting agreements and disagreements among various authors as well as to identify unanswered questions and gaps. The identified keywords and outcomes in literature review search strategy include IoT, impact of smart farming irrigation systems, IoT architecture, IoT integration benefits and challenges of IoT implementation in smart farming irrigation systems. Concepts ideas, and problems identified formed the basis for developing a theoretical framework model that will be used to filter and guide the literature review. Developing a theoretical framework model eliminates irrelevant literature that is not pertinent to the study. A theoretical framework forms the basis upon which knowledge is constructed in a literature review (Osanloo and Grant, 2016).

IoT is a development of several predecessor technologies that include information systems, sensor networks and network development. These technologies are designed to collect data from computing devices and consumer electronics for processing (Serpanos and Wolf, 2017). An IoT system will consist of sensors and several actuators with the primary purpose of processing real-time data generated by devices. IoT Systems must be designed taking into account efficient data transmission and power consumption. Energy consumption is a key success metric to be used in IoT irrigation systems (Serpanos and Wolf, 2017).

It is evident that IoT significantly improves crop production and water utilisation, this is seen by how IoT assists farmers to preserve water and monitor irrigation scheduling thus enabling them to make informed decisions (Misra *et al.*, 2015). This is supported by a research study conducted by Darshna et al (2015) , the study examines various IoT smart farming irrigation models used to minimise water waste in agricultural fields. It proved that integrating IoT models with irrigation systems resulted in saving water by up to 53 % as compared to manual irrigation by sprinklers in a field measuring one thousand square meters under study. The increased use of IoT in irrigation systems has been associated with an increase in crop productivity (Goap *et al.*, 2018). It is suggested that replacing old traditional irrigation systems with IoT technologies that use sensors such as moisture sensors, PH sensors, and photocell sensors will result in more efficient collection of data (Darshna *et al.*, 2015).

Most countries' economies are heavily dependent on agriculture as a centre of economic activity and food security (Bruinsma, 2017). Recent reports by the World Health Organisation (2018) estimated that about 820 million people are still undernourished world-wide. This is a decline by approximately 180 million over the past 10 years. This aggravates increased fear that food production will not match the exponential growth of the world population thereby threating food security. Therefore, research work should focus on improving food security. Efficient IoT technologies directly and indirectly assists farmers improve crop production by allowing farmers to efficiently utilise water, reduce energy consumption requirements for pumping water and efficiently scheduling irrigation times (Hogan et al., 2007). IoT becomes a key success determinant in sustaining and supporting agricultural dependent economies.

Integrating older traditional irrigation systems such as drip, sprinkler, and centre pivot irrigation techniques with intelligent IoT technologies will significantly improve plant germination and shorten the average crop life cycle due to correct water application. Such an approach will subsequently reduce the overall cost of crop production (Debauche *et al*., 2018). Despite the low initial capital investment requirements for traditional irrigations, their poor efficiency and labour intensiveness make them very unsuitable for large-scale commercial use. For communal subsistence farmers who typically irrigate less than 2 hectares of land, traditional irrigation practices have been proven to be sufficient. However, for large scale commercial farmers who typically irrigate more than 10 hectares of land, more innovative cost-efficient solutions have to be explored in order to continuously sustain agricultural food production and food security to cater for the ever-growing global population (Kulecho and Weatherhead, 2006).

2.2 UNDERSTANDING IOT TECHONOLGIES

IoT can also be defined as a network of interconnected devices and systems for the purpose of gathering and sharing data (Wortmann and Flüchter, 2015). IoT makes use of wireless networks embedded with various data collection sensors to connect devices and systems to each other and the internet with low human interaction (García *et al.*, 2020). Previously, data transmission was limited to computing and mobile devices. IoT is a rather novel topic arising within more established concepts on computer telecommunication. IoT is therefore an extension of computer network engineering. It drastically increases the number of connected smart devices, systems and appliances (Palattella, 2015).

GSMA (2014) IoT devices survey predicted that the total number of connected devices world-wide is set to reach 25,5 billion by the year 2020. Cisco's IoT Connectivity report also supports the widespread use of IoT technologies, it is estimated that the total number of connected devices globally will reach 28,5 billion by the year 2020. The same report projects that the average broadband internet speed will be approximately between 11,7 Mbps to 28 Mbps by the year 2020 (Emear *et al.*,2018).

2.2.1 IoT hardware Infrastructure

IoT hardware is a set of physical components that are responsive in nature, possessing the ability to collect data from the surrounding environment. There is a wide range of IoT devices on the market, these devices consist of sensors, switches, routers, and single-board processors such as Arduino and Raspberry Pi. The most critical hardware component at the core of IoT systems is the sensor. Sensors are devices that generate electronic pulses based on a physical condition, these devices constitute of power, radio frequency and energy modules (Serpanos and Wolf, 2017). The primary purpose of the sensor is to acquire electronic signals from the devices that is being monitored and converting them to pulses that are usable by a computer system. Data collected from sensor hardware normally includes moisture content, pressure, humidity, speed, vibration, and temperature. Typically, IoT irrigation sensors are very expensive making them unaffordable for small-scale communal irrigation farmers. However, new low-cost sensors are being developed by manufactures. Therefore, the cost of sensors is continuously decreasing over the years (García *et al.*, 2020). However, the decrease in the cost of sensors could mean compromising the quality, performance, and reliability of the sensor. Previous experimental studies have proven that various variables must be considered when determining the performance of a senor relative to cost (Abba *et al., 2019*). Variables such as configuration settings, calibration settings, application usage and deployment characteristics also play a significant role in determining the performance of a sensor.

The next block of devices to be considered is the data processing devices or modules. These devices are responsible for the transformation of data collected by sensors to a more meaningful form

(Serpanos and Wolf, 2017). Arduino and Raspberry Pi are the most widely used processing devices in IoT systems. These processing devices are stripped computer processing systems that can be used to perform basic processing tasks which can be done by a computer. The cited reasons for the wide adoption of these two processing modules in IoT systems is largely attributed to low-cost, open source, simple programming platform, and hardware extensibility (Nandhini *et al.*, 2017).
Marso and Macko (2019) conducted a systematic literature review study on prototyping solutions using Raspberry Pi. The primary purpose of the survey was to investigate on the usefulness of Raspberry Pi in IoT projects. The findings of the survey reported that most Scientific Researcher's and Engineers choose Raspberry Pi for creating prototypes, the primary reason cited being price relative to performance.

Lastly, communication network infrastructure is a key requirement for successful implementation of IoT systems. Traditional networking infrastructure will consist of connectivity devices such as hubs, routers, modems, wired and wireless technologies. These devices perform basic dedicated tasks to provide access to network services (Serpanos and Wolf, 2017). It is vital to determine whether the current state of network infrastructure is sufficient to handle the load generated by billions of IoT devices that need to exchange data. Wireless networking technologies can typically provide between 300 megabits per second to approximately 1 gigabit per second, while fiber optic connectivity can deliver up to 100 gigabits per second (GSMA, 2014).

2.3 IOT SYSTEMS ARCHITECTURE

In essence, IoT architecture can be treated as a system which can be physical, virtual or a combination of the two consisting of a collection of active physical devices, sensor actuators and cloud services specific for IoT protocols (Serpanos and Wolf, 2017). While there are various IoT systems implementation, the underlying architecture and principles of information processing remain the same. Although IoT is still an emerging technological idea, it is still seeking to form its own reference architecture model. Its usefulness in smart farming is evident through saving overall operational costs and enhanced water utilisation. The absence of a universal de facto IoT architecture is limiting the full potential of IoT. Porter and Heppelmann (2014) suggest that IoT architecture will assist in providing a set of design standards for device vendors to enhance interoperability especially for legacy devices and systems. Having architecture in mind further assists in conceptualising how the various components of IoT-based smart farming irrigation system integrate. A model becomes a blueprint of system functionality and development. However, it is generally argued that architectural frameworks could restrict practical application on different scenarios since they are often generic, complex, and too theoretical (Kumar and Mallick, 2018). This section will review previous IoT architecture proposals.

2.3.1 Three Layer IoT Architecture

While there is no consensus on a single IoT architecture which is universally accepted. The three layer architecture was introduced in the early development of IoT. It is considered to be the most basic, convenient and easy to comprehend. The development of the layered approach is inspired by the popular Transmission Control Protocol / Internet Protocol (TCP/IP) architecture model that also uses the layered approach. TCP/IP consists of four layers that specifies a family of protocols that have collaborating functions for each layer (Kumar and Mallick, 2018). The Three-layered IoT architecture proposes three layers namely perception, network, and application. According to Kumar and Mallick (2018), these layers have the following specifications:

1. **Perception Layer** is synonymous to the network access layer of the TCP /IP architecture model. It specifies devices and sensors for gathering data on the environment where smart objects are located. The data collected at this layer will be subsequently transmitted to the next middleware layer where data is stored and analysed using data analytics techniques (Muccini and Moghaddam, 2018).
2. **Network layer** is responsible for enabling internetwork connectivity with other smart devices. Other scholars refer to this layer as the transmission layer instead of Network layer (Al-Qaseemi *et al., 2016*). This layer generates a lot of research attention since its acts as a bridge between the perception layer and the application layer hence it is sensitive to interoperability issues and common security attacks.
3. **Application Layer** the application layer specifies the provision of application specific services to the end user. It describes the applications that IoT can make available (Muccini and Moghaddam, 2018). The end users in this instance include systems such as smart irrigation systems, smart cities and automated health care services.

Three layer IoT architecture forms the basis for fundamental features for sustaining IoT to enable interoperability and integration of smart devices and systems. However, Kumar and Mallick (2018) argued that it is not adequate to cover the nitty-gritties in IoT systems implementation. Therefore, further research proposed expanding the number of layers in the architecture to include the processing, business, and support layer to come up with the four and five layer IoT architecture.

1. **Processing layer** is at the core of the conventional IoT architecture. This layer is primarily responsible for collecting data generated by the lower layers and transforms the data into meaningful information for data analytics. This layer makes use of supporting technologies such database management systems, network telecommunication systems, and information process management (Kumar and Mallick, 2018).
2. **Business Layer** provides services that enables end-users to manage and control the functionality of IoT systems. It further defines business and profit models used in IoT systems implementation (Burhan *et al.*, 2018*)*.
3. **Support Layer** the sole reason for adding the support layer in the three layer architecture is to cater for security threats that are prevalent on the internet. Support layer is proposed to address key security functions namely authentication and secure transfer of data between the three layers of the IoT architecture (Burhan *et al*., 2018). Authentication is important in IoT systems since it enables secure access to resources which includes data, hardware, and applications (Al-Qaseemi *et al., 2016*). The second function of the support layer is to ensure secure transmission of data to avoid common network threats particularly Denial of Service (DoS) attacks. (Burhan *et al., 2018*) describes a DoS attack as an attack targeted at shutting down systems functionalities.

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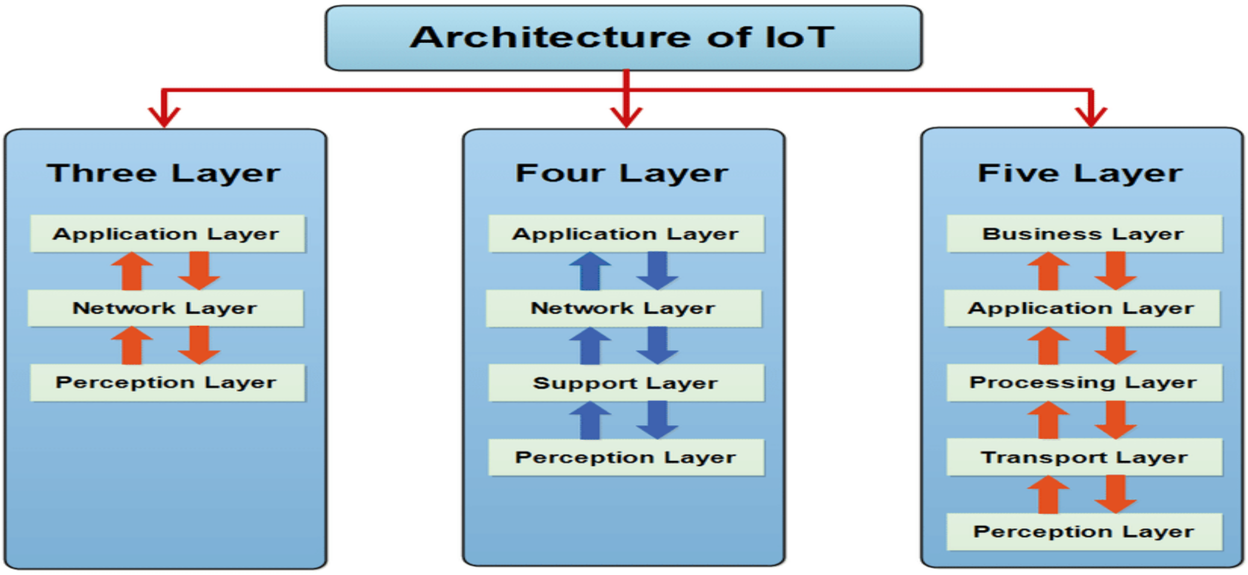


Figure 1 The Layered Architecture of IoT (Burhan et al.,2018)

Figure 1 illustrates the similarities and differences between the Three-layered, Four-layered and Five-layered architecture of IoT.

2.3.2 IoT Organisation Architecture

Serpanos and Wolf (2017) specify an IoT architectural model that demonstrates the organisation of an IoT system. The model classifies the IoT organisation into various components as opposed to using a layered approach. These components include:

1. **Plant and environment** this component is responsible for the physical systems in which IoT systems transmit data through procedural interfaces. This component performs functions similar to the physical layer of the Open Systems Interconnect (OSI) model and the perception layer of the three layer IoT architecture. Physical layer of the OSI model defines the hardware devices, cabling, and pulses for transmitting raw binary bits over a physical data link connecting network devices (Goralski, 2017).
2. **Device** component specifies a set of sensors for interconnecting hardware equipment together. Sensors are typically embedded into other system components thus providing capabilities for sensing, recording, and transmitting data over an internetwork. Data gathered by the device component can be analysed and reports can be generated to allow users to make better informed decisions. Furthermore, alerts are generated based on triggers when a particular event criterion is met (Serpanos and Wolf, 2017).
3. **Hub** component provides central connectivity of multiple devices into a network to enable communication between multiple devices. In this case hub component can include processing and storage capabilities. This component is synonymous to the network layer of the TCP/IP architecture reference model. According to Goralski (2017), the network layer provides a critical function of forwarding packets across a network using logical address or Internet Protocol (IP) address.
4. **Fog Computing and Cloud Services: -** Fog computing also known as Edge computing refers to computing methods used to provide services more immediately by extending cloud computing to the edge of the network (Mahmood, 2018). Large amounts of data generated by IoT is growing exponentially, the nature of the data generated by IoT systems is disruptive for predictable data processing. Therefore, the current network and data centre infrastructure is poised to be strained (Burhan *et al., 2018*). It is inefficient to transmit large amounts of data through cloud infrastructure due to high costs of bandwidth, data transmission delay and lower response times. Recent research studies have recommended the implementation of Fog computing to overcome these challenges. Fog computing in this case extends the fundamental functionality of cloud computing by integrating closer together devices or things that generate the data and processing of data. These devices are referred to as Fog devices, they are typically

installed and configured across the network. It is proven that Fog Computing architecture significantly reduces the overall network latency during data transmission as compared to cloud computing (Burhan *et al., 2018*).

2.3.3 IoT Technology Framework Model

Porter and Heppelmann (2014) proposed an IoT framework model that can be applied across multiple domains. The foundation of this model is based on the principle that IoT can be subdivided into multiple layers. Each layer performs a series of related activities. Layering enables each layer to handle its activities independently. Furthermore, it allows users and developers to understand how hardware (things), networks (internet), and software elements function together. Figure 2 illustrates Porter and Heppelmann (2014) IoT Framework Model. The model consists of three core layers namely IoT cloud, connectivity, and things/ device layer. IoT cloud layer governs how software components execute, store and interface with the end user. The connectivity layer is primarily responsible for data transmission between the device and IoT cloud applications. Thing / device layer defines the mechanical and electrical connectors', this includes sensors, actuators, connectivity ports, and wireless antennas (Porter and Heppelmann, 2014).

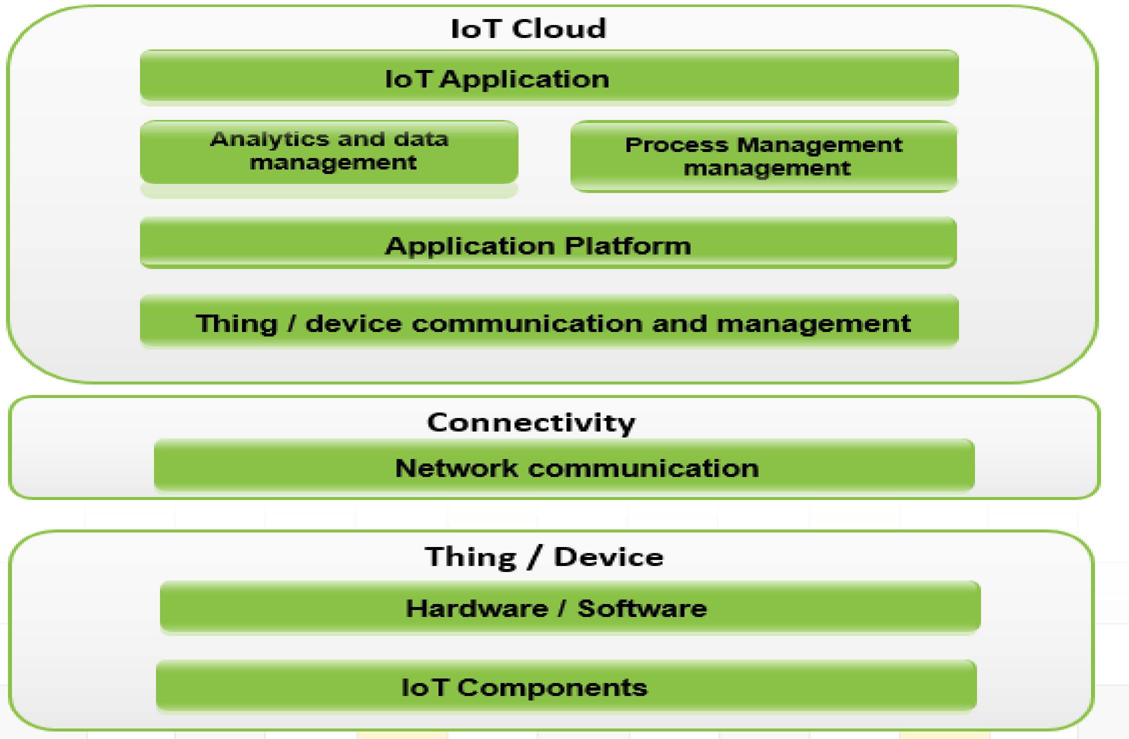


Figure 2 IoT Technology Framework Model (derived from Porter and Heppelman, 2014)

Wortman and Flüchter (2015) propose a similar revised IoT product and service logical Framework based on a layered approach has illustrated in Figure 3. For instance, the tractor operates at the Thing layer of the IoT product service logic framework. Integrating tractor functionality with IoT will enhance collection of data used for predictive maintenance and enhanced operational device performance. Improving utilisation and performance of connected devices or things will require a network of interconnected hardware devices and software components in a hierarchical layer as illustrated in Figure 3 (Wortmaman, and Flucher, 2015).

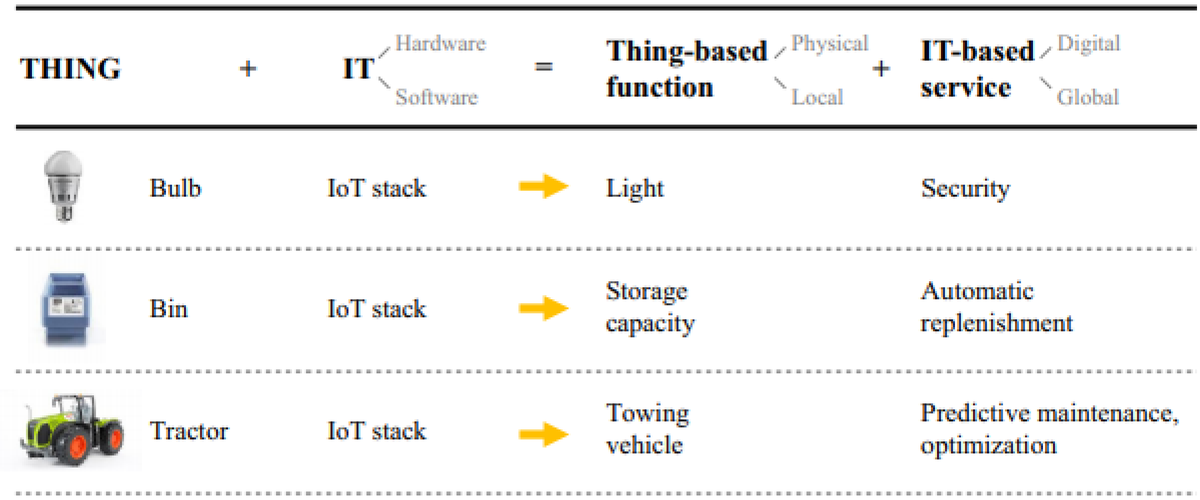


Figure 3 IoT Product-Service Logic (based on Fleisch et al., 2014)

2.4 IOT IN SMART FARMING IRRIGATION SYSTEMS

The agricultural economic sector is the largest consumer of water resource through irrigation systems (Goap *et al.*, 2018). A number of irrigation schemes in many countries are faced with the growing need to maximise water utilisation. In-efficient use of water is negatively affecting the level of food production thereby posing a threat to food production and economic growth (Anila *et al.*, 2017). However, many farmers are still using older traditional irrigation systems. The low participation is largely attributed to attitudes and unwillingness of farmers to adopt technologies that are still in early development (Misra *et al.*, 2015). Another factor is the prohibitive cost of intellect and infrastructure required for IoT-based smart farming irrigation systems implementation (Sahu and Behera, 2015). Zenvus a leading Agri-tech company in Africa is selling a range of soil sensors that are integrated with micro-SD wireless network interfaces for use with smartphones and computers at a cost of between USD$ 200 to USD$ 650 for a single sensor which covers an area of approximately three hectors (Panel, 2018). Most small to medium scale farmers will not have access to computing equipment and they will not be able to afford the required number of soil sensors.

This section will review some previously proposed IoT based smart farming system models and prototypes as well as to evaluate the usefulness of these models in enhancing irrigation performance.

2.4.1 Paddy Growth Monitoring Systems

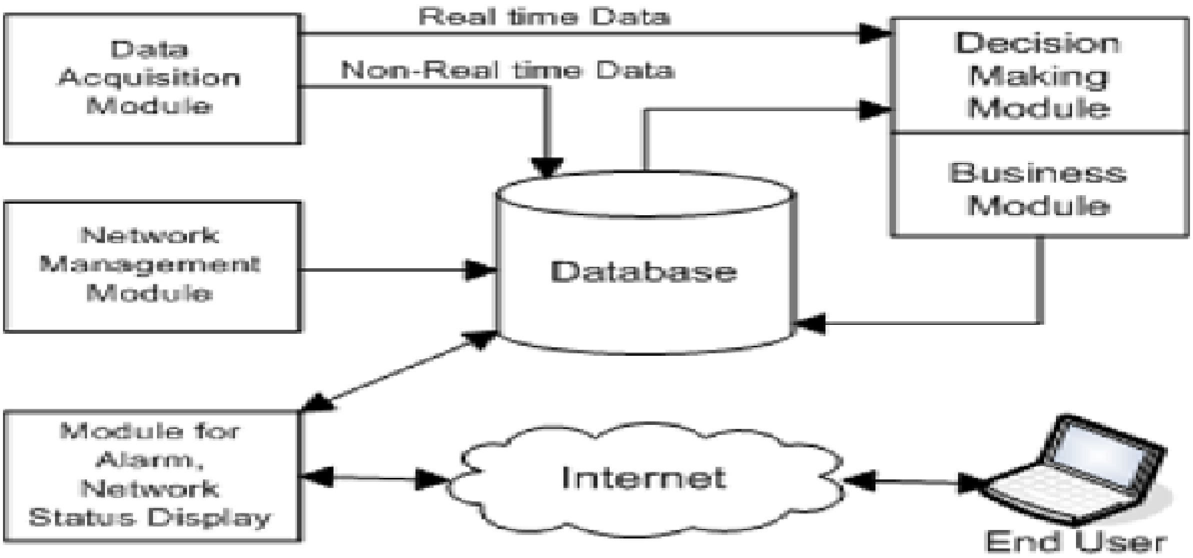


Figure 4 Paddy Growth Monitoring Prototype (Setiyono et al., 2017:9)

Paddy Growth Monitoring system was developed by researchers to address challenges of low rice productivity and yield. It is noted that most farmers are not practising precise agriculture and modern water management techniques coupled by shortage of labour and energy resources (Setiyono et al., 2017). The proposed Paddy Growth Monitoring system is aimed at enhancing rice productivity through the provision of a cost-effective outdoor growth monitoring system built on wireless sensor networks. Figure 4 illustrates the proposed prototype, it consists of various sensors placed in the agricultural field, these sensors collect data on environmental variables such as temperature, humidity, and moisture content. Upon collection of relevant data, the data is then transmitted to a centralised server for processing and analysis using expert and machine learning systems.

2.4.2 IoT based smart Irrigation Monitoring Prototype

It is not always feasible for irrigation workers to keep track of all activities within the irrigation field due to typical sizes of crop fields. This will often result in underutilisation of scarce water and energy resources. To overcome these problems, Goap et al (2018) developed an IoT based smart irrigation system prototype. In this prototype, traditional irrigation system objects are embedded with humidity, temperature, and soil moisture content sensors to sense the environmental conditions. The data collected by the sensor environment will subsequently be transmitted using wireless sensor networks to a centralised micro processing device. Irrigation status information is continuously updated using microcontrollers such as Arduino and Raspberry Pi. Furthermore, updates are pushed to the end user using different web application interfaces and dashboards on Microsoft Windows, Android or Mac OS platforms. Various other IoT based smart irrigation monitoring systems have been developed in other research work. Gondchawar and Kawitkar (2016) designed a similar prototype for monitoring the irrigation field using ZigBee. In this case, ZigBee is an alternative replacement protocol for Wi-Fi due to its low power consumption, bandwidth requirements and ability to support mesh networking.

2.4.3 Sensors used in IoT Based Smart Farming Irrigation Systems

The following section will explore various sensors that are specifically used in IoT Smart Irrigation systems.

1. **Soil Moisture Sensor -** this device is primarily used to measure the moisture content present in the soil, it uses capacitance to measure dielectric permittivity of surrounding medium (Goap *et al., 2018*). Soil moisture sensors are easy to install and configure. Moreover, they are relatively inexpensive. However, it is recommended to conduct an intensive study of the irrigation field conditions before installation since they require specific calibration depending on the type of soil (García *et al., 2020*).
2. **PH Sensor-** this is a device used in IoT irrigation systems to measure alkalinity and acidity of water. The pH scale ranges between 0 to 14 where pH 7 is considered the neutral point. Most soils have pH values ranging between 3.5 to 10. However, in areas with higher rainfalls, soil pH values range between 5 to 7. On the other hand, lower rainfall areas typically have pH values of between 6.5 to 9 (Oshunsanya, 2018). Soil treatment to correct soil pH values is often needed. This can be done either through the addition of limestone or sulphur to adjust the pH value as per plant requirements. The most suitable pH range for most agricultural crops is between 6.0 to 7.0 (Miller, 2016). Installation of pH sensors in irrigation systems enables correct monitoring of PH levels. Soil PH determines how well plants grow, root development and availability of correct nutrients (Goap *et al*., 2018).
3. **Temperature sensor -** is a device used to measure environmental temperature and convert it into readable format. There are two implementations of temperature sensors in irrigation systems namely direct contact and indirect contact. Direct contact requires close contact with the object where temperature is being measured while indirect contact does not require close contact with the object under observation (Gondchawar and Kawitkar, 2016). Thermostats are widely used temperature measurement instruments in the agricultural field due to the number of benefits which include low cost, small size, and huge sensitivity as compared to other temperature measuring instruments such as resistance temperature detectors and Infrared thermometer (Barrios and Kleiminger,2017).

2.5 THE USE OF IOT IN SMART FARMING IRRIGATION SYSTEMS

The global population growth rate is greater than the exponential increase in food production. United Nations population data analysis estimated that by the year 2050, the world population will approximately be 9,3 billion (Stonawski *et al., 2015*). The agricultural sector is challenged to cater for the increased demand for agricultural products caused by global population expansion. Expanding the use of IoT into smart irrigation systems will significantly impact the efficiency of irrigation systems resulting in increased agricultural products yield. A quantitative assessment on the impact of IoT technologies in irrigation systems conducted in India proved that integrating IoT technologies with irrigation systems for farmers cultivating sugarcane resulted in increased yield (Dhakal *et al.,* 2018). This section will review the usefulness of IoT in smart farming irrigation systems, benefits of integrating IoT in irrigation systems and explore challenges encountered with the implementation of IoT based smart farming irrigation systems.

2.5.1 Water Utilisation

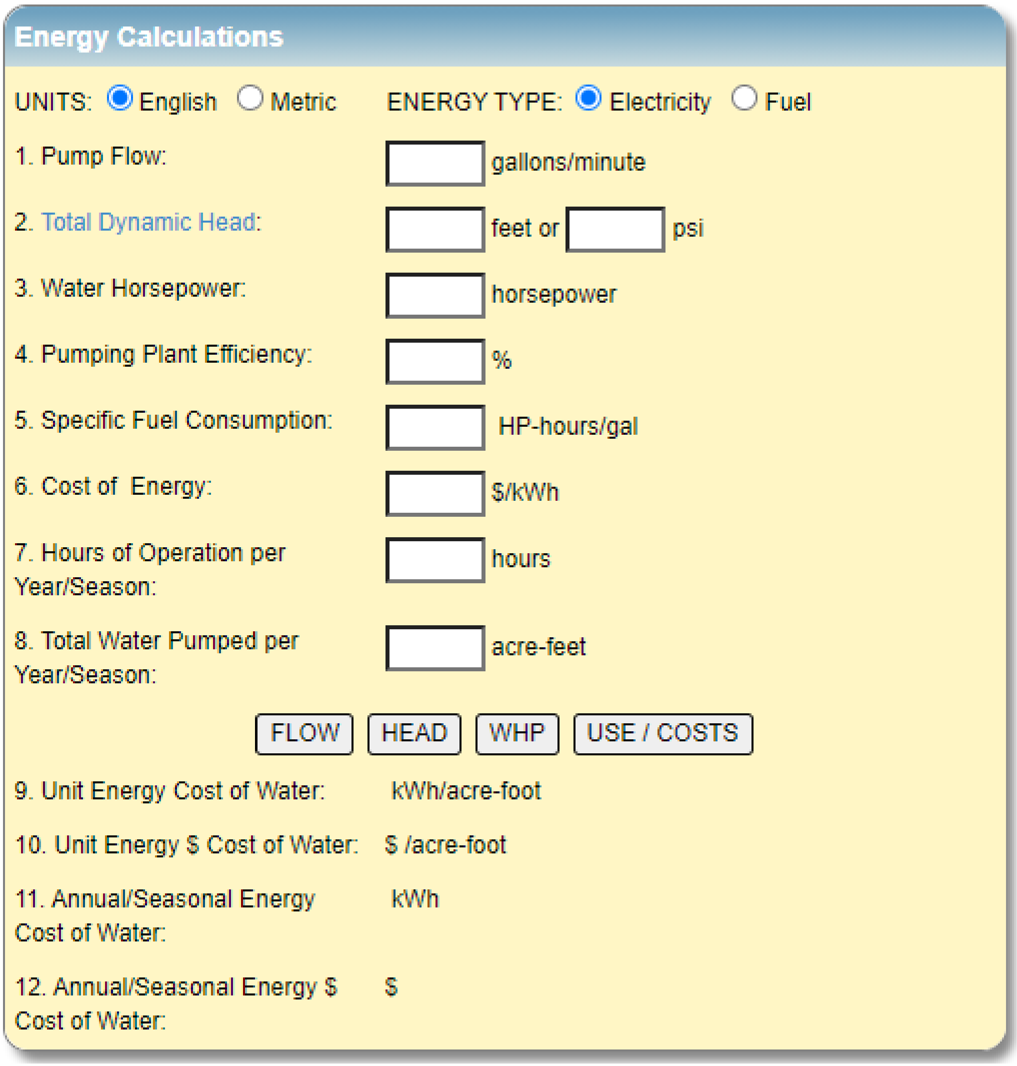
Irrigation water is considered a scarce precious resource within the agricultural sector particularly in drought-stricken regions. Agriculture irrigation consumes approximately 70 percent of freshwater (Garcia et al., 2020). Therefore, it is critical for irrigation systems to efficiently use water resources. Irrigation water efficiency use refers to smart application of water in the irrigation field to minimise the amount of water used without compromising the quality of crops (Grafton, 2018). Traditional irrigation systems waste on average 30 percent of water pumped into the field as a result of inefficient irrigation methods used and improper configuration of irrigation infrastructure. Under-irrigation and over-irrigation are major concerns in irrigation systems. The adverse impact of over-irrigation and under-irrigation includes water loss, increased power consumption, root decay, germination problems, nutrition leaching, reduced crop quality and yield (Vorster, 2015). IoT based irrigation systems have been previously proposed and developed to address the problem of under-irrigating and over-irrigating. An IoT based irrigation system can collect weather data on water requirements for crop production based on soil moisture content, humidity and temperature. Weather data is often gathered from reliable metrological weather department stations, various sensors placed in the irrigation field or achieved statistical weather patterns (Abba *et al., 2019;* Goap *et al.,*2018; Togneri *et al., 2019*). The data collected by IoT based smart irrigation systems enables better informed decisions to support precision watering and reduce in-efficiencies in distributing water.

IoT smart farming irrigation scheduling uses technologies that assist farmers make informed decisions on the exact amount of water to apply at the correct time. These technologies incorporate timers integrated into irrigation infrastructure. An irrigation timer is an integral hardware component of an automated irrigation system, it is an electronic device embedded with a system clock providing mechanisms to program the frequency of irrigation, calculate the start time, end time and duration of irrigation (Fidelis and Idim, 2020). These functionality features enable saving of gallons of water applied into the irrigation field. Barlow *et al* (2004) invented and patented a remotely controlled irrigation timer with fault detection. The principal technological strategy applied in this timer allows remote scheduling of multiple separate timers located across the irrigation field enabling centralised management of water scheduling.

2.5.2 Irrigation Operational Costs

According to Hogan et al (2007), irrigation operational costs refers to the expenses related to the ongoing operation of the irrigation system payable thought the lifetime of the irrigation system. Irrigation operating costs can be subdivided into three broad categories namely labour costs, infrastructure maintenance and energy consumption. Labour requirements for irrigation purposes in this study are calculated based on number of hours spent per hectare under irrigation. Traditional irrigation practices such as overhead sprinklers and pivot systems are considered more labour intensive since they require manual monitoring of soil moisture content, fault detection and managing watering schedules. A series of IoT based irrigation systems prototypes have been previously developed to demonstrate the usefulness of IoT in improving labour efficiency in irrigation systems. The key findings of these prototypes reveal that IoT based irrigation systems allows farmers to save labour hours spent monitoring water levels and irrigation scheduling (García *et al*.,2020). Furthermore, this decreases human interaction and errors while achieving similar watering requirements as compared with traditional irrigation systems. IoT smart farming irrigation application software allows employees to navigate using a dashboard on a smartphone or computer to access functionalities that include real-time remote monitoring and notifications on irrigation activities. These functionalities significantly improve labour productivity and communication between employees.

Agricultural irrigation is very energy intensive. Diesel, electricity and solar are the most widely used sources of energy for powering irrigation pumps. These sources of power can be very costly considering the duration of irrigation, pumping pressure and application efficiency (Martin *et al., 2011*). Energy in irrigation systems is often wasted due to inefficient energy usage practices. Hence it is imperative to implement technology systems that reduce power consumption through constant monitoring of usage patterns. IoT based irrigation systems allow farmers to calculate energy usage requirements based on various metrics such as duration of irrigation, pump flow, water horsepower and energy tariffs. In addition, IoT based systems can incorporate smart electronic meters to capture data on power consumption patterns. This data enables irrigation farmers to make better informed decisions on power usage thus significantly reducing operational costs. Figure 5 shows an IoT dashboard for calculating energy consumption and costs.



Energy Calculations

UNITS: English Metric ENERGY TYPE: Electricity Fuel

1. Pump Flow: gallons/minute
2. Total Dynamic Head: feet or psi
3. Water Horsepower: horsepower
4. Pumping Plant Efficiency: %
5. Specific Fuel Consumption: HP-hours/gal
6. Cost of Energy: $/kWh
7. Hours of Operation per Year/Season: hours
8. Total Water Pumped per Year/Season: acre-feet

FLOW HEAD WHP USE / COSTS

9. Unit Energy Cost of Water: kWh/acre-foot
10. Unit Energy $ Cost of Water: $ /acre-foot
11. Annual/Seasonal Energy Cost of Water: kWh
12. Annual/Seasonal Energy $ Cost of Water: $

Figure 5 Irrigation Energy Calculator Menu (after Hogan et al., 2007)

Irrigation maintenance refers to the monitoring and repairing of components of an irrigation system. These components include but not limited to power distribution, pumping systems and water distribution equipment (Martin *et al.*, 2011). Regular preventive maintenance of equipment is crucial to avoid the likelihood of failure of irrigation equipment components. Preventative maintenance results in improved efficiency and availability as it is proven that well maintained production infrastructure performs better (Martin *et al.*, 2011). Downtime caused by unplanned interruptions often leads to decrease in employee productivity ultimately resulting in loss of income.

IoT can assist irrigation operators reduce the likelihood of irrigation equipment failure by facilitating data collection and processing. IoT connected devices and smart sensors embedded into traditional irrigation equipment collect data insights on irrigation components metrics that include pressure, vibration, and temperature. For instance, vibration and pressure sensors can be used to detect potential wear and tear of water pipes and water leaks (Dhulavvagol, 2017).

2.6 BARRIERS TO IOT BASED SMART FARMING IRRIGATION SYSTEMS IMPLEMENTATION.

IoT presents numerous opportunities to enhance irrigation systems performance. Previous studies have proven that implementing IoT in irrigation systems significantly increases crop yield, improves water utilisation, and reduces power consumption (Wolfert *et al*., 2017). However, the full potential of IoT is accompanied by barriers that hinder its successful implementation in irrigation systems. This section seeks to describe barriers and potential threats in the implementation of IoT in irrigation systems.

2.6.1 IoT interoperability and Integration

IoT interoperability as the ability of various information technology system components to interoperate without requiring additional hardware and software configuration changes (Noura and Gaedke, 2019). Whereas IoT integration refers to interconnection of independent heterogeneous system components so they can function well together, this involves integrating IoT devices, data platforms, legacy systems, and applications without the need for additional custom system development (Verdouw *et al*., 2016). How well IoT architectural models integrate with legacy irrigation systems is a key success factor to improving the overall performance of irrigation systems.

According to Rose *et al* (2015), the lack of standards and well-established best practices in IoT architectural models negatively impacts the potential use of IoT. This causes IoT systems to malfunction and produce undesired output. IoT architectural designers are faced with design complexities to maintain compatibility with older irrigation systems. They further identify the challenges of integrating legacy systems with new novel IoT architectural frameworks.

Firstly, numerous data is collected by various types of sensors placed in the irrigation field. Often this data comes in many different formats such as structured and unstructured data. Commonly used traditional database management systems based on structured query language are not capable of managing and processing large complex volumes of data generated by IoT devices within a limited time frame (Cai *et al., 2016*). Database management systems concepts need to be realigned to cater for the emergence of IoT data. This will enable better organisation and presentation of data that is suitable for the end user.

Secondly, it is expected that the total number of connected devices globally is set to reach 25,5 billion in the year 2020 (GSMA, 2014). It is crucial to assess network communication infrastructure readiness to support the increased number of IoT connectivity devices. Irrigation Engineers and Researchers that have conducted previous studies tend to focus more on the application of IoT in irrigation systems and neglect telecommunication infrastructure requirements. Literature on IoT infrastructure performance is quite limited. However, in a study conducted by Rafique and Shah, (2016) to determine the current state of IoT infrastructure performance using key metrics that include availability, bandwidth rating and load. The study utilised simulation software and mock system hardware to assess the performance of IoT infrastructure in various deployment case scenarios. Key findings revealed that IoT infrastructure issues were mostly centred on bandwidth usage. The majority of IoT systems are built of Wireless-Fidelity (Wi-FI) standard that typically has a bandwidth rating of 10Mbps. This rating is considered insufficient taking into consideration the data transfer load typically experienced in IoT systems.

2.6.2 IoT Technology Adoption and Diffusion

Sustainable development of IoT irrigation systems is heavily reliant on the adoption and diffusion rate of IoT technological realm at this stage of development. Technology Acceptance Model (TAM) is an information technology framework that models how users embrace and utilize a new innovative technology. TAM suggests that perceived usefulness, technological ease of use and peer pressure significantly determines the rate of adoption of a new technology (Alomary and Woollard, 2015). Earlier studies on Diffusion of innovation also explained how new innovative technologies infiltrate into societies and cultures from inception to widespread adoption (Rogers ,2010). Since then, several reviews on diffusion of innovation have been conducted under various scenarios (García-Avilés, 2020; Zanello *et al.,* 2016). It is critical to identify key barriers to IoT irrigation systems adoption, without user buy-in, the desired benefits of IoT will not be achieved. Level of education and training is a key predictor of user adoption of a new novel technology. Studies have indicated that there is a positive correlation between level of education and training of users with perceived value (Nicolescu *et al., 2018*). There is need to develop educational content and programs targeted at influencing farmers attitudes and perception towards IoT use in irrigation systems.

2.6.3 IoT security Issues

The primary goal of security in the broadest sense is to protect valuable assets from damage, threats as well as disruptions (Stallings and Brown, 2017). This broad goal is also applicable in IoT security. Confidentiality, Integrity, Availability (CIA) triangle is an information systems model that provides a reference framework for securing information systems assets (Stallings and Brown, 2017). Confidentiality principle ensures that data is only accessible by authorised users and objects. It is critical to ensure that IoT sensors and users do not access each other's data and memory space. Additionally, integrity principle specifies that data should be consistent, accurate and trust worth. IoT devices generate large volumes of data that needs to be transferred from objects under investigation to processing devices via an internetwork. The challenges presented is to ensure that the volumes of data transmitted is not modified or lost during transmission due to intentional and unintentional interference (Kumar and Mallick, 2018). The last goal in the CIA triangle is availability. Availability is guaranteed accessibility of information to the intended users, IOT irrigations systems should aim to minimise downtime. The vast majority of IoT attacks target availability of IoT systems. As mentioned earlier, IoT irrigation systems potentially generate voluminous data, this posed as vulnerability as attacks make use of this data to consume available bandwidth and processing power.

2.7 CONCLUSION

The advent of IoT technological realm brings various opportunities for redesigning almost all economic sectors. Irrigation systems are no exception to this technology manifestation. IoT technology emergence is challenging existing irrigation system practices and methods. There is no doubt that integrating IoT with traditional irrigation system has a positive impact on the overall performance of IoT systems. Previous literature has shown the role played by IoT in smart irrigation systems to increase crop yield, conserve water and reduce irrigation operating costs. However, there are various barriers that hinder the successful implementation of IoT in smart irrigation systems that need to be explored. It is equally important to understand IoT's enabling technologies that encompass sensor hardware, software, and telecommunication infrastructure. Currently there is no agreed IoT architecture model for software and hardware vendors to follow. Research will be required to assess the possibility of reaching a consensus on IoT architecture model to be adopted by various vendors. Lastly, technology diffusion rate is a key determinant for the successful implementation of IoT in irrigation systems. Literature has identified the need to influence farmers perceived value on IoT implementation in irrigation systems.

CHAPTER 3 RESEARCH METHODOLOGY AND DESIGN

3.1 INTRODUCTION

This study investigates on the influence of IoT in improving the overall performance of smart farming irrigation systems. Investigating such a phenomenon requires research methods that allow participants to share their personal experiences and understanding. This chapter presents a detailed description of the research methods applied in this study to answer the critical research question. The researcher outlines the techniques and procedures used to describe and collect data on the observed phenomenon of interest using qualitative research approach. The chapter provides justification on research methods applied in this study. The Delphi research survey technique used to gather data is described and how validity and reliability is ensured. Furthermore, the chapter explains how the sample size is derived and the criteria used to select the panel of experts. Lastly ethical considerations are discussed.

3.2 RESEARCH DESIGN

Creswell and Poth (2016) define research approach as plans and procedures for research that includes the steps from broad assumptions to detailed methods of data gathering, examination and interpretation. This involves making informed intelligent decisions on the most appropriate approach to sufficiently answer the research questions and attain credible results. According to Kumar (2018), the most important objective of the research design section is to communicate to target audience the manner in which the study was conducted to ensure accuracy, completeness, and validity of the research. One can either use qualitative or quantitative or mixed research designs. This research study uses qualitative research methodology.

3.2.1 RESEARCH PHILOSOPHY

Research philosophy is defined by Saunders *et al* (2009) as beliefs on how data about a phenomenon of interest is collected and interpreted to answer the research questions. Research philosophy is deeply rooted on the ideology of how the world operates and individuals' perceptions of what they deem reality relative to their prior acquired knowledge and experiences. Individuals' opinions on world views determine how they acquire and decode new knowledge (Babbie, 2020). Previous research efforts identified and discussed four major research philosophies namely positivism, pragmatism, interpretivism and realism (Saunders *et al*, 2009). According to Babbie (2020), positivism theory states that knowledge is gained through experience of senses, observations, and experiments. Pragmatism is a research philosophical stance that specifies that human actions and thoughts are derived from past experiences. Pragmatism is based on the premise that solutions to problems can be viewed through consequences of actions (Creswell and Poth, 2016). According to Saunders et al (2009), realism in philosophical research is a principle that attempts to reflect reality on a subject matter independent of preconceived ideologies. It is argued that human beings are born without pre-existing ideas, but rather acquired through interaction in the real world. Realism encourages critical thinking through challenging pre-existing knowledge gained from past experiences (Tuffor, 2017). Therefore, researchers should not base their conclusions using their own pre-conceived ideas.

The philosophical research stance adopted for this paper is interpretivism. Interpretivism also known as interpretivist refers to approaches that place emphasis on shared meaningful nature of people's character and participation in social and cultural life (Saunders, *et al*., 2009). The assumption that interpretivism adopts is that access to reality is through constructions such as language as a tool for communication and shared meaning. According to interpretivist approach, it is important for the researcher to understand the diversity of participants in the study (Saunders, *et al*., 2009). The reason for using this philosophy, is that even though factual data can be used to formulate statistics, the study is mainly based on expert participants opinions and experience on IoT-based irrigation systems technologies. Rather than gathering scientific data to validate or reject a hypothesis as positives often prefer, this study uses interpretivist approach to understand individual and group experiences when implementing IoT in smart farming irrigation systems. Tuffour (2017) also argues that human beings cannot be studied using scientific methods as positivist suggest. The panel of experts' opinions and experiences will be dependent on the context and their social location.

Interpretivism produces more valid and reliable findings than positivism as it probes into deeper insights as opposed to shallow social facts, this allows researchers to reveal hidden meanings and social trends (Saunders, *et al*., 2009). To ensure validity and reliability of research findings in this study, triangulation and respondent confirmation will be applied as elaborated in section 3.6. Critics of Interpretivism philosophy suggest that it leaves room for bias from the researcher since primary data collected is heavily influenced by what participants in the study think, their values and what kind of problems they are encountered with. Another limitation of interpretivism is that due to its in-depth approach, the research scope is narrow in scale and selects a sample from groups that are deemed to be a typical representation of the entire population (Pham, 2018). Therefore, interpretations cannot be generalized in a wider population scale.

3.2.2 Research Strategy

This research will use qualitative research. Qualitative research is described as a method of observation to gather non-numerical data. This research method infers meanings, concepts, definitions, and description of things which are not measurable or expressed numerically (Creswell and Poth, 2016). Qualitative research is focused more on gaining an understanding of human personal experiences that are subjective in nature. The data obtained from the respondents' personal experiences is then interpreted and analysed to formulate a generalised statement (Kumar, 2019). According to Leavy (2017), researchers use qualitative research approach to robustly explore and give a narrative description of a phenomenon of interest. Qualitative research approach becomes the most appropriate choice in this study to fulfil the research objectives and answer the critical research question.

Yin (2015) provides the following key features of qualitative research that justifies why the researcher chooses this methodological approach:

1. Allows the researcher to carryout studies on a variety of diverse topics and areas of specialisation using simple understandable terminology by a wide range of audience.
2. Enables the researcher to understand human interaction and experiences within the context under investigation. In contrast to the use of quasi-experiences in a controlled or simulated environmental context.
3. Ensures a fair representation of respondents' opinions and perspectives since qualitative research conforms to ethical principles of informed consent and anonymity of participants.
4. Qualitative research is not dependent on one source of data. It permits for the use of various sources of data to validate the integrity of research findings. This assures credibility and validity of data.
5. It is common for research study design to evolve during the execution of the research. Qualitative research permits researchers to alter research parameters and questions to capture more insights missed and enhance research responses.

However, using qualitative research approach for this study presents some shortcomings. One major shortfall is researcher confirmation bias. Researcher confirmation bias is described as a tendency from the researcher to come up with data interpretations to validate or ascertain preconceived ideologies (Powell et al., 2012). The researcher is also considered an expert in IoT systems. Therefore, there exists a tendency from the researcher to unconsciously favour particular point of views derived from prior knowledge and skill set on IoT based smart farming irrigation systems. To effectively eliminate such a type of bias, Yin (2015) recommends formulating clearly stated parameters for including and excluding data sets from participants. It is also suggested to continuously challenge existing assumptions and prior knowledge on the data collected.

3.2.3 Methodological Choice

Phenomenological research approach seeks to describe experiences that are lived in phenomenological terms. This research approach is concerned with understanding experiences from the participants' point of view (Creswell and Poth, 2016). Phenomenological research is deeply rooted in trying to understand human experiences and personal wisdom within a particular context thereby continuously challenging common assumptions and norms. It is argued that human beings effectively learn from other people's experiences as opposed to learning from artificial data obtained outside the contextual environment being studied (Tuffour, 2017). IoT is a novel technological realm with new knowledge and concepts that need to be explored to gain more insights. Phenomenological research approach is appropriate for this research study since the study seeks to explore, comprehend, and learn from experts' personal experiences. The use of phenomenological research approach provides voluminous unstructured data that is often difficult to sort, normalise, organise, and analyse. When dealing with unstructured data, thematic analysis is one of the most widely used forms of analysis in qualitative research. It is a method that emphasis on identifying patterns, themes and categories extracted in a data set (Jackson, 2017; Nowell, 2017). This eliminates redundant data and allows for development of relationships between themes for easier comparative analysis. Phenomenology requires the researcher to provide a platform that successfully captures the experiences and opinions of participants (Tuffour,2017). Moreover, when addressing technical concepts on IoT smart farming irrigation systems, participants might not possess the required eloquence to describe IoT concepts using appropriate verbose.

3.3 DATA COLLECTION

Qualitative data is a data type that describes information. It is descriptive, investigative, and often open ended, allowing participants to fully express their views on a phenomenon of interest. Qualitative data cannot be expressed numerically but rather categorized based on attributes and characteristics of an entity (Kumar, 2019). Qualitative data collection can either involve direct interaction with individual participants or a panel of participants (Mason, 2017). The nature of qualitative data is often tedious and expensive to gather due to the depth of data insights obtained from the process. Therefore, smaller sample sizes are used.

Delphi method was developed by Norman Dalkey, Olaf Helmer and Nicholas Rescher during the 1940's and 1950's for a military project on future technology capabilities (Barrett and Heale, 2020). Ever since, there is notable wide-spread use of the method in various research areas and business forecasting (Lund, 2020). For this research, the Delphi survey technique often referred was used to gather data from a panel of expert participants in the IoT smart farming irrigation system domain. This technique allows a group of experts to reach a consensus of opinions through expressing their views and prior experiences on a subject matter (Thangaratinam and Redman, 2005). In this situation, a series of questionnaires are sent to a panel of expert participants. Upon completion of the previous round of questionnaire responses, the findings of their opinions are summarized and provided to the participants before proceeding to the next round of questionnaires (Linstone and Turoff, 2002). Based on the summarized responses, participants can review their previous round responses. It is believed that through this process, the group will reach a consensus and converge towards a correct answer, the median score of the rounds will determine the results (Thangaratinam and Redman, 2005).

According to Thangaratinam and Redman (2005), a Delphi process should consist of at least two iterative rounds of questionnaire surveys and thereafter repeat until an agreement is reached. Therefore, this study adopted the recommended standard of at least two iterative rounds. Additionally, Linstone and Turoff (2002) suggest that the most appropriate number of participants in a Delphi survey is seven. However, the number of participants in previously conducted Delphi surveys has varied between four to even three thousand participants (Thangaratinam and Redman, 2005). For the purpose of this study, the panel will consist of twelve expert participants. This figure is derived considering the complexity of managing a large number of participants and time constraints.

3.3.1 Questionnaire Method of Data Collection

A questionnaire is one of the most used instruments for collecting primary research data. It is beneficial to use a questionnaire within this study because firstly, a questionnaire is convenient under the current Covid-19 government regulations on social distancing, the instrument does not require physical presence in the field of study. Secondly, according to Yin (2015) a questionnaire permits the researcher to manage time more efficiently as participants responses can be obtained concurrently contrary to interviews and observations that cannot be conducted simultaneously. Lastly, a questionnaire is an excellent instrument for collecting data that aids in making comparisons between responses from multiple participants. However, the researcher needs to apply due care and apply good principles of constructing questions in a questionnaire. IoT is considered an advanced topic that leverages multiple facets in computer networking, big data analysis, software, and hardware architecture (Burhan *et al., 2018).* Therefore, due to the complexity of IoT there is a possibility of respondents misinterpreting questions that are not properly formulated or ambiguous.

The two types of survey question formats that can be posed to the panel of experts to gather data can either be open-ended or closed-ended. A closed-ended question format requires respondents to choose an answer from a predefined set of response options while an open-ended question format allows respondents to provide answers in their own words (Denzin and Lincoln, 2017). The use open-ended questions in this study permit respondents to provide more insights and opinions making it possible to obtain diverse data from the Delphi panel of experts. This study will make use of open-ended question format style for data collection. The questions to be posed to the participants will seek to gather data that answers the critical research question. Furthermore, this will entail probing questions that determine how existing IoT-based architectural frameworks can be integrated with smart farming irrigation models.

Well formulated questions in a questionnaire reveal deeper insights and stimulate thoughts (Sauro, 2018). The questions should be precise, unambiguous, and straight forward. The researcher considered the cognitive level of participants when formulating questions. Cognitive level refers to the level of mental thinking and processing. Bloom identified a hierarchy of cognitive thinking from lower level thinking of recall and recognition to higher level of thinking of evaluation and analysis (Adams, 2015). All participants chosen in this study are experts capable of interpreting and evaluating the topic of smart farming irrigation systems using IoT. Therefore, higher cognitive level questioning style is applied. The concept of data collection instrument validity and reliability measures the degree in which a research instrument sufficiently reflects the true understanding of a topic under investigation by participants. Research instrument validity guarantees that each question is derived from the objectives and critical research questions whereas reliability is a measure of the ability of a questionnaire to reproduce the same or similar responses (Bolarinwa, 2015). All questions asked have a logical connection to the research objectives and critical research question. Two expert moderators consisting of an Internet Systems and a Systems Engineering Lecturer reviewed and pre-tested the questions to ensure validity and reliability of the questionnaire. The moderators checked for readability, spelling errors, formatting style, ambiguity of questions and determined if the questionnaire will provide adequate insights. Question skip logic is applied in this survey, it allows participants to skip questions not applicable to their domain (Sauro, 2018). Farmers have an option to skip technical questions on IoT architectural frameworks.

3.4 DATA ANALYSIS

Data analysis can be defined as a process of bringing order, structure, cleaning, and modeling data with the purpose of deducing useful information to support better intelligent decision making (Marshall and Rosman, 2011). Data analysis consists of two-dimensional facets which are qualitative and quantitative data. The nature of the data collected from the Delphi survey panel of experts in each iterative round of questionnaires is qualitative. There are numerous methods that can be used to analyze qualitative data. This study will adopt the narrative analysis methodology using questionnaires. Researchers that conduct narrative data analysis allows participants to give a written account of their personal experiences in a phenomenon of interest (Leavy, 2017). This approach is deemed appropriate for this research study as it enables the researcher to obtain a first-hand account of expert participants' views and experiences on the application of IoT in smart farming irrigation systems. Under the narrative analysis method, the first step is to arrange and format the data into a relational table consisting of rows and columns using Microsoft Excel statistical software. This is achieved by classifying the data set into four primary elements namely codes, categories, patterns, and themes (Creswell and Poth, 2016).

According to Mason (2017), qualitative data is more alphabetic than numeric. Qualitative data can be presented in narratives that include text tables, matrices, diagrams, and paraphrased passages reflecting the participants' personal experiences, opinions, and attitudes. Furthermore (Mason, 2017) discusses the use of relational tables in presenting analyzed qualitative data. This entails creating a summarized statement of findings entered in a two-dimensional table. The researcher will present the analyzed data results in a relational tabular format that is informative, clear and demonstrates the relationships between the variables under study. Furthermore, adequate time is allocated in analyzing the primary data gathered from the Delphi iterative rounds to ensure that the findings truly reflect the experiences of participants.

3.5 SAMPLING

Selecting research participants is a critical component of Delphi research since it is their expert opinions upon which the output of the Delphi is based (Thangaratinam and Redman, 2005). Purposive sampling is a non-probability sampling technique were researchers use their own personal judgment when selecting participants in a survey, the primary objective of purposive sampling is to focus on a subset of participants who meet a particular profile based on qualifications and traits to best answer the critical research questions (Elder, 2009). This sampling technique is commonly used for studies based on a very small number of participants under study (Elder, 2009). Purposive sampling technique is the most suitable for this study since the researcher intends to select individual participants who are proficient and well-informed in the subject matter of IoT smart farming irrigation systems phenomenon of interest. Homogeneous purposive sampling allows for collecting a very specific subset of experts that fit into the required portfolio the researcher intends to reach (Etikan, 2016). Therefore, participants who do not meet the required profile will be discarded when creating the sample. The desired number of participants for this study was 12 as illustrated in table 1. An invitation to participate was sent out to approximately over 35 prospective participants. 10 participants expressed interest and commitment to take part in the survey. The survey was conducted in two iterative rounds. 10 participants responded in the 1st survey round and 9 participants responded in the second survey round. The estimated sample size of 10 participants was derived from experts in the domain of IoT-based irrigation systems and irrigation farming. Irrigation farms selected for this study are situated in Brits an agricultural town that lies in North-West province of South Africa irrigated by waters of the popular Harbeerspoort Dam. IoT solutions experts are drawn from network infrastructure IoT solutions consultancy firms and academic institutions based only in South Africa.

It is important to define what constitutes an expert in this field of study. An expert exhibits outstanding competency, experience, knowledge, and level of education within a particular domain (Holtskog, 2017). Based on this assumption, the panel of experts for this study were chosen from certified professionals and end users with at least five years' experience in implementing both traditional and IoT-based smart farming irrigation systems. All expert participants in this study share common interest and understanding of the phenomenon under study. The initial recruitment process of participants guarantees that all participants share equal interest and understanding in IoT based smart farming irrigation systems. This is achieved through vetting expert participants based on job functions, years of experience, skills matrix and level of education. These experts include IoT Irrigation Solutions Architects and Irrigation Farmers. Table 1 shows the selection criteria for expects.

Table 1 Selection Criteria for experts (adapted Irrigation Jobs | CareerJunction, 2020)

Domain Area	Related Job Specifications	Estimated Number

Irrigation Farm Managers / Farmers	**Desired knowledge outcomes** Ensure fields are irrigated optimally according to requirements. Assisting in compiling maintenance schedule and irrigation equipment for various sites. Overall management of crop growth and fertigation as per crop requirement. Experience in using various irrigation systems such as drip, pivot, and computerized irrigation management systems. Increase production of farms supply and advice on irrigation schedules. **Work Experience** At least 5 years **Level of Education** Certification in Agricultural Irrigation or related field.	6
IoT Solutions Architects / Academics	**Desired knowledge outcomes.** Design, installation and prototyping of computerized or non-computerized smart farming irrigation systems. Development of IoT services using different platforms such as Microsoft Azure and AWS. Hardware and software programming using various platforms. IoT network engineering. Topology surveys, technical drawing, design different irrigation systems. **Work Experience** At least 5 years. **Level of Education** At least a degree in computing or related field.	6

The recruitment, capacity and willingness to participate in a Delphi survey is a critical success factor in the entire process (Thangaratinam and Redman, 2005). To minimise the dropout rate of participants and maintain engagement in the entire iterative rounds, this research study adopted the following recommendations. The researcher identified highly committed participants as determined in the selection process. A recruitment letter attached in appendix A with details of the survey was sent out to prospective participants, curiosity will be built through prompt timely feedback of each iterative round. An additional incentive for participation until the end of the survey would be to provide results to participants that complete the entire process (Hall *et al.,* 2018).

3.6 VALIDITY AND RELIABILTY

"Validity refers to the extent to which a measure is actually tapping what we think it is tapping. Reliability refers to the consistency of results" (Leavy, 2017, P.113). The researcher will ensure that the data gathered from the survey is credible and trust worth. This can be ensured through triangulation. Triangulation involves collecting evidence in an investigation of a phenomenon from multiple diverse sources (Kumar ,2019). In research, the principle of triangulation is aimed at evaluating at least three sources of information to strengthen the credibility and validity of data collected under a study (Yin, 2015). They are four major classifications of triangulation, namely methodological triangulation, data triangulation, investigator triangulation, and theory triangulation (leavy, 2017). This study will concentrate on the use of triangulation of methods approach which emphasis on the use of various data collection methods such as questionnaires, document analysis reviews and literature review. In this case data originated form the panel of experts listed in table 1 is compared against company document publications and past published research papers. The researcher reviewed and read extensively on smart farming irrigation systems up until a point of saturation. Search engines and digital libraries were used to search namely for research journals considered most relevant. Google Scholar was the starting point in the literature search strategy. A total of 30 published research journals were subsequently identified and chosen from the pool of literature sources. The list of keywords, concepts and ideas used in the screening of papers included smart farming in irrigation systems, IoT architectural framework, IoT integration and operability, water utilisation and operational costs. The three search strings shown in table 2 were used in the search strategy for relevant literature.

Table 2 Literature Search String

SS1	("Internet of Things in Smart Farming Irrigation Systems" and "IoT based Smart Irrigation Systems")

SS2	(“IoT architectural Frameworks for Smart Irrigation Systems” and “ IoT Architecture Frameworks”)
SS3	(“IoT in Irrigation Systems” and “Challenges in IoT implementation in Smart Farming Irrigation Systems”)

Triangulation can validate the reliability of a study as it provides multiple datasets to understand the same phenomenon of interest. The researcher believes that data collected from the Delphi technique will be reliable allowing further researchers to produce the same or similar results. The reason for this assumption is based on the fact that Delphi process is grounded on the principle that forecasts from a structured panel of experts are more accurate as compared to unstructured groups (Hall *et al.*, 2018). Delphi survey process assures anonymity of participant’s responses.

The nature of a Delphi survey process involves participants receiving analysed results at each iterative round, thus consequently permitting respondents to validate their responses and refute interpretations that do not reflect their opinions. Additionally, recursion produced by Delphi research technique allows respondents to review initial responses, correct errors, and clarify intentions. This allows disagreements to be explored and realigned. This whole process will ensure that the panel of experts will reach a convergence with accurate stable results (Thangaratinam and Redman, 2005). It is argued that this process makes the data analysis phase more rigorous, systematic and eliminates researcher bias (Powell et al., 2012). Unfortunately, the inherent problem with respondent validation is time constraints, often IoT irrigation systems experts and farmer participants chosen in this study have a busy work schedule and do not have the time to repeatedly confirm and validate their responses. As mentioned in section 3.6 this problem is addressed by recruiting highly motivated participants as well as providing incentives for continued participation in the study.

3.7 ETHICAL ISSUES/CLEARANCE

Research ethics is based on the Greek principal of moral life. It involves the professional conduct to protect the dignity of subjects and the publication of the information in the research (Fouka and Mantzorou, 2011). Upholding good ethical standards and practices is important when conducting a research study since the researcher has an obligation to protect human subjects and respect the rights of study participants (Yin,2015). The researcher will implement the following good research ethical practices has suggested by Yin (2015):

1. Obtaining informed consent, during the initial recruitment process, participants will be briefed with the details of the research objectives, methodology applied, and inconveniences participants might encounter during the entire survey process. The panel will complete all iterative rounds with their informed consent, no participants will be forced or paid to take part in the survey. Therefore, participants have the right to withdraw from the Delphi survey at any stage during the iterative process.
2. Anonymity and confidentially, expert participants often are willing to disclose information and make comments if their identity is kept in confidence. For the purpose on this research study, all participants recruited in the Delphi survey will remain confidential, their identify is not disclosed even after completion of the exercise. For report write-up purposes, participants and Farms are assigned pseudo-names.
3. Deceptive practices applies when a researcher purposively misleads participants by withholding or falsifying information on a topic (Resnik and McCann, 2015). To address such an issue, it is important to provide detailed explanations on the purpose of the research study. However, it is not always feasible to furnish participants with complete details about the research. Therefore, participants are encouraged to openly query and clarify issues that they do not understand. The questionnaire design will ensure that no questions asked will negatively impact any participants.

It is a mandatory requirement for the researcher to obtain ethical clearance from the University of Witwatersrand (Wits) Ethics Clearance board prior to commencing research involving human subjects. Ethics clearance was submitted and approved. The ethics clearance number for this report is MIAEC 002/21.

3.8 CONCLUSION

The research methods chapter is very crucial section of this research report that seeks to answer how the researcher plans to address the research problem. Various research methods are highlighted and discussed in this section. The researcher explains and justifies which approaches are the most appropriate to answer the critical research question. The foremost important objective is to communicate with the reader how the study was conducted in a manner that ensures the integrity and trustworthiness of results obtained. It should be noted that the researcher also points out short-comings in some of the chosen research approaches and states how theses short-comings will be tackled. Additionally, a thorough discussion of how the results are interpreted and presented in an intriguing way to the audience is highlighted. The writer peels the research onion demonstrating the stages of research work development to be applied in this study as illustrated by Saunders et al (2009).

CHAPTER 4 DATA ANALYSIS AND FINDINGS

4.1 INTRODUCTION

In the previous chapter 3, a detailed description was given on the research methodological procedures employed in this study to collect and analyse the data. The data gathered was used to provide answers to the critical research question and address the research objectives. An initial invitation to participate in the Delphi survey on Smart Farming Irrigation Systems using IoT was sent out to approximately over 35 prospective expert participants.10 participants expressed their interest and consent to participate in the Delphi survey. 9 experts participated in the entire Delphi survey process. Literature review was used to ensure validity and reliability of data collected. Literature review on previous research studies either confirmed the data presented by the panel of experts or identified data not consistent with previous research studies. Themes and categories were identified and thoroughly discussed as they relate to the critical research question and objectives.

4.2 CONTENT ANALYSIS

Content analysis was used in this research to study the data obtained from the questionnaires sent out to the Delphi panel of experts. The initial phase in the content analysis involved an iterative process of re-reading and going through the data obtained to gain an understanding of participant's opinions and experiences on smart farming irrigation systems using IoT. This was followed by identifying codes and themes thus reducing the data into mean full categories that can be easily managed and analysed. Appendix D shows an extract of the process of identifying themes and categories performed by the researcher. The next step conducted involved formulating inferences and interpretations based on categories and themes identified. Lastly, content analysis revealed rich insights on the phenomenon of interest. A detailed discussion of each theme is presented in a manner that is understandable by the prospective reader. An extract of the critical literature review matrix is attached in appendix E.

4.3 PANEL OF EXPERT PARTICIPANT PROFILES

Participant's responses gathered from the Delphi survey exercise are analysed noting down ideas and concepts about what they said about the critical research question and objectives. The researcher reports and discusses their responses using direct quotations and references. For report writing purposes, participants were assigned pseudo-names to protect their identity. Table 3 describes expert participant's profiles linking them to their pseudo-names. Participant 7 is an exception inclusion in the panel of experts. This participant does not have a formal certification in agriculture or related field as specified in table 1 on selection criteria of experts. However, the participants vast years of experience, knowledge attained informally, and active involvement various irrigation systems is considered.

Table 3 Participant Profile

Pseudo-name	Profile Summary
Participant 1	Software developer with 8 years' experience in developing various software applications. Working in a project team for developing software solutions for aquaponic farming and irrigation water management.
Participant 2	Hardware and software programmer with over 7 years' experience. Working in a project team for developing software solutions for aquaponic farming and irrigation water management.
Participant 3	Solutions Architect with 5 years' experience in building various software's for IoT including smart agriculture and industrial automation.
Participant 4	Lecturer with 12 years' experience facilitating learning on courses in network engineering, IoT Programming, and database development. Supervising various student projects on smart agriculture, smart irrigation systems, smart homes. Supervising undergraduate research. Research interests include IoT engineering, data management systems, systems, and network engineering.
Participant 5	Lecturer with 6 years' experience in facilitating learning on courses in software engineering, hardware programming and IoT development. Supervising student projects on aquaponics farming, smart farming irrigation systems and Smart home automation.
Participant 6	A Farmer on a farm family business. 7 years' experience in agricultural irrigation on a large-scale using sprinkler, pivot and drip irrigation systems. Participated in smart farming irrigation prototype modelling project using IoT and machine learning techniques.

Participant 7	Attended various training workshops, seminars and exhibition shows on irrigation and greenhouse crop production. A farm supervisor with over 15 years' experience in irrigation systems implementation and maintenance.
Participant 8	Co-farm owner with over 12 years' experience in farming on a small-scale plot measuring approximately 20 hectares of arable land. Cropping interests are in horticultural products that include vegetables and flowers.
Participant 9	Apprentice trained in a Sugar Caine plantation. An Irrigation technician with 10 years' experience landscape irrigation and other various irrigation systems installation and maintenance.

The Delphi survey was conducted in two iterative rounds. The decision to conclude the survey at round two was reached on the rationale that no new data was obtained in the second round. Participants managed to converge to similar responses as discussed in this section. Furthermore, it ensured that a significant number of participants would complete the entire Delphi survey. The initial round sent out had a very high and timely response rate with 10 participants completing the survey within one week of receiving the questionnaire. However, in the subsequent round, the response rate was lower with 9 participants submitting responses. Generally, participants took longer than anticipated to submit responses with an average of 2 weeks response time. Email notifications were sent to remind participants of the survey. That approach yielded positive results.

4.4 DISCUSSION

The reporting style and format adopted by the writer is illustrated in figure 7. Two key themes were identified based on the responses given by the panel of experts. These themes were further subdivided into categories. The primary purpose of this study was to determine in what ways can IoT be useful in improving performance in smart farming irrigation systems. The secondary objective was to determine how existing IoT-based architectural frameworks can be integrated with smart farming irrigation systems.

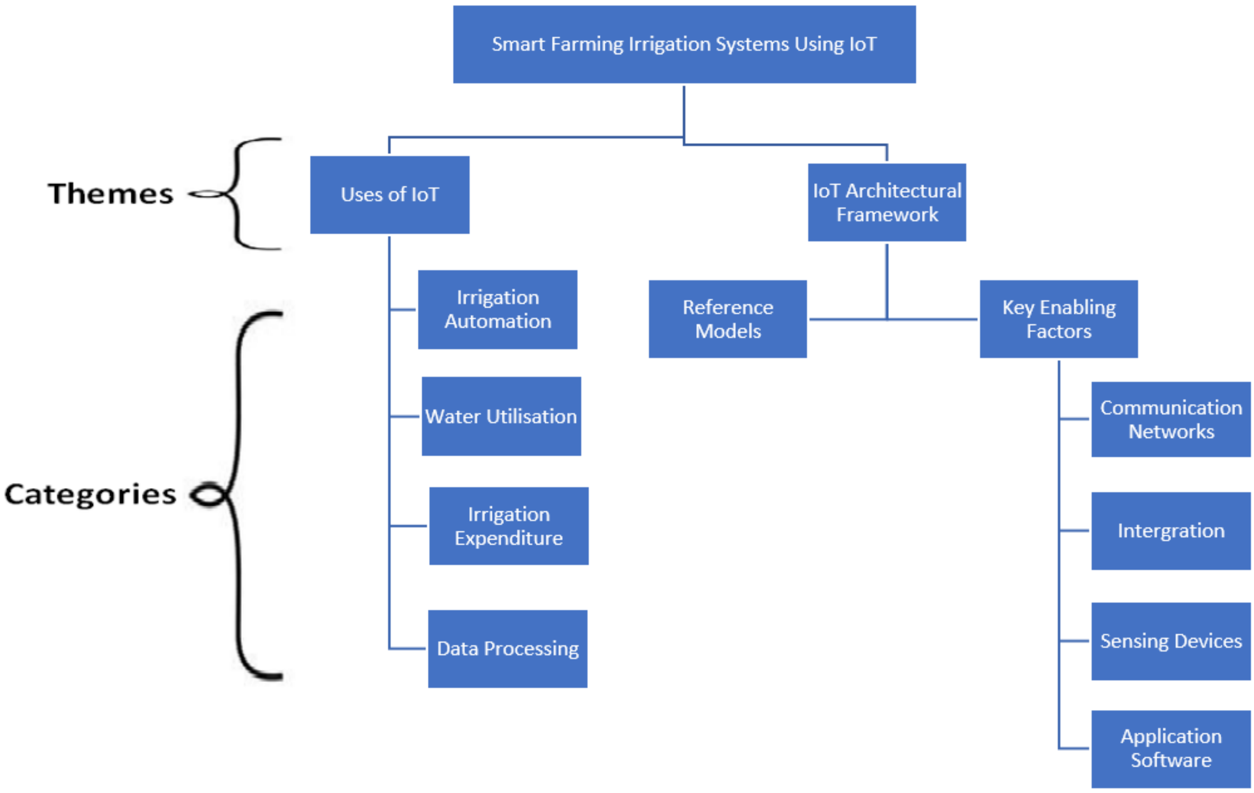


Figure 6 Themes and Categories: Smart Farming Irrigation Systems using IoT (adapted Nowell *et al.*, *2017)*

4.5 THEME 1 USE OF IOT IN SMART FARMING IRRIGATION SYSTEMS

There is overwhelming evidence presented by data obtained from participants on the usefulness of IoT in improving the overall performance of smart farming irrigation systems. Participants described several key application areas where IoT significantly enhanced the performance of smart farming irrigation systems. The application areas are discussed in the following categories.

4.5.1 Water Utilisation

IoT smart farming irrigation systems collect data through various sensors placed within the irrigation field. The sensors collect valuable climatic data used to monitor water irrigation. This promotes efficient utilisation of water resources. Farmers can determine the most appropriate schedule for watering crops. According to Participant 8, vegetable crops are much more dependent on critical timing of water application. One day of improper watering can make a difference between a marketable crop and a non-marketable crop. Participants would often describe how IoT based smart farming irrigation systems save water as compared to other irrigation practices that do not use IoT.

"Popular irrigation methods are sprinklers, pivot and drip. These irrigation systems typically waste water because of lack of precision. We can use IoT for irrigation scheduling to determine how much the water, when the water and where especially to apply that water to a specific crop." (Participant 9).

However, determining the exact volume of water saved through IoT implementation is quite difficult. This view is expressed in the response:

"Figuring out the amount of water used and saved is a complex task. So many things come into play when trying to figure out water saved" (Participant 8)

The majority of the panel of experts are of the opinion that IoT implementation in irrigation systems saves water. Considerable literature publications also reported on how IoT improves water utilisation in smart irrigation systems. Debauche et al (2018) mentions that older irrigation practices such as centre-pivot have commonly been used to apply water through overhead sprinklers that typically distributes uncontrolled water into the irrigation field. Such practices waste water. Newer centre-pivots incorporated with modern IoT automation features can save significant litres of water.

4.5.2 Irrigation Automation

The most discussed use of IoT in smart farming irrigation systems was irrigation automation. Participants reached a consensus on how IoT significantly automates several routine tasks that would normally require human intervention.

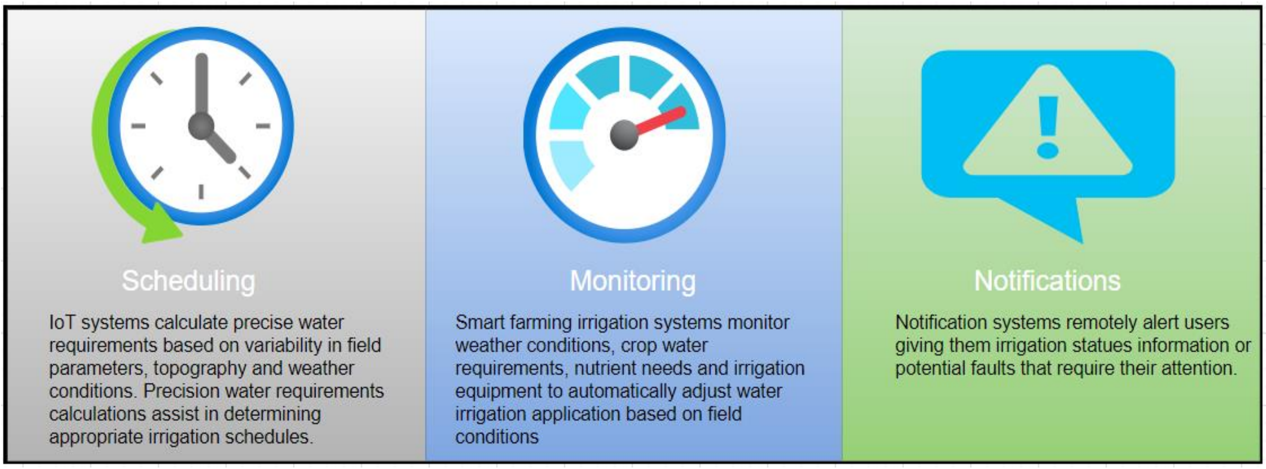


Figure 7 Participants views on the uses of irrigation automation.

> “ *Irrigation workers spend lots of hours usually during the night physically checking irrigation pipes, pumps etc and checking if the correct water has been irrigated. By using IoT, we can be able to check and monitor all of these using our smartphones or even computers*” (Participant 7).

Participant 8 is of the opinion that irrigation automation has a significant impact on the overall performance of irrigation systems. The participant alludes to the fact that farm workers are generally difficult to manage; the less the number of workers used the better.

However, Participant 6 revealed insights contrary to popular views of the panel of experts. The participant indicated that smart farming irrigation systems do not perform up to expectation. Marketers of IoT based smart irrigation systems products at agricultural shows and field days present useful features but often on the ground, they do not perform as advertised. These insights presented by the participant are often ignored or not discussed in existing literature. The same participant future describes undesirable outcomes.

> *“Sensors often give false data depending on configuration settings. Sensors are also affected by high temperature and their failure rate is high. The extent to which IoT systems saves water and operational costs is quite questionable given the high failure rate of IoT components”* (Participant 6)

4.5.3 Irrigation Expenditure

The majority of the participants share the view that IoT improves smart farming irrigation efficiencies and productivity. IoT introduces efficiencies into irrigation processes thus subsequently reducing the operational costs of irrigation. Participants were asked to indicate how IoT can assist in reducing the overall costs of irrigation crop production. The responses indicated that IoT implementation reduced the need for human intervention thus significantly lowering labour costs.

> “*From our involvement in aquaponics based farming systems, the main benefit is the reduce labour effort in monitoring the system. Field workers only need to be sent when the system picks up an issue that needs to be manually resolved. This reduces the total number of working hours for labourers.”(*Participant 2)

Irrigation operational efficiencies mentioned by participants included:

1. Energy utilisation efficiency
2. Automation of processes that would normally be done by labour force.
3. Efficient utilisation of water and reduction of water waste.

In the second round Delphi survey, the panel was requested to evaluate the costs and benefits of using IoT in smart farming irrigation systems. Participant 6 pointed out that the initial investment cost for irrigation infrastructure is a barrier for most farmers. The addition of another capital expenditure such as IoT could possibly make irrigation systems very expensive. Farmers also highlighted their inability to access funds from both the government and financial lending institutions. This view is also supported participant 8 who mentions that:

> *"In my point of view, IoT actually increases costs of production because it is an additional feature"*

There is an overall agreement that IoT improves irrigation operational efficiency, therefore the investment is worth it. Pernapati (2018) supports the need to lower the investment and operational costs of smart irrigation systems. They developed a low-cost smart irrigation system for monitoring and scheduling irrigation. The system consists of low-priced moisture sensors, humidity sensors and temperature sensors. These sensors forward the data collected using low power Zigbee wireless standard and is operated by Arduino microcontroller chip.

4.5.4 Data Processing

One of the key findings in this study mentioned by the survey participants was how IoT assists in collecting, processing, and storing data. This data is collected by sensing devices and used by irrigation systems to make informed decisions on irrigation scheduling and monitoring. IoT data processing function in smart farming irrigation systems is widely discussed in various scholarly articles (Abba et al.,2019; Togneri et al., 2019). According to Togneri et al (2019) IoT based irrigation systems collect valuable data on weather, crop management and soil parameters. This data is then processed using machine learning techniques to estimate crop water requirements. Figure 8 illustrates the data processing model for water requirement estimation.

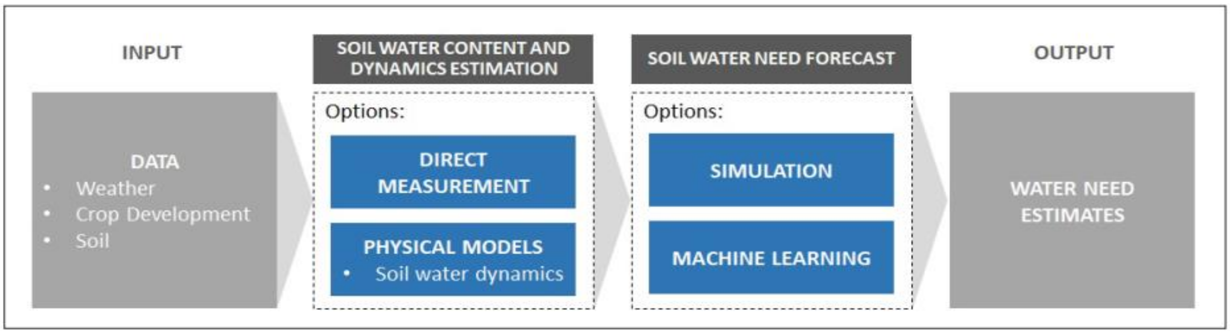


Figure 8 Data Processing Model for water requirements estimation (Togneri, et al., 2019).

It should be noted that participants expressed their dissatisfaction on the reliability of IoT data processing infrastructure that mainly includes sensors and communication networks. It was mentioned that IoT irrigation sensors have many points of failure and give inaccurate data readings. Additionally, network connectivity issues were mentioned as a common occurrence in IoT based smart farming irrigation systems.

> "*If sensors and wireless LAN modules are not charged, they tend to reduce frequency range and produce random errors*" (Participant 4).

These insights revealed by this participant are rarely discussed in existing literature reviewed by the researcher for triangulation purposes. Most of the scholarly articles tend to focus more on the positive impact of IoT data processing in smart farming irrigation systems.

4.6 THEME 2: IOT ARCHITECTURAL FRAMEWORK FOR SMART FARMING IRRIGATION SYSTEMS

The usefulness of IoT on smart farming irrigation systems is heavily dependent on a well-defined IoT architectural framework. The absence of a widely accepted IoT architectural framework limits the potential of smart farming irrigation systems. An architectural framework will assist in providing a set of design standards for IoT irrigation systems development and implementation. The following section will discuss participants' insights and opinions on which IoT architectural framework integrates with smart farming irrigation systems.

4.6.1 Reference Models

The first Delphi survey questionnaire asked the panel on their view on which IoT architectural framework should developers adopt as a de facto standard. The participants that responded mentioned several IoT architectural frameworks listed in table 4. Not enough insights on IoT architectural framework for smart irrigation systems were revealed in the first iterative round. There was no consensus of opinions as participants described various frameworks. The researcher then summarised their findings together with literature sources and allowed participants to review their initial responses. Participant 9 a farmer did not respond to the particular question on IoT architectural frameworks. The reason cited by the participant was lack of adequate technical knowledge on the subject matter. Table 4 shows summarised findings responses.

Table 4 Summarised Responses on IoT Architectural Framework

IoT Architectural Framework	Summarised Description
Three layer, Four Layer and Five layer Architecture	Three participants favoured the use of layered IoT architectures such as three or four layer. The three layer approach is one of the earliest IoT architectural framework developed during the formative years of IoT. It covers the fundamental concepts of IoT. Furthermore, it is easy to understand. Layered IoT Architectural frameworks typically consist of the perception (physical), network, transport, support, application and business layers (Muccini and Moghaddam, 2018). Using a layered approach assists in visualising the broader spectrum of IoT. A layered approach most importantly ensures that technical specifications in one layer do not interfere with other layers. However, layers can interact and form adjacency relationships (Gorulski, 2017).
TCP/IP Architecture	Participant 3 is of the opinion that the TCP/IP model is the best ideal architecture. This model has dealt with internet systems communication between various devices. The TCP/IP and OSI models are the underlying frameworks used in data communication networks. Designers and vendors of network applications and hardware components should closely follow these reference models. TCP/IP model has inspired the development of the development of the three layer IoT architecture (Serpanos and Wolf, 2017). Therefore, the development of an IoT architecture should be rooted in the principles of OSI and TCP/IP model.

Service Oriented Architecture (SOA)	Two participants preferred cross-platform interoperability SOA frameworks such as Alljoyn and middleware. Microsoft Windows has integrated Alljoyn services in recent Windows versions (Schmutz et al, 2010). OpenIoT middleware is another SOA architecture that has been used before in some agricultural projects. Participant 2 a systems developer explains how it is difficult to single out an IoT architectural framework. Developers usually choose an approach based on the requirements for the project which may change the optimal architecture dependant on what the constraints are. These constraints include but not limited to network stability and operating environment. According to Schmutz *et al* (2010) SOA's allow a number of services to communicate with each other by passing data from one service to another. The use of SOA's further permits standardised communication between various components and services of a system. Manufactures can share vital services through this approach.
IoT Cloud Platforms	Two of the participants share the view that IoT cloud-based platforms such as Google Cloud IoT platforms and Amazon Web Services offer the best fundamental features. Amazon web services offer various services over the cloud. These services include storage, networking, database management systems, analytics, administration and IoT deployment tools (Mathew and Varia, 2014). Due to the large number of users on the cloud, service providers can attain significant economies of scale.

In the second iteration, participants reached a close consensus on an IoT architectural framework for smart farming irrigation systems. The majority of the responses revealed similar insights despite different terminology used. Participants preferred an architectural framework that consists of the following components.

1. Sensing Layer – Participants reference this layer using other names such as Physical, Perception and Thing. The primary purpose of this layer mentioned is to gather data on moisture, light, humidity, and other environmental parameters. This data can also be manually entered.

2. Network layer – Participants popularly reference this layer also as the Network Layer. Participant 3 refers to this layer as the Network Link. This layer specifies network communication between IoT devices. Network communication standards mentioned in the survey responses included Wi-Fi, Bluetooth and Zigbee.
3. Application layer – This layer is popularly mentioned by the participants. It is described as a user interface for application services and web-based application support.

Figure 9 illustrates an abstract view of the layers of the IoT architectural framework expressed by participants.

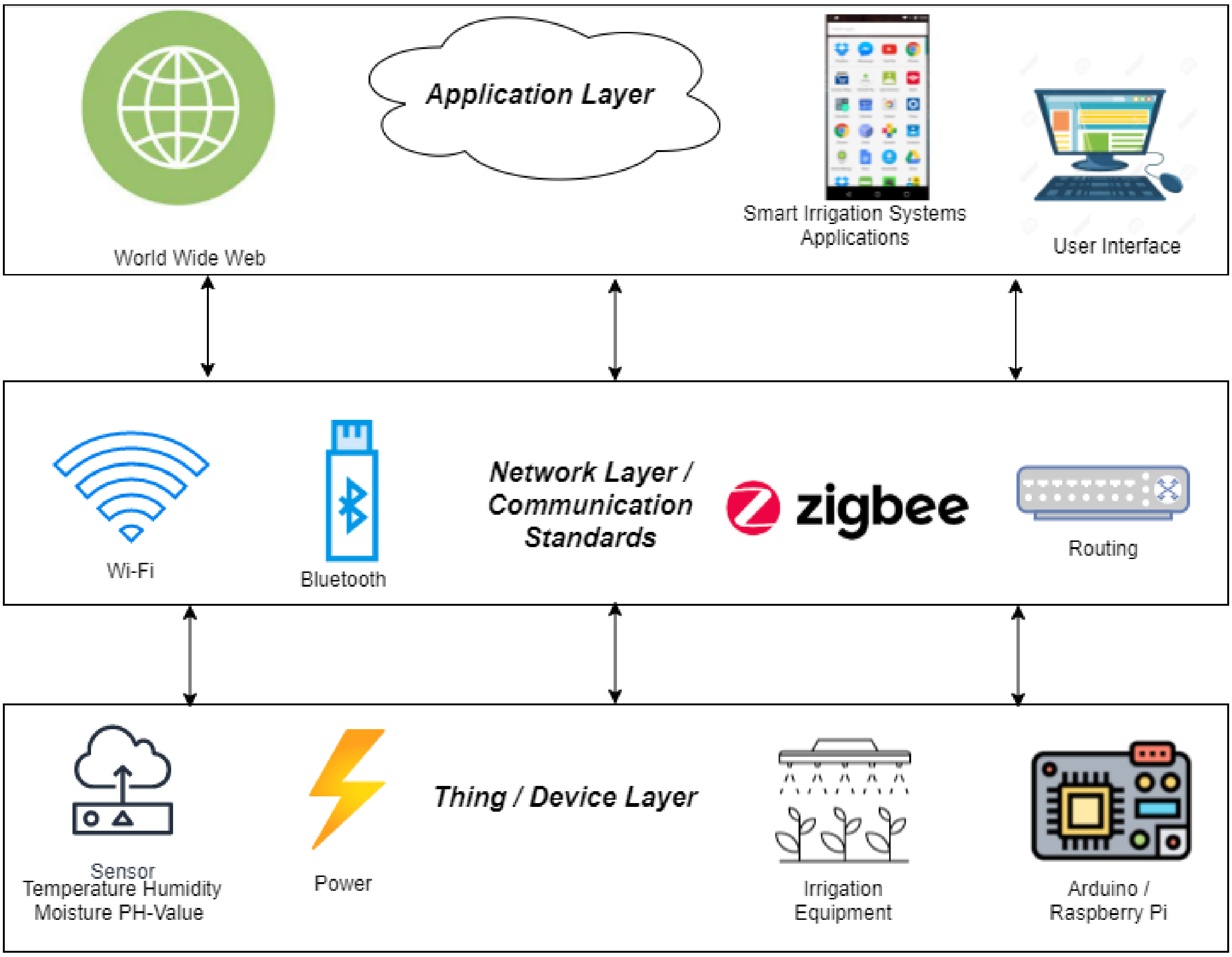


Figure 9 Participants abstract view of the layers of the IoT architectural framework (Adapted Kumar and Mallick, 2018)

Participant 1 maintained the initial response on the TCP/ IP Model for data communication networks. The justification given is that the TCP/IP model has dealt with these concepts and it is a protocol stack used for network design and implementation.

4.7 KEY ENABLING FACTORS

The following section presents insights revealed by participants on the key enabling factors that significantly impacts of the performance of IoT in Smart Farming Irrigation Systems. Figure 9 below illustrates an overview of four key enabling technologies that support IoT systems.

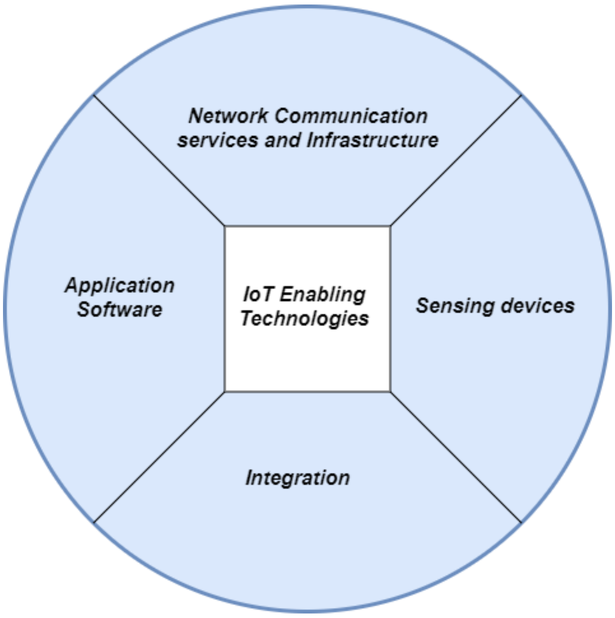


Figure 10 An overview of IoT key enabling technologies.

4.7.1 Communication Networks

Experts that participated in this study were clear and consistent on the importance of reliable network communication infrastructure as a key enabling factor. The future success of IoT is reliant on the ability of communication network infrastructure to support the increased number of IoT devices. It emerged through participant's responses that network availability is a key requirement for successful implementation of IoT based smart farming irrigation systems.

> *"Constant network availability at high bandwidth, providing cloud storage capabilities. Wireless range is important particularly for large scale farming land."*(Participant 5)

> "*Zigbee (2.4GHz) simplelink – Zigbee based communication, the range of up to 100 meters , low power consumption"* (Participant 1)

Three key network communication concerns were raised. Firstly, wireless local area network (WLAN) modules require constant power to function properly. It is not feasible to install electrical and LAN cabling in a large irrigation field. According to Participant 3 these cables can be affected by tractors and other farming equipment. The power source often used is 3v coin cells batteries. It is should be noted that these batteries require constant recharging. An alternative power source suggested by the same participant is to use solar power. Figure 9 shows an image attached by a participant of a solar weather sensor.

Figure 11 Solar weather sensor (Participant 3, 2021)

Secondly farmers particularly expressed concerns on the failure rate and range of network communication infrastructure. This could be a major contributing factor for not using IoT. Low data rates and latency is experienced where there need for real time data exchange.

> "*Downtime is another challenge, downtime caused by parts that breakdown. One component failure can result in the entire system failing causing serious crop stress. The components dependant on each other for proper functioning."*
> (Participant 7)

Lastly irrigation equipment security was mentioned as a key concern. Often irrigation equipment is left unattended in the irrigation field. Vandalism and theft of irrigation equipment is a common occurrence mentioned in the survey responses. Surprisingly, only a few participants expressed concerns about network security issues as stated in literature. IoT security attack issues are widely discussed in several scholarly articles. The most common attacks mentioned in literature include IoT hijacking attacks, distributed denial of service (DDOS) attacks, rogue IoT attacks and device flaw attacks (Deogirikar, 2017; Stallings and Brown, 2017).

4.7.2 Integration

Integration was identified as a major barrier to successful implementation of IoT in smart farming irrigation systems. The current IoT architectural frameworks do not support data structure compatibility, platform computability, and hardware compatibility. The primary reason cited for the incompatibility issues was that the building blocks of IoT based smart farming irrigation systems come from different suppliers.

> "*With older irrigation schemes designed decades ago, nothing ever goes wrong. These irrigation techniques were invented decades ago, very reliable and efficient. Integrating internet and computing will add another layer that is bound to fail. Trying to integrate mechanical components with computing systems will lead to compatibility issues"* (Participant 6).

The majority of participants seem to share the same generalised view. However, participant 3 is of the opinion that some irrigation systems solutions companies are developing the entire irrigation system therefore, integration concerns can be solved through this approach.

4.7.3 Sensing Devices

In this section, the writer discusses the insights highlighted by the participants on the use of sensors in IoT based smart farming irrigation systems. Participants were asked to discuss the technological requirements for high performance implementation. Sensors were highlighted as the most important hardware component. Popularly used types of sensors mentioned in the responses included moisture, humidity and temperature sensors. The primary purpose of the sensing devices is to collect weather data from the irrigation field. The number of sensing devices required per hectare is approximated as:

"*A typical field of 1 hectare will require at least 5 moisture sensors depending on the type of crop and water sensitivity requirements. Vegetable products and flowers will need more sensors as opposed to cereal crops"* (Participant 7).

Participants generally outlined the importance of high-quality sensing devices for successful implementation of IoT. However, they raised the following issues pertaining to sensors.

1. The cost of sensors is quite high depending on the quality. Prices range between R1000 to R5000.
2. Sensors require constant power to enable them to function. Inadequate power source was highlighted as a common problem.
3. Sensors require proper calibration depending on soil type. If sensors are not properly configured, they can give improper readings.

4.7.4 Application Software

Web based applications are typically used to present the data collected by the sensing devices using smartphones or computing devices. They visualise the data in an understandable manner to the end-user. End-users can then make informed decisions based on the reports. Lastly, it is mentioned that IoT solution providers are locking customers into using their products through rigorous marketing and business practices. Eventually users will have no option but to use their solutions being pushed to the farmers.

4.8 CONCLUSION

The Delphi survey exercise revealed valuable insights on the usefulness of IoT in improving the overall performance of smart farming irrigation systems. It was evident from the data provided by the panel of experts that IoT has a significant improves irrigations systems performance. Older irrigation systems typically waste water as a result of in-efficient methods applied. The advent of IoT allows smart farming irrigations systems to collect data from the sensing environment. This data facilitates the automation of several irrigation routine tasks that would normally require human effort. The use of IoT features such as notification systems, irrigation scheduling and resource monitoring improves irrigation efficiency and productivity. Efficiency as a result of IoT implementation will subsequently reduce the overall operational irrigation costs and conserve water resources. Experts agreed that the benefits of IoT in smart farming irrigation systems outweigh the costs. Moreover, participants managed to reach a close consensus on an IoT architectural framework for smart farming irrigation systems.

It should be noted that there are several barriers identified by participants that hinder the full potential of IoT in Smart Farming Irrigation Systems. Challenges highlighted that are frequently encountered when using irrigation sensors included power source, high failure rate and configuration issues. Another common challenge discussed by the majority of the participants was network communication reliability, security and availability issues. Integration and compatibility problems were cited as a major barrier to successful implementation of IoT in smart farming irrigation systems. The strengths and limitations of the methodological approaches used to collect, analyse and validate the data obtained are referenced in this chapter but elaborated more in chapter 3.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, conclusions and recommendations are drawn based on the results and discussions of the data presented in chapter 4. This chapter begins by providing a summarised overview of the study on Smart Farming Irrigation Systems using IoT. The researcher describes limitations experienced while conducting the study. The chapter is concluded by outlining recommendations on smart farming irrigation systems implementation and possible further research outcomes.

5.2 SUMMARY OF THE STUDY

Water scarcity is a growing concern as it threatens sustainable crop production. Older irrigation methods are being continuously challenged. This problem motivated the need to consider IoT as an opportunity for making irrigation systems smarter and more efficient in utilising resources. According to Hogan et al (2007), IoT innovative technologies significantly improve the overall irrigation efficiency thus subsequently improve crop yield and water utilisation. The main objective of the study was to determine in what ways can IoT be useful in improving performance in smart farming irrigation systems. The first sub objective was to determine how existing IoT architectural frameworks can be intergraded with smart farming irrigation systems. The second sub objective was to evaluate the usefulness of IoT-based smart farming irrigation systems on reducing the overall cost of crop production.

Establishing the background of the study was done through an in-depth literature review. The researcher explored previous research publications to gain an understanding of the key ideas and concepts on IoT smart farming irrigation systems prototypes, IoT smart irrigation architectural frameworks, uses of IoT, the benefits and challenge. Based on the existing literature review, the researcher identified the most appropriate methodological approach for the study.

The study used qualitative research approach which focuses more on gaining an understanding of human personal experiences that are subjective in nature (Creswell and Poth, 2016). It is further argued that human beings effectively learn from other people’s experiences (Tuffour, 2017). The researcher justified why qualitative research was the most appropriate method to answer the critical research question and fulfil the study objectives. For this research, the Delphi survey technique was used to gather data from the panel of experts within the IoT smart farming irrigation systems domain.

Questionnaires were used as the primary research instrument for collecting data from the panel of experts. A questionnaire was more convenient under the COVID-19 government regulations on social distancing at the time the study was conducted. This study was a two-round Delphi exercise. 10 participants completed the 1st iterative round and 9 participants in the second iterative round. Previous scholarly articles were used to validate the reliability of data obtained from the participants. Literature either confirmed or refuted data not consistent with previous scholarly articles.

The findings from data presented by the participants revealed that IoT has a significantly improves the performance of smart farming irrigation systems. Participants highlighted key application uses of IoT. It also emerged that efficiency as a result of IoT implementation subsequently reduces the overall cost of crop production. Participants managed to reach a close consensus of opinions on an IoT architecture Framework for smart farming irrigation systems.

5.2.1 **Conclusion of Objective # 1** Determine in what ways can IoT be useful in improving the overall performance of smart farming irrigation systems.

Agricultural irrigation plays a very important role in sustaining increased crop production. Over the past two decades, there has been a noticeable increase in the adoption of IoT technology in smart farming irrigation systems. The outcomes of the investigation on the primary research objective indicated that that older irrigation systems are less efficient and have numerous drawbacks. IoT based smart farming irrigation systems efficiently utilise water resources. Data collected using various sensors placed in the irrigation field enables irrigation systems to determine precise crop water requirements thus avoiding waste and crop stress. The study revealed that IoT implementation automates regular tasks that would normally require human intervention. Irrigation automation significantly reduces labour requirements by eliminating the need to frequently monitor irrigation field conditions. In addition, IoT based smart farming irrigation systems provide features to deploy web-based application interfaces to visualise real-time data collected by sensing devices. The user can obtain notifications and configure irrigation schedules based on soil moisture content, temperature, and humidity.

The outcomes of the investigation on the primary research objective of this study concur with previous literature studies that investigate on IoT implementation in smart farming irrigation systems. As discussed in the literature review, IoT directly and indirectly reduces water waste, reduces labour requirements, increase energy efficiency utilisation, and improves crop quality (Abba et al, 2019;

Barlow and Pattiani, 2004; Darshna et al 2015; Garcia et al, 2020). Therefore, IoT presents opportunities to sustain increased crop production. However, most of these studies tend to focus on the positive impact of IoT implementation and are often silent on the challenges. This study revealed several challenges. Communication networks and power management issues were a cause of concern. High-speed data internetworks are required for reliable data transmission between IoT sensors and applications. Frequent internetwork downtime, latency and low data transfer rates are often reported in irrigation systems. Furthermore, WLAN modules and sensing devices require constant power to function properly. It is not feasible to install electrical cabling within the irrigation field. Several powers sources where explored, it emerged that solar powered WLAN modules are a close alternative for constant power source. Integration and compatibility issues arise when trying to integrate older mechanical irrigation system components with IoT systems. The current IoT architectural framework does not support data structure, platform, and hardware compatibility.

5.2.2 **Conclusion of Objective # 2** Determine how existing IoT based architectural frameworks can be integrated with smart farming irrigation models.

The technical maturity of IoT based smart farming irrigation systems has not yet reached its optimal level. To date, there is no consensus on a single universally accepted IoT architectural framework. Numerous studies have proposed several IoT architectural frameworks such as the three layer, four layer, five layer, Paddy growth monitoring and service oriented architectures (Setiyono *et al., 2017*; Kumar and Mallick, 2018). Debate continues on which IoT architectural model is most suitable for smart irrigation systems. In this study, the panel of experts reached a close consensus in round 2 of the Delphi survey. The participants converged to similar responses on the principles of an IoT architectural framework for smart farming irrigation systems. The principles and concepts of an IoT architectural framework will vary depending on implementation and deployment. Based on the data collected from the panel of experts, IoT architecture for smart farming irrigation system should contain the following: Physical layer responsible for collecting data from the irrigation field using sensors such as temperature sensors, moisture sensors and humidity sensors. The sensors are often embedded into the mechanical irrigation components. The networking layer is responsible for data transmission over an internetwork. The application layer is responsible for managing data transmitted from the networking layer. Thus, the sub-objective on determining a framework for smart farming irrigation systems was addressed in this study.

5.2.3 Conclusion of Objective # 3 Evaluate the usefulness of IoT-based smart farming irrigation systems on reducing the overall costs of crop production.

It emerged from the insights provided by the participants that IoT introduces efficiencies into irrigation processes thus subsequently reducing the overall costs of irrigation. IoT connected sensors transmit valuable data on irrigation equipment status. This information facilitates detection of faults before they impact on irrigation processes. This approach reduces downtime and increases the life expectancy of irrigation equipment. Additionally, IoT implementation improves labour efficiency within the irrigation field. It allows farmers to save on labour hours spent monitoring irrigation equipment, water levels and managing irrigation schedules. The overall benefits of adopting this technology are worth-it at this stage of development.

5.3 LIMITATIONS OF THE STUDY

The researcher encountered limitations during the study. The panel of experts consisted of experts in the field of IoT systems and irrigation farming. Farmers selected for this study were in Brits an agricultural town in North-West Province of South Africa. A wider geographical sphere could have potentially revealed more significant insights. The usefulness of smart farming irrigation systems depends to a large extent on geographical locational factors such as climatic conditions, water supply, labour availability, soil topography and other operating costs. Participants' exposure relative to their geographical sphere will influence their level of technical knowledge, skillset, and perceptions.

5.4 RECOMMENDATIONS

The findings of this study contributed to the understanding of IoT implementation in smart farming irrigation systems and an IoT architectural framework for smart farming irrigation systems. The study will benefit Irrigation farmers, IoT practitioners, Policy makers and the farming community at large. The researcher gives following recommendations based on the findings and discussions drawn from the study.

5.4.1 Recommendations for Irrigation farmers

1. Securing IoT based smart farming irrigation systems from various network attacks, theft and vandalism was a cause of concern. Various literature sources discuss best practices that farmers can adopt on securing their physical and network environment (Adkins et al., 2020; Burhan et al., 2018; Deogirikar and Vidhate, 2017). These practices include but not limited to

access control best practices, building a reliable secure system, and mitigating common security attacks.

2. The majority of the participants cited internetwork connectivity issues that include frequency range limitations and downtime. Network connectivity issues can be addressed by investing in Mobile IoT technologies. According to GSMA (2018), mobile IoT technology is a cost-effective solution that provides low power, secure and reliable internetwork connectivity within a large geographical area. Mobile IoT technology allows interconnected sensing devices to transmit information on irrigation parameters such as soil moisture, temperature, and humidity to a central processing console. The user will have real-time overview of the irrigation field conditions. This will significantly impact on the performance of network communication.

5.4.2 Recommendations for IoT Practitioners

1. Common challenges with irrigation sensors identified included power source issues and costs of irrigation sensors. Continuous effort should be made by manufactures of irrigation sensors to provide alternative sources of power. There is growing interest on solar powered irrigation sensors and wireless LAN modules. It has become clear that solar energy provides numerous benefits over other sources of power. According to Dhakal et al (2018), the most important benefit of using solar energy for powering irrigation sensors and wireless LAN modules is that solar is a cost-effective renewable source of energy. This solves the problem of frequently recharging batteries and feasibility of installing electrical cables within the irrigation field. Therefore, solar energy should be considered as a close alternative. Several prototypes and published articles exist on low cost IoT implementation in smart farming irrigation systems. The aim of the proposed work is to investigate on how to minimise the costs of developing IoT based irrigation systems without compromising the quality. These systems typically use low cost IoT building blocks such as Raspberry Pi processor, climatic sensors, and web-based dashboards (Abba et al, 2019; Barlow and Pattiani, 2004; Debauche et al., 2018; Pernapati et al., 2018). Adopting such as approach will make IoT smart farming irrigation systems for affordable to the end users.

3. Several irrigation systems providers are now adopting the One-Stop-Shop concept. One-Stop-Shop is an emerging trend in irrigation systems development were a manufacturer designs and builds the entire IoT based smart farming irrigation system from pumps, irrigation equipment, web based applications and sensors. In some cases, manufacturers can also provide finance

and after sales support (Hartung and Pluschke, 2018). This approach gives a holistic view of irrigation systems as a complete system as opposed to separate systems. It is therefore recommended that irrigation solutions products should already integrate IoT functionality during the manufacturing process.

5.4.3 Recommendations for IoT Policy Makers and Financiers

1. Currently, there is no consensus on an IoT architectural framework for irrigation systems. International Standards Organisation (ISO) is a widely recognised body that sets standards across multiple domains and industries (Serpanos and Wolf, 2017). ISO should formulate an IoT architectural framework through consultations with various stakeholders involved. This approach will significantly minimise the challenges of integration, interoperability, and lack of common standards.

2. The capital investment requirements for IoT smart farming irrigation systems are beyond the reach of many small to medium scale farmers. Access to finance is vital for the provision of initial IoT irrigation investment and operational cash flow. The majority of small to medium scale farmers do not have access to finance from financial lending institutions. Baiyegunhi and Fraser (2014) examined key reasons why small to medium scale farmers in Amathole district municipality in Eastern Cape Province fail to obtain finance from leading institutions. The findings of the study found that poor creditworthiness was a major contributing factor. The study also revealed that farmers lack collateral and understanding of factors that influence attaining a good credit record. It is recommended that financial lending institutions should re-evaluate how they can narrow the gap for access to finance by small to medium scale irrigation farmers. This move will certainly stimulate agricultural irrigation. Agriculture remains a key economic activity that employs a substantial number of people.

5.5 RECOMMENDATIONS FOR FURTHER RESEARCH

During conducting this study, the following outcomes were identified for possible future research.

1. Future research is required to determine the extent of the usefulness of IoT in improving the performance of smart farming irrigation systems. It was equally difficult to determine to what extent does IoT impact on the performance of smart farming irrigation systems using qualitative research methodological approach. Qualitative research approach focused more on

gaining an understanding of personal views and experiences on the phenomenon of interest as they are described by the participants. Quantitative or mixed methodological approach would help confirm and further measure in numerical terms the magnitude of the impact of IoT implementation.

2. The problem of lack of a standardized IoT architectural framework for smart irrigation systems requires immediate attention. Professionally recognised bodies such as IEEE and ISO should explore the possibility of developing a universally accepted de facto architecture. Specifications for IoT systems should be clearly defined through collective consultations with various stakeholders. Such an approach will address the current challenges of integration, IoT systems development and implementation.
3. The context and location of the study was limited to participants within Brits and Pretoria geographical sphere. It is equally important to address the same research problem within a wider or global geographical sphere. More insights can be revealed if the sphere of influence is increased.
4. Researchers should always be on constant guard for newer IoT security threats and attacks. Despite the numerous measures put in place to mitigate commonly known IoT security attacks, the IoT security landscape is ever involving and changing. Security systems are unable to keep up with the pace of change. A possible further research topic can focus on leveraging machine learning techniques and artificial intelligent to automatically learn and actively detect evolving IoT security attacks.

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APPENDIX A PARTICIPANT INFORMATION SHEET

Dear {Insert Prospective Participant Name}

You are among a panel of experts invited to participate in a Delphi survey exercise on Internet of Things (IoT) based smart farming irrigation systems. The researcher is a part-time student in the School of Mechanical, Industrial and Aeronautical Engineering at the University of Witwatersrand supervised by Professor Raj Siriram. A Delphi survey technique allows a group experts to reach a consensus of opinions through expressing their views and prior experiences on a subject matter. The process involves participants completing a series of questionnaires in iterative rounds. The responses obtained in each iterative round is summarised and retained back to the participants. Based on the summarised responses, participants are given an opportunity to review, correct and adjust their initial responses. The process will continue until a group consensus is reached.

The primary purpose of the study is to investigate how IoT can be used to enhance smart farming irrigation systems to solve the water scarcity problem thereby improving agricultural crop production at optimal costs. The study is conducted solemnly for educational purposes, a research in fulfilment of the requirements for the degree of Masters in Engineering. Survey responses will be collected online using google forms. Due to research timeline limitations, participants are kindly requested to submit their responses within five days at each iterative round.

Participation in this Delphi Survey is done voluntarily with your informed consent, you have the right to withdraw from participation at any point during the survey. Your identity will not be disclosed even after completion of the survey and no results will be reported in a manner that reveals the identity of participants. For reporting writing purposes, respondents and Farms are assigned pseudo-names. The findings in the survey will form part of chapter 4 of my research report.

We value your knowledge, expertise and vast experience in the domain of IoT and smart farming irrigation systems. We would appreciate the value added through your participation. If you wish to contribute please respond to this email communication and further correspondence on the first round will be sent.

Your Sincerely

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APPENDIX B QUESTIONNAIRE ROUND 1

1. In what ways does IoT impact the overall performance of smart farming irrigation systems ?

2. Discuss changes you think need to be effected to improve IoT based smart farming irrigation systems overall performance.

3. Which IoT architectural framework should smart farming irrigation systems developers adopt as a de facto standard ? Justify.

4. What challenges arise when integrating IoT with smart farming irrigation systems

5. How do IoT based smart farming irrigation systems assist in reducing the overall costs of crop production?

6. What do you think are the key enabling factors to IoT technology adoption in smart farming irrigation systems?

7. What challenges do you encounter when implementing IoT based smart farming irrigation systems?

8. Discuss the technological resource requirements for high performance implementation in IoT based smart farming irrigation systems.

APPENDIX C QUESTIONNAIRE ROUND 2

1. In your own opinion what are the overall benefits of using IoT in Smart Farming Irrigation Systems?
2. What are some of the Challenges you have experienced when using IoT based Smart Farming Irrigation Systems?
3. Do you think the benefits of IoT implementation in Smart Farming Irrigation Systems outweigh the costs?
4. How do you view the future of IoT in Smart Farming Irrigation Systems?
5. Which IoT architectural framework is most suitable for Smart farming irrigation systems?

APPENDIX D CATEGORISATION PARTICIPANTS RESPONSES EXTRACT

Theme 1 : Use of IoT on Smart Farming Irrigation Systems

Expert Participants Responses Examples	Category	Frequency
Using IoT devices such as sensors help us in water application within the field and green houses. Irrigation such as pivot and flood sprinklers use too much water in a short space of time. The problem with this is water getting finished in the dams or reservoirs, crop stress, leaching, waste of water and pumping expenses (electricity and fixing pumps, pump stop working). IoT together with pivot irrigation helps in watering the correct amount of water required for crop production thus saving gallons of water. Water saving, monitoring atmospheric parameters in the green house, for good water quality. Figuring out the amount of water used and saved is a complex task. So many things come into play when trying to figure out the water saved.	Water Utilisation	7
Generally, farmer workers are challenging to handle, the less the workers involved in irrigation the better. Technology advancements on the farm extend a farmers' overall capacity and automate routine tasks normally done by people. Internet of things has various uses in irrigation. Farmers that use IoT are no longer concerned about water distribution to plants during the night. They also do not worry about minerals levels for plants. These jobs can be programmed and scheduled via smart mobile devices, laptops and computers	Irrigation Automation	9

IoT technology will benefit farmers by allowing them to receive notifications on issues on the farm, without having to physically be there. smart irrigation systems assists more reliable monitoring and management of natural resources, such as air and water quality. IoT in can detect irregular water being used and pressure. This usually caused by pump failure, water leakages etc. Messages are then sent to the user to attend to the problem. The features I have descried there are the ideal typical systems that are desired.		
From our involvement in aquaponics based farming systems, the main benefit is that it reduces labour effort in monitoring the system. Field workers only need to be sent when the system picks up an issue that needs to be manually resolved. This reduces the total number of working hours for labourers The initial investment costs of popular irrigation systems using sprinklers, pivot systems are beyond the reach of many farmers. Maintenance and operational costs are also very high. The inclusion of another IoT layer into irrigation equipment adds more costs to the already expensive irrigation processes. At times if farmers are not careful they might not have return of their investment costs. The impact of IoT is seen by how it significantly increases crop yield as compared to systems that do not use IoT. I also believe that IoT is the greatest invention of time after the industrial revolution. Irrigation uses too many workers and electricity or even diesel for motor pumps. We use Internet connected devices to monitor water and energy use thus saving on time human effort and irrigation expenses.	Irrigation Expenditure	7

Sometimes it will be more expensive and even the lack of knowledge to buy the required components for automated irrigation system hence for the irrigation systems to be fully implemented the government needs to subside and finance farming irrigation. The costs of setting up IoT irrigation is too high. Training on how to use IoT systems is also needed. Reduce the price of sensors and irrigation equipment. Sensors are quite pricey considering the number of sensors that are required especially for green houses and highly water sensitive crops such as vegetable cabbages and lettuce.		
IOT can have a positive impact if implemented well. Information is sent to the server and stored and used for correct times for watering with the help of IOT. IoT can be used for capturing data from the irrigation field that can be used for wise decision making. In irrigation, various sensors are connected to sprinklers / drip to input data used to schedule irrigation time. Farmers can also obtain real-time data on activities within the field and avoid guess work. Pump failure and pipe-line leakages are very common and hard to identify.	Data Processing and Forecasting	9

IoT systems give valuable data on energy efficiency utilisation. Correct timetables will eliminate unnecessary irrigation.		

Theme 2 : IoT Architectural Framework for Smart Irrigation Systems.

Expert Participants Responses Examples	Category	Frequency
The TCP/IP Model has dealt with these concepts mentioned for decades since its inception. In a way I see IoT just as an extension of this model. TCP /IP model is extensible. The additional changes is on the introduction of the device (thing layer). Much focus should be placed on the device or thing component or layer, since this is the most important layer that facilitates integration.	Reference Models	
The best ideal architecture must consist of Cloud management whether intranet or extranet. It must also cover network communication based on the TCP/IP model. Developers usually choose an approach based on the requirements, which may change the optimal architecture based on what the constraints are (network stability, operating environment, etc.) Internet based IoT architectures that allow for future expansion of IoT. An architecture that allows for the web and local network connections as well.	Communication Networks	
The architecture should always meet specific stakeholder concerns. However, the desired architectural framework should include technologies that incorporate the four layers of the architecture model that are the Sensor Layer, the Network Layer, the Service Layer and the Application Layer	Application Services	

With older irrigation schemes designed decades ago, nothing ever goes wrong. These irrigation systems were invented decades ago, very reliable and efficient. Integrating internet and computing will add another layer that is bound to fail. Trying to integrate Mechanical irrigation components with computer systems will often lead to compatibility issues. This increases many points of failure to the irrigation system. For instance a pump can fail due to pressure or a pipe line can burst. An internet system will not be able to fix this. An internet system can merely send an error message For cross-platform interoperability these are frameworks like AllJoyn (already present in Windows) that are widely used, and OpenIoT middleware has been used before by some agricultural projects. It is difficult to say what should be the standard as it would depend on the scalability and capabilities required by the project. Developers usually choose an approach based on the requirements, which may change the optimal architecture based on what the constraints are (network stability, operating environment, etc.)	Integration & Operability	

APPENDIX E LITERATURE REVIEW MATRIC EXTRACT

Article(s) Title	Authors & Dates	Outcomes	Literature Discussion
IoT based Smart Agriculture Irrigation pivot-center connected low cost.	(Gondechawar et al., 2016) (Debauche et al., 2018)	Data Processing , Water Utilisation	Real time data is collected within the field using various types of sensing devices. The sensors collect important data that is used to monitor water distribution supporting precision water application thus significantly reducing water use. IoT integrated into irrigation systems presents various benefits that directly enhances irrigation systems performance, reduces labour requirements and increases crop yield production. Older irrigation practices such as centre-pivot have commonly being used to apply water through impact pressure sprinklers that flood the irrigation field. Such practices neglect the actual plant water requirements. Therefore, centre-pivot irrigation systems do not efficiently utilise water. IoT plays an important role in automating older traditional irrigation practices.
Connected Farm for Smart Farming An Architecture for Smart irrigation	(Ryu et al., 2015)	Impact of IoT IoT Architectural Framework.	Agriculture plays an important role is sustaining economic development and ensuring food security. The agricultural sector is faced with the challenge to cater for the growing population. IoT has the potential to transform and develop the agricultural sector. The concept of connected Smart farming uses IoT technologies to manage

			farming activities that include crop , irrigation systems and animal monitoring. Connected Smart Farming seeks to increase quality and quantity of agricultural products while minimising labour requirements. IoT is a communication network consisting of various connected devices with the primary purpose of sharing resources and services. The lack of standardisation and agreement on which IoT architectural model is best suited for Smart Irrigation systems will significantly impact the potential use of IoT.
An Architecture for Smart irrigation An IoT based smart irrigation management system	Triantafyllou et al., 2019 (Goap, 2018)	Sensors , Reference model	The Three-layered IoT architecture proposes three layers namely Perception, Network and Application. Network layer is responsible for enabling internetwork connectivity with other smart devices. Other scholars refer to this layer as the transmission layer instead of Network layer Perception Layer is synonymous to the network access layer of the TCP /IP architecture model The application layers primary function is to allow applications to interface with devices within an IoT network. It specifies the provision of application services to the end-user.

			An IoT based irrigation system is capable of collecting weather data on water requirements for crop production based on soil moisture content, humidity and temperature. Weather data is often gathered from reliable metrological weather department stations