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Digitalization in ship management and operations: use of digital twin technology to monitor marine fouling

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DIGITALIZATION IN SHIP MANAGEMENT AND OPERATIONS: USE OF DIGITAL TWIN TECHNOLOGY TO MONITOR MARINE FOULING.

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

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Abstract

Title of Dissertation: **Digitalization in Ship Management and Operations: Use of Digital Twin Technology to monitor Marine Fouling.**

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The purpose of this study was to understand the extent of use of digital twin technology (DTT) in gauging marine fouling. It aimed at evaluating the status and level of its acceptability and adoption, respectively, in the Maritime Industry, identifying the influential factors to embracing it, establishing its pros and cons and lastly to anticipate its future on ships for the Ship Managers and Operators.

Numerous literature were reviewed in line with the research design and framework. Survey questionnaire was used to collect data and views of targeted respondents and a qualitative descriptive analysis was conducted and findings subsequently followed and discussed.

DTT was found to be at infancy stage, though gaining popularity in monitoring marine fouling and the hull condition as many who had not adopted were planning to soon do so. This was noted from the encouragement with various technological, economic, and environmental factors influencing its adoption. DTT provided users with access to real time data that allowed timely and well-informed decisions to be made. In turn, ships performance and efficiency are ensured and maintenance costs kept to minimal. DTT has been considered cost effective and an opportunity cost. Shortcomings noted were on sensor reliability and model failures that can create anomalies in the quality and integrity of data collected, system compatibilities and complexity, data security and absence of guiding regulations.

The study concluded with the statement ***"Digital Twin Technology is the way to go, a step towards the right direction and is the future in monitoring marine fouling and condition of the ships hull"***.

KEYWORDS: Digitalization, Digital Twin Technology, Marine Fouling, Ship Management and Operations.

Table of Contents

List of Tables

List of figures

List of Abbreviations

ABS	American Bureau of Shipping
AFS	The International Convention on the Control of Harmful Anti-fouling Systems on Ships
AI	Artificial Intelligence
BC	Block chain
BD	Big Data
DV	Data Visualization
DTT	Digital Twin Technology
EEDI	Energy Efficiency Design Index
ETA	Estimated time of arrival
IoT	Internet of Things
IIoT	Industrial Internet of Things
IMO	International Maritime Organization
PMS	Preventative Maintenance Systems
ROV	Remotely Operated Vehicle
SDG	Sustainable Development Goals
SEEMP	Ship Energy Efficiency Management Plan

Chapter 1: Introduction.

1.1 Background.

Global trade and economy's backbone has been acknowledged to be the Maritime Transport (UNCTAD, 2019) as a result of ships moving at least 70% of cargo in value and 80% in volume (UNCTAD, 2018) making shipping a derived demand (Ma, 2020). Shipping assets are considered to be of capital intensive in nature and their investments remain relevant and significant (Kavussanos & Visvikis, 2016) thereby necessitating to keep the costs of managing and operating them at the minimal (Panayides & Visvikis, 2017) since such related costs may range to extremes (Goulielmos et al., 2011; Latifov, 2019).

The fact that digitalization is transforming, reshaping, and restructuring the Maritime Industry, its operations and strategies cannot be argued (Lambrou et al., 2019) and certainly not ignored. Many other industries like mining, manufacturing, aviation and others have already advanced in digital technologies like Internet of Things (IoT), Artificial Intelligence (AI), Digital Twin (DT), Big Data (BD), data visualization (DV), automation, block chain (BC), Sensors, mobile technologies and 3-D printing which are developed to drive the 4^{th} industrial revolution (Sanchez-Gonzalez et al., 2019).

Similar to other industries, Shipping faces global competition challenges and experience continuous demand for efficiency (Suresh, 2020) and while ship managers and operators are under mounting pressure to remain competitive in the market (Farkas et al., 2020), new IMO regulations on marine environment also exert immense pressure to monitor the accumulation and fouling thereby proactively scheduling maintenance early thus avoiding further costs i.e bunk costs, unplanned maintenance, penalties for environmental non-compliance, that may emanate from heavy accumulation of biofouling. Recently researchers, shipping liners and experts discovered that the use of *Internet of things*, *Digital Twin* and *Sensor Technologies* have the needed capabilities to provide real live information detecting the accumulation of biofouling on the hull & propeller and predict any required maintenance and thereby effectively monitor the performance of the vessel (Elosua et al., 2011; Fonseca & Gaspar, 2021).

The purpose of this study is to understand the extent of use of digital twin technology in gauging marine fouling thereby evaluating its status quo in adoption, identify the driving factors influencing its adoption, establishing its benefits, and attached risks and lastly anticipate its future on ships for the Ship Management and Operators.

1.2 Problem Statement.

Impact from Marine fouling is both economic and environmental (Bressy & Lejars, 2014). The marine fouling builds up on the hull and keel of the ship causing resistance in water and reducing speeds which subsequently enforce more pressure in propulsion in order to maintain the same vessel speed, thereby consequently burning more fuel and increasing emission of greenhouse gases (Chang et al., 2016). By far, shipping bunker accounts for 50 – 60 percent of the Vessel Operating Costs (VOC) (Han & Wang, 2021) and marine fouling can increase fuel consumption to between 15% and 40% (Van Dokkum, 2016) while in the worst case scenario, heavy calcareous fouling may results in drastic increase in engine deficiency of 85% resulting in frequent dry-docking operations to clean, repair and coating of the hull (Bressy & Lejars, 2014). This comes at a heavy cost to ship operators and operational days lost while the vessel is out of operation leads to loss of revenue while fixed costs cannot be avoided (Farkas et al., 2020).

Coraddu et al., (2019) in a journal "Data-driven ship digital twin for estimating the speed loss caused by the marine fouling" elaborated on the importance of developing technologies in the maritime industry to enhance ship efficiency by reducing consumption of fuel and avoiding unnecessary maintenance operations and related costs. Impact of marine fouling on ships speed reduction, increase of bunkers, costly dry docking for propeller and hull cleaning are noted and a digital twin ship built using onboard sensors to ascertain speed loss as a result of marine fouling. Such technologies were found to have the ability to improve performance and effieciency of ships and in promoting shipping sustainability.

Our study will therefore focus on the use of Digital Twin technology to monitor marine fouling, its applicability, current status and its future in providing necessary predictions and assist ship managers and operators in maintenance scheduling, cost reduction and maintaining safety and efficiency of ships, and in overall decision making.

1.3 Aim of the study.

Focus of the research is to understand the potential, ability, and reliability of Digital Twin Technology in monitoring marine fouling, and in providing accurate and timely information to help in making decisions towards ensuring efficiency and performance of the ship and ensuring timely preventive maintenance of the hull are conducted, keeping in mind that marine fouling is one of the major costly aspects that need continuous monitoring, especially when it affects speed of the ship, increases fuel consumption and emissions. This research in general, is intended to provide a better understanding of the current and future of the use of digital twin technology in the maritime industry and open doors to more and broader studies.

1.4 Research Objectives and Questions.

To achieve the purpose of this dissertation and meet its objectives, a set of research questions have been developed as per the below table 1.

Table 1. Research Objectives and Questions.

Research Objectives	**Research Questions**
1. To evaluate the status quo of digital twin technology in monitoring marine fouling.	*1. What is the current status of digital twin technology in monitoring Marine Fouling?*
2. To identify the factors that influence the adoption of digital twin technology in monitoring marine fouling.	*2. What are the factors influencing the adoption of digital twin technology in monitoring marine fouling?*
3. To establish the competitive advantages and shortcomings in use of digital twin technology in monitoring marine fouling.	*3. What are the derived competitive benefits and risks in the use of digital twin technology in monitoring marine fouling?*
4. To determine the future of digital twin technology in monitoring marine fouling.	*4. How is the future of the digital twin technology in monitoring marine fouling anticipated?*

1.5 Composition of the chapters.

This research is made up of five chapters. The first chapter comprises of the introduction, problem statement, the aims, objectives, and research questions which all form part of the background to this study.

Literature review follows in chapter two where the concept of digitalization is brought to light. Overview of digitalization in the maritime industry is then introduced with the digitalization in ship management and operations along with a brief understanding of the activities in ship management and operations. The chapter lastly narrowed down to the digital twin technology and marine fouling and the two knotted together to derive to the research questions.

The third chapter discusses the methodology and provides a detailed process of the design and framework for this study. It explains the research ethics complied with, how data was collected, its reliability and validity and, the limitations to this study. The fourth chapter analyses the survey questionnaire and describes the findings.

Finally, chapter five, discusses the research outcomes categorised from the three themes, namely “Adopted”, “To Embrace” and “Analogue” and uses the results to answer the research questions. It also provides recommendations and wraps up with a conclusion.

Chapter 2: LITERATURE REVIEW.

2.1 Define Digitalization.

Digitalization is defined by *Gartner, (2021)* as “the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business”. Though the term has continuously gained popularity and momentum across variety of industries, there still exists confusion in the use of the terms “*Digitization*”, “*Digitalization*” and “*Digital transformation*”. They need to be well distinguished and clearly understood (Legner et al., 2017) since they are often being used interchangeably (Brennen, J.S & Kreiss D., 2016).

Digitization, described by Bloomberg, (2018) as the conversion process from analogue to digital form i.e converting hand or type written texts into digital form and according to Reinsel et al., (2018), data is the lifeblood of that process.

Digitalization has no one particular definition (Bloomberg, 2018). Brennen, J.S & Kreiss D, (2016) referred to digitalization as the adoption of computer and digital technologies. Bloomberg, (2018) distinguished digitization from digitalization to transformation of information and transformation of processes. *Gartner IT glossary* shared the same views. Terminals and port gate systems developed using Internet of Things (IoT) and sensors, automatically capturing movement of vehicles and containers at each step, data being reflected on the system, accessible, and updated across the network of users is a good example of digitalization.

Bengtsson, C. & Bloom, M. (2017) in an article “Human Resource Management in a Digital Era. A qualitative study of HR managers’ perceptions of digitalization and its implications for HRM. *Lund University School of Economics and Management, Sweden*.” described digitalization as a disruptive change that required organizations to comply with whether they like it or not. This can be argued to be an opinion and differ from others on what digitalization really is. Parida et al., (2019) compiled interpretations of the term “*Digitalization*” from different researchers as per *table 2* below.

Table 2. Definitions of Digitalization.

Reference	Definition
Gardner glossary, 2018	Digitalization is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business.
Gobble, 2018	Digitization is the straightforward process of converting analog information to digital. Digitalization refers to the use of digital technology, and probably digitized information, to create and harvest value in new ways.
I-scoop.eu, 2018	Digitalization means turning interactions, communications, business functions and business models into (more) digital ones which often boils down to a mix of digital and physical as in omnichannel customer service, integrated marketing, or smart manufacturing with a mix of autonomous, semi-autonomous, and manual operations
Luz Martín-Peña et al., 2018	Industry 4.0 is being encouraged by the introduction of digital technologies that push the specialization of the value chain and also connectivity between actors. Industry 4.0 heralds greater operational efficiency and the development of new products, services, and business models.
MITSloan Management Review, 2018	Digitalization is the innovation of business models and processes that exploit digital opportunities.
Rachinger et al., 2018	Digitization (i.e., the process of converting analogue data into digital data sets) is the framework for digitalization, which is defined as the exploitation of digital opportunities. Digitalization by means of combining different technologies (e.g., cloud technologies, sensors, big data, 3D printing) opens unforeseen possibilities and offers the potential to

	create radically new products, services and BM.

On the other hand, *Digital Transformation* has numerous definitions, and to mention a few, has been described as, the changes that relate to the usage of digital technologies in organizations or in the operations of such organizations by Parviainen et al., (2017), processes triggering reactions that prompt necessary strategies to keep pace with changes, developments and in managing obstacles by Vial, (2019) and Bloomberg, (2018) referred to digital transformation as the customer driven key business changes that requires implementation of digital technologies. It involves organizational changes, not technological changes. That aspect distinguishes digital transformation from digitization and digitalization. Lind et al., (2021) argued that it does not matter how the 3 terms are used interchangeably or by differentiating them, but rather what matters the most is how the use of advance technologies and business network connectivity to transform processes, increase efficiency and into creating a sustainable world. This logic was in line with those who took the stand that those who use these terms interchangeably are making a mistake.

2.2 Overview of digitalization in the Maritime Industry.

Digitalization in the Maritime Industry lags significantly, despite having experienced drastic growth in operations in the last decade (Sanchez-Gonzalez et al., 2019). Sanchez-Gonzalez et al., (2019) in an article "Towards Digitalization of Maritime Transport", considered digitalization a key aspect and emphasized on the importance of the Maritime Industry to embrace the latest digital technologies: Autonomous vehicles and robotics; virtual reality, augmented and mixed reality; digital security; artificial intelligence; internet of things; the cloud and edge computing; big data; and additive engineering and 3D printing. There is a great need for the Maritime Industry to rise up to speed and come to the same level of digitalization as other industries.

Undoubtedly, the concept of digitalization and development have become subject of discussions at different forums in the Maritime Industry with different interests i.e. Industry experts, researchers, scholars etc exploring processes in place can be optimized through digitalization while at the same time enabling trade facilitation, opportunities and transforming supply chains (UNCTAD, 2019). According to Fruth & Teuteberg, (2017) sectors within the Maritime Industry like Sea Ports, Logistics, and Shipbuilding are accelerating digitalization even though they are at present still considered to be dragging behind in comparison to other industries such as Aviation, Mining and Manufacturing.

2.3 Ship Management & Operations.

Fruth & Teuteberg, (2017) described Ship Management and operations as a core system in the shipping industry and among the sectors in the Maritime Industry that lags in digitalization. Although recently, there has been attempts to accelerate the propulsion of digitalization and optimize from its capabilities, there is still less data available on how the use of digital technologies is helping ship management and operations (Ando, n.d.).

Ma, (2020) describes the emergence of digital transformation as the largest revolution in the history of maritime and like any other revolution, major changes are expected to completely change the whole industry from its historical image. As some researchers allude to the notion that maritime industry is found to be slow and/or even resistant to adoption of new technologies (Inkinen et al., 2019), the evolution of technology brings with it, efficiency and digitalization is changing the future of maritime transport and how business is conducted (Ma, 2020). According to Panayides & Visvikis, (2017), Ship management activities and services entails among others the technical management and operations management of a ship (King & Mitroussi, 2003; Panayides & Visvikis, 2017).

According to Dalaklis, (2017), effective and efficient technical management is characterized by provision of ships that are safe and environmentally friendly and within the international framework of rules and regulations. It would be demeaning of the technical function if we cannot extend the efficiency and effectiveness of the function to maintenance, inspection, vetting, budgeting, dry docking, certification, quality assurance, performance monitoring, procurement, emergency contingencies, energy efficiency management and comprehensive reporting. These are the main activities that keep the existence of the technical management services. It cannot be argued that ships are highly expensive assets, and the strength of the ship owners and operators is determined by the availability and readiness of the ships. However, ship availability is dependent on how Preventative Maintenance Systems (PMS) are effectively implemented. Maintenance scheduling is one of the major component of PMS (Avgerou & Li, 2013; Deris et al., 1999) and considered the biggest challenge for ship managers and operators. It is a process of deciding the time to start maintenance activities that fulfil all the priorities, resource requirements and ship availability optimization and the maintenance in this case is of two types: *corrective maintenance* and the *preventive maintenance.* (Mattila & Virtanen, 2014; Meneghetti & De Zan, 2016).

At the centre of ship management services is operations management (Panayides & Visvikis, 2017). When the technical services have provided the assurance that the ship is seaworthy and ready to carry out commercial tasks and that the commercial services have committed to charter fixtures, the operations manager's responsibilities is to ensure that the ship fulfils its commitments efficiently (Tony, 2015). The terms "efficiency" in ship operations is highly significant and key to the relevance of operations management function (Coraddu et al., 2019). Ship operators find the achievement of efficient operation of a ship to be challenging thereby continuously seeking ways to reach operational conditions that are economically and environmentally efficient (Poulsen & Sornn-Friese, 2015).

2.4 Digital Twin.

2.4.1 What is Digital Twin Technology?

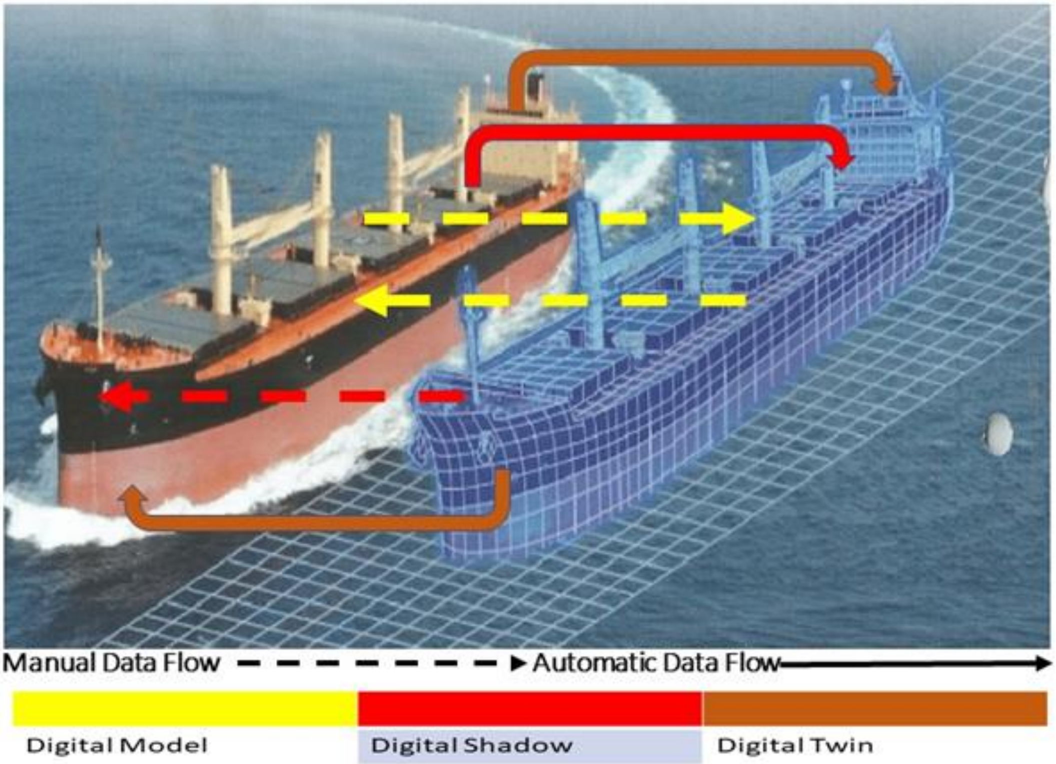
Digital Twin Technology (DTT) is a virtual replica of a physical item (Stachowski, T.H & Kjeilen, 2017). In an article, *Digital Twin: origin to future*, Singh et al., (2021) referred to Digital Twin (DTT) as 'the virtual copy or model of any physical entity (physical twin) both of which are interconnected via exchange of data in real time'. In essence DTT mirrors or replicates all the important properties and characteristics of the actual physical twin and can be used throughout the life cycle of such a physical entity (Schroeder et al., 2016). Scholars, researchers and academia's define DTT differently, in line with their respective fields of research (Singh et al., 2021). While some define DTT by its abilities to clone physical objects into a software counterpart (Minerva et al., 2020), this study has adopted to a common meaning associated with virtual representation of real world entities (Taylor et al., 2020) i.e physical assets, objects or systems like; ships, cars, buildings, wind turbines, power grids, engines, etc (Smogeli, 2017) that allows users to continuously monitor, conduct analysis and simulations for future plans, decision makings and in taking necessary actions (Rødseth & Berre, 2019).

In view of the existing confusion, Singh et al., (2021) went a step further to propose the below quoted definition in efforts to simplify the understanding of what Digital Twin Technology refers to and hoping it would become a universally accepted description, irrespective of its application or related industry:

"A Digital Twin is a dynamic and self-evolving digital/virtual model or simulation of a real-life subject or object (part, machine, process, human, etc.) representing the exact state of its physical twin at any given point of time via exchanging the real-time data as well as keeping the historical data. It is not just the Digital Twin which mimics its physical twin but any changes in the Digital Twin are mimicked by the physical twin too".

DTT is basically made of the physical (Actual) part, Virtual (Digital) part and the interaction between the two parts. The interation part can be from sensors and IOT devices that provides a flow of real time data between the actual and digital parts via simulations of digital part that provides feedbacks from simulations in digital environment to the physical one (Hinduja & Kekkar, 2020). The flow of such data in between the two according to Kritzinger et al., (2018) is either exchanged manually (Digital Model), Semi automated (Digital Shadow) or Fully automated (Digital Twin). In the Digital Model, data exchange between the physical and Virtual assets is manually. Changes in one part are not reflected in the other directly. Digital Shadow (also refered to as Static Digital Model) is where data flow from physical to virtual asset is automatic but remains manually from virtual asset to the physical asset, thereby any changes in the physical can be relected in its virtual copy, but not on the contrary. Lastly The Digital Twin (also refered to as Dynamic Digital Model) is where the data flow is automated and changes in either assets, physical or virtual, results to changes in the other directly. Refer to Figure 1.

Figure 1. Types of DTT based on the level of integration. Adopted from Kritzinger et al., (2018).



The DTT can be *predictive* for anticipating behaviour and performance or *interrogative* for investigating and examining past and present state of the physical item, respectively and irrespective of its location (Grieves & Vickers, 2017). Its application focuses on the product, involved process or its performance (Castro et al., 2020). DTT is composed of technologies such as IoT, IIoT, AI, BD, Simulation, and cloud computing, among others and have continuosly been evolving (Singh et al., 2021).

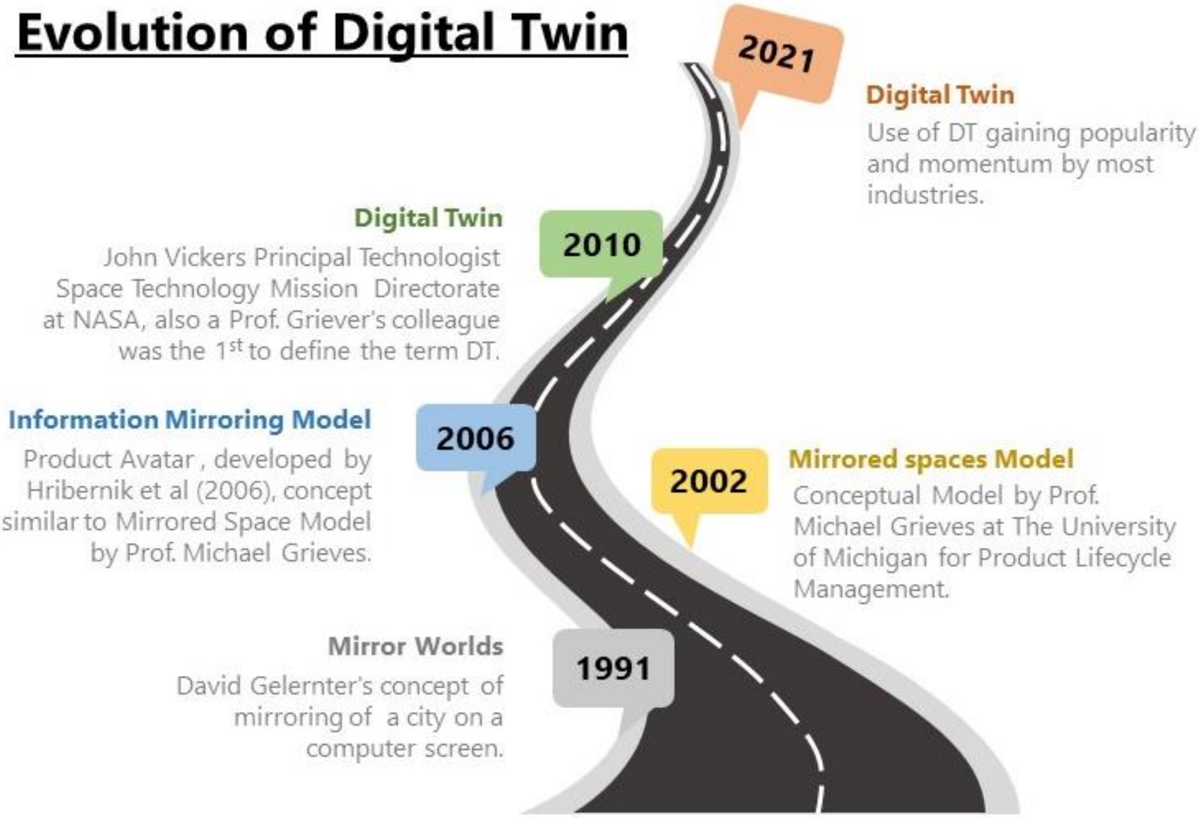
The industry 4.0 is improving digitalization and revolutionizing the industrial production by bridging the two worlds; physical and virtual. DTT and IoT are considered the crucial building blocks in Industry 4.0. IoT is about connecting devices to the internet, collecting the physical world data and connecting resources while DTT is about the virtual representations, structuring and managing such data to be used; the two are mostly overlapping one another while in use i.e resources discovery, describing and accessing (Jacoby & Usländer, 2020).

DTT applies to different industries in planning, designing, optimizing, safety, decision making, remote access, tranining activities among others, and can play greatly at enhancing efficiency, productivity and competitiveness (Kritzinger et al., 2018). It has the ability, in real time, to connect the virtual and physical worlds and provide realistic images and predictions of various scenarios (Parrott & Warshaw, 2017).

2.4.2 Evolution of Digital Twin.

Digital Twin Technology although having gained popularity and momemtum in the Maritime Industry (Rødseth & Berre, 2019), it is not a new concept and according to (Singh et al., 2021), the concept of DTT goes all the way back to 1991. David Gelernter, in his book "Mirror World", described the future of technology by imaging computer screens showing the reality like a complete image of a city with moving traffic patterns. He referred to such representations as Mirror Worlds (Larson, 1992). In 2002, another researcher, Prof. Michael Grieves at the University of Michigan followed with another concept termed "Mirrored Spaces Model". This concept was used for management of product life cycle (Flumerfelt, 2017). It was in 2006 when Information Mirroring Model a concept that was similar to Mirrored Space Model of Prof. Grieves emerged with Product Avatar developed by Hribernik et al., (2006). In 2010, John Vickers Principal Technologist Space Technology Mission Directorate at NASA, became the first to embrace the concept used to create space capsules and craft digital simulations for testing and named this model "Digital Twin" Technology (Flumerfelt, 2017). It was first defined as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Singh et al., 2021). At the time of this study (2021) DTT continued to transform and gaining popularity in different industries. Figure 2 shows the evolution of DTT.

Figure 2. Evolution of Digital twin, Source: Developed by Author.



2.4.3 Drawing Capabilities of DTT in shipping and other industries from Aviation.

The DTT originates from the aerospace sector (Singh et al., 2021). Its application in the aerospace and manufacturing sectors has been optimised, while still at infancy in the agriculture, automobile, healthcare and construction but with increase in demand in health and pharmaceutical sectors due to the Covid 19 pandemic (Singh et al., 2021). The covid-19 pandemic has changed the way prodcution and maintenance are perceived and has accelerated adoption of DTT (Erol et al., 2020).

A study conducted by Ibrion et al., (2019), “*On Risk of Digital Twin Implementation in Marine Industry: Learning from Aviation Industry*” based on lessons learnt from aviation industry found that DTT despite having numerous advantages in its implementation and usefulness, is also associated with high risks and uncertainties especially on sensor reliability, model failures and wrong decisions as an output to data processing. The maritime industry still has a lot to learn from the aviation sector, specifically on autonomous ships.

Next paragraphs will provide explanation on Marine Fouling and the role played by DTT to monitor its growth.

2.5 Marine Fouling.

2.5.1 What is Marine Fouling.

Bressy & Lejars, (2014) described marine fouling as the build-up of macro and micro-organisms to the submerged surfaces of a ship's hull and keel. The negative impact of Marine Fouling is both environmental, safety related and economic. Animals and plants make up macro fouling while micro-fouling refers to a viscous blend of bacteria, a slimmy pile and other micro organisms. The attachment of macro-fouling is stronger than that of micro-fouling and over 4,000 organisms result to hull fouling (Van Dokkum, 2016) and have been identified globally. The common macro-organisms are barnacles, tubeworms, bryozoans, mussels, and algae that settle on the hull of ships while bacteria, diatoms, and algae spores are the common micro-organisms. The most common transmitter of marine species into marine ecosystems of foreign jurisdictions is fouled ships. Marine species attached to the hull easily invade non-native environment and potentially causing ecological and evolutionary competition with native species (Bressy & Lejars, 2014).

2.5.2 Impact of Marine Fouling on Ships Operation.

Marine Fouling causes roughness on the surface of the ship thereby not only increasing the drag resistance in moving swiftly through waters, but also fuel consumption and green house gas emmissions (Bressy & Lejars, 2014; De Nys & Guenther, 2009; Han, E. S. et al, 2020; Demirel et al., 2017). This reduces vessels speed and increases fuel consumption by up to 15% and 40%, respectively. In order to maintain speed of the ship, engine power may require to be increased by 23 - 38% (Van Dokkum, 2016; Yusim et al., 2018) and in worst cases, excessive calcareous fouling may result in drastic increase in engine deficiency of more than 85% leading to frequent dry-docking operations for cleaning, repairing and coating of the hull (Bressy & Lejars, 2014). This comes at a heavy cost to ship operators, especially when fuel costs accounts for 50 – 60 percent of the Vessel Operating Costs (VOC) (Han & Wang, 2021) and dry docking leads to loss of revenue for vessel being out of commercial services (Farkas et al., 2020), as mentioned earlier.

2.5.3 Anti fouling.

Anti-fouling (AF) refers to the prevention of marine growth (Van Dokkum, 2016) and according to The International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS), Anti-fouling system has been defined as “a coating, paint, surface treatment, surface or device that is used on a ship to control or prevent attachment of unwanted organisms” (IMO, 2019).

2.5.3.1 Purposes of Anti Fouling.

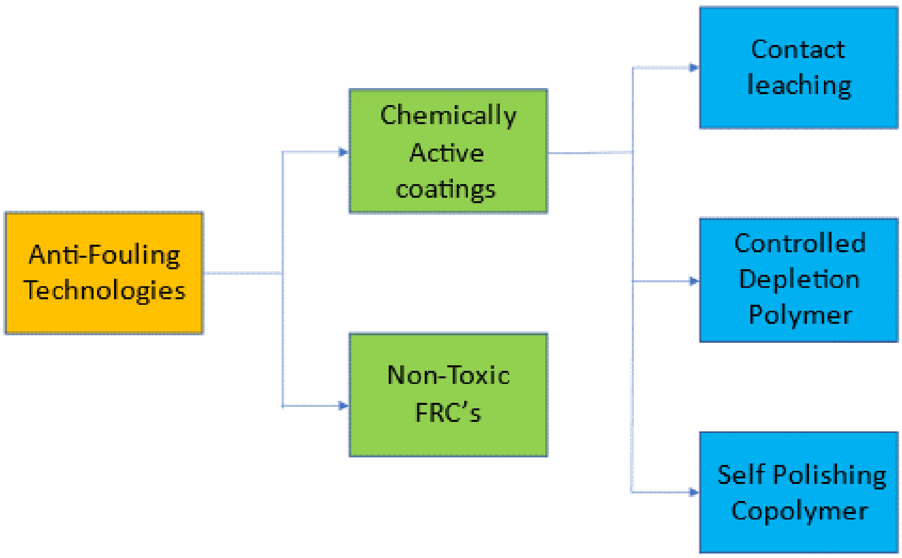
The purpose of AF is to avoid underwater marine growth. It also prevents the paint layer plus the steel underneath not to be damaged by organisms. Marine Fouling causes a lot of problems affecting the efficient operations of a ship and according to Van Dokkum, (2016), as the ships friction resistance increases, among others, it leads to speed loss, power required to maintain speed increases, fuel consumption shoots up to 40%, prolongs stay and frequency of dry docking, affects manoeuvvrability, increases engine wear, NOx and Sox emmissions, either huge inspection and or drydocking cost for under water surveys, corrossion as result of paint substrate damages, and underwater cleaning. This shows the usefulness of AF systems, offsets its costs against cost of fuel and loss of time saved as a result and certainly shows the importance of maintaining reliable applications of AF, monitoring marine fouling and timely scheduling preventive or periodic maintenance.

2.5.3.2 Types of Anti Fouling.

There exist several methods of AF used, however, at present, the best and useful approach known is the use of control coatings adopted against accumulation of marine fouling (Chambers et al., 2006; Tezdogan et al., 2015).

The current market of AF coatings is categorised into two: 1. chemically active coatings which uses chemically active compounds on organisms to limit their settlement and 2. non-toxic Fouling Release Coatings (FRC) which without any chemical reactions can limit their settlement and makes it easy to remove them. The chemically active also known as Biocide-Based Coatings because of releasing biocides (tin-free active compounds) can be divided into three categories: 1. Contact leaching coatings also referred to as hard matrix coatings, 2. Controlled Depletion Polymer coatings (CDP) and, 3. Self-Polishing Copolymer (SPC) (Bressy & Lejars, 2014; Van Dokkum, 2016; Uzun et al., 2019).

Figure 3. Types of Anti Fouling Technologies. Developed by author.



This study will not get into details of the AF types mentioned but rather touch on the methods used to monitor marine growth and investigate how that can be accomplished by use of DTT.

2.5.4 Monitoring of Marine Fouling.

Maintaining a smooth and fouling free hull of a ship is of utmost importance to ship operators and managers and acts as a major driver for reduction of fuel consumption, greenhouse gas emissions, ships operating costs and to the transfer of invasive species (Schultz et al., 2011).

A ship would be scheduled for dry docking periodically i.e. under-water inspection every 5 years for class ABS (American Bureau of Shipping). This is quite an expensive operation in direct dry-docking costs as well as in loss of revenue for vessel being idle instead of engaging in commercial operations but without choice must be scheduled to satisfy class survey requirements and regulations. This is when the hull would be inspected, extent of marine fouling gauged, previous AF coatings assessed, hull refurbished, and possibly new coatings applied (Swain & Lund, 2016).

Numerous studies have been conducted to investigate and ascertain the models used to monitor marine fouling, next paragraph intended to point out a selected few of the present models and solutions used for that purpose for the sake of directing and providing a link to the motive of this study topic.

Song et al., (2020), Demirel et al., (2017) and Tezdogan et al., (2015) discussed the use of Computational Fluid Dynamics (CFD) to predict biofouling on ships resistance, Erol et al., (2020) assessed the impact of the underwater growth by way of analysing ship automation data, Coraddu et al., (2019) investigated the use of a data-driven ship digital twin for estimating speed loss as a result of marine fouling, Foteinos et al., (2017) estimated the growth by use of shipboard measurements, focusing on power increase over time, and the use of shaft torque calculation by use of engine model, Demirel et al., (2019) generated practical added frictional resistance drag diagrams to foresee impact of ship performance as a result of marine fouling, Lajic et al., (2019) discussed the influence of fouling on ship performance and monitoring using speed log on an article “Transformation of Vessel Performance System into Fault-tolerant System – Example of Fault Detection on Speed Log”, and Uzun et al., (2019) presented a time-dependent marine growth model for gauging the foul and its effects on ships powering and resistance etc.

Underwater inspection of the hull is also conducted by divers with special devices like underwater video systems for monitoring and measuring and along with fouling cleaning tools. An ROV (remotely operated vehicle) equipped with laser equipment is also developed for surveying and cleaning the marine foul (Kostenko et al., 2019).

2.6 Ship performance monitoring and management.

Ship Managers and Operators are continuously working proactively to ensure ships perform efficiently and that preventive measures or maintenance are timely in place. While operating a ship, energy efficiency is the focal point of focus in ensuring control in the process of fulfilling shipping commitments to be achieved economically and in an environmentally friendly manner. Efficiency in operating a ship is achieved by monitoring the performance of the ship including voyage execution, speed reduction, engine monitoring, trim optimization, and weather routing (Poulsen & Sornn-Friese, 2015).

In recent years' ship operators utilize advanced technologies for ship Performance Monitoring. Bruun, (2018) of the Denmark Maritime Authority indicated in an article "digital twin for blue Denmark" that digital technologies such as digital twin, IoT & Sensor technologies have the ability to provide insights into all factors affecting operational performance. Digital technology can be used for regular monitoring of factors that possibly affect performance of the fleet, for example, fuel consumption, trim, speed, hull and propeller conditions (Ballou et al., 2008). If these technologies are well optimized, they can help operators in controlling the reduction of emissions and day to-day decision-making (Uzun et al., 2019). There are continuous discussions on the regulations and the conventions on maritime safety, efficient voyage, and prevention of marine pollution at the IMO and the importance for an international convention that covers the prevention of pollution by ships from operational, accidental, or emissions.

Armstrong & Banks, (2015) categorised the inspirations behind performance management on-board ships into three categories: 1. international regulatory compliances (Perera, 2016). To improve ships operational efficiency, strict regulations were implemented by the International Maritime Organization (IMO). For instance, EEDI (Energy Efficiency Design Index) was introduced by MEPC (The Maritime Environment Protection Committee) to regulate and control design of new ships and therefore bringing the requirement of having SEEMP (Ship Energy Efficiency Management Plan) onboard to enhance operational energy efficiency on all ships at sea (IMO, 2012). The plan entails operational strategies in relation to evaluation of operational performance and analysis of transportation productivity (Soner et al., 2018), 2. Economic aspects, relating to minimizing of operational costs and maximizing revenues (Mak et al., 2014) i.e fuel costs which constitutes up to 50% operations costs on ships according to Eide, (2011), Hasselaar, (2011), and Yusim et al., (2018) and 3. Customer expectations, for example, customers become more concerned about global warming, climate change, and energy efficiency and in turn influence ship owners and operators to improve on ship operational efficiency (Armstrong & Banks, 2015).

Operational performance and in particular the aim of minimizing fuel consumption on ships by ship managers and operators has increasingly grown to become an item of great deal of importance (Yu et al., 2019) and of recent aspects that have gained momentum to monitor operational performance of ships in the maritime industry are simulation analysis and optimisation modelling (Gracia et al., 2017; Thun et al., 2017) as mentioned on a journal "Use of tree based methods in ship performance monitoring under operating conditions" by Soner et al., (2018) where the tree based model used random forest, bagging and bootstrap to evaluate the operational peroformance of a ship. Yan et al., (2020) on another article, developed a two stage prediction of consumption of ship fuel and reduction model for a ship. The model considers total cargo weight, sailing speed, weather condition and that of the sea and then anticipates main engines fuel consumption hourly. A speed optimization model is then developed guaranteeing the estimated arrival time of the ship and the results showed the model can reduce, over 8-day voyage, fuel consumption by up to 7% leading as well to reduction of CO_2 emissions.

In view of the number of recent research studies that have come to light, one would not argue that ship performance management and digitalization is becoming a topic of interest into the industry especially with Ship Managers and Operators under ship operations and performance management.

2.7 Use of DTT to monitor marine fouling.

Under the "*Impact of marine fouling on ship management & operations*", biofouling was described as having economic and environmental damages in that, heavy calcareous fouling may result in drastic increase in engine deficiency by 85%

resulting to the increase of power in propulsion (Bressy & Lejars, 2014) as mentioned earlier.

Coraddu et al., (2019) in a journal “Data-driven ship digital twin for estimating the speed loss caused by the marine fouling” elaborated on the importance of developing technologies in the maritime industry to enhance ship efficiency by reducing consumption of fuel and avoiding unnecessary maintenance operations and related costs. Impact of marine fouling on ships in speed reduction, increase of bunkers, costly dry docking for propeller and hull cleaning are noted and a digital twin ship built using onboard sensors to ascertain speed loss as a result of marine fouling. Such technologies were found to have the ability to improve performance and effieciency of ships and in promoting shipping sustainability.

Ship Operations and management is therefore indeed another sector that can benefit a lot from the advanced technologies in shipping industry as their key objective is to manage and operate ships safely and efficiently (Ramboll & Advokatfirma, 2018).

Digitalization has of late frequently been addressed in both economic as well as scientific literatures (Inkinen et al., 2019) covering different industries and specific technologies of relevance to them. This research has adopted to such researches with aim to see whether similar finding apply to DTT and Marine fouling i.e Orji et al., (2020) in a journal, evaluated the factors influencing use of block chain in the freight logistics sector plus many others which have influenced the research questions and objectives.

Chapter 3: Research Methodology.

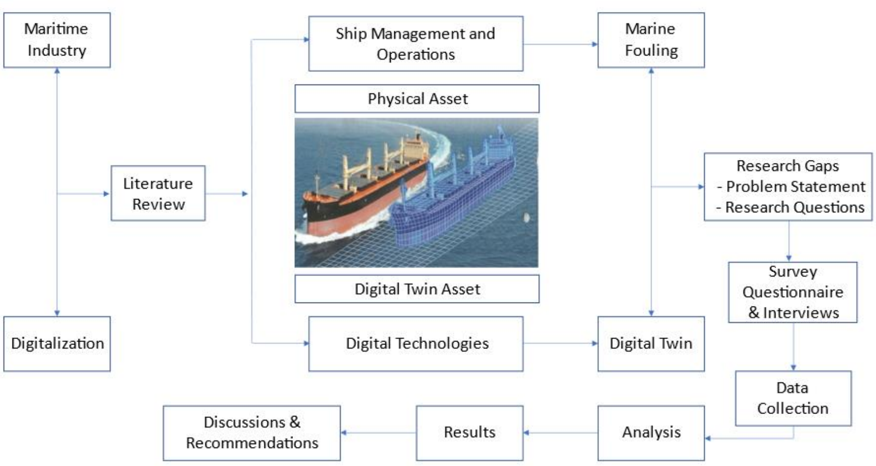
3.1 Introduction.

Research methodology has been described by Kothari, (2004) as the systematic approach used to solve research problems and referred by Igwenagu, (2016) as the systematic techniques utilized in conducting research. Literature was thoroughly reviewed in the previous chapter to discover the gaps and the comprehensive understanding of the literature guided to the respective research questions developed. This chapter will discuss the research approach adopted which is organized into the following sections namely, research design and framework, research ethics, data collection, development of the survey questionnaire, interviews, methods of data analysis embraced to process the received data to answer the research questions along with its reliability and validity, and the limitations associated to this research.

3.2 Research Design and Framework.

Research design is regarded as a framework on how the research data is gathered, processed and analysed. Kerlinger, Fred N., & Lee, (2011) defined it as "the plan, structure, and strategy of investigation conceived to obtain answers to research questions and to control variance" and according to Saunders et al., (2019) consists of a selection of data collected and analysis appraised by research philosophies and approaches. The following framework has been developed by researcher to guide this study as a road map.

Figure 4. Research Framework. Developed by Author.



3.3 Research Ethics.

According to Oliv, (2003), ethics for both the participant as well as the researcher on collection of data has implications to the research process. Ethics are therefore essential in data collection process due to involvement of human element and for that reason the survey questionnaire was subjected to rigorous review and scrutiny by the WMU Ethics Committee to ensure highest ethical standards are adhered to before it was approved. In addition, considerations to anonymity, confidentiality, data protection, and freedom to withdraw from participating in the survey at any point are strictly complied with to protect the privacy and rights of the participants. Participation and contribution are clearly indicated to be on voluntarily basis and at no cost. Data received will not be altered and all information received and utilized for the purpose of this research be deleted on the final submission date of this dissertation.

3.4 Data Collection.

Due to the nature of this topic, primary data collected directly from the industry experts is essential for gaining the latest information on digital technologies related to marine fouling, enabling us to investigate the driving factors and barriers of digital twin applications in ship operations management. This implies that the data collected was specifically for the purpose of conducting this research (Igwenagu, 2016; Alvesson & Sköldberg, 2009). The standard and robustness of a research depends on a careful procedure adopted for data collection. On that regard, a sophisticated survey questionnaire was developed by the researcher based on the research questions and deemed most appropriate and relevant method for collecting first hand, in depth, accurate and quality information. Cho & Lee, (2014) regards qualitative analysis framework to be having the ability to providing better access to personal experiences and allows researcher to be able to closely interact with the data collected while Wilkinson, D., & Birmingham, (2003) refers to a survey questionnaire to be suitable for collecting considerably large amounts of data, protecting participants anonymity and in facilitating data analysis. Collection of data began on 11th August 2021 using the survey questionnaire and was completed by the end of August 2021.

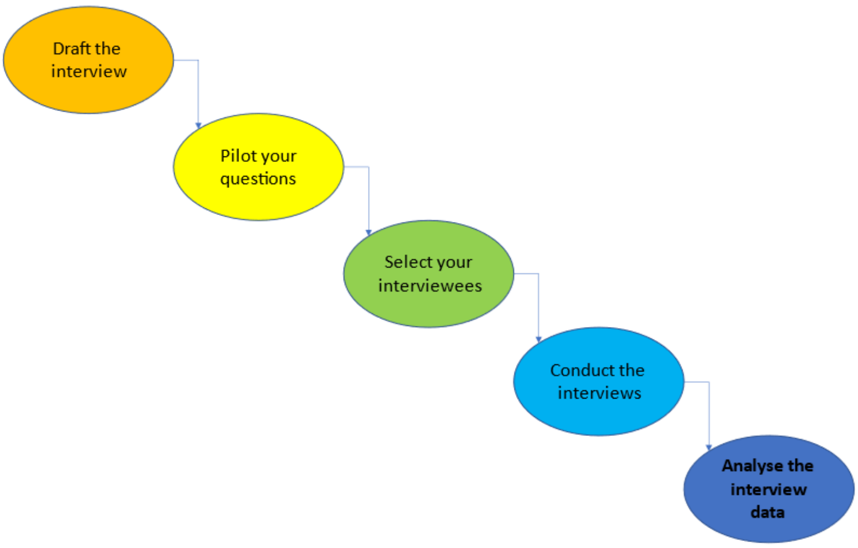
3.5 Development of the survey questionnaire.

To meet the research objective and answer the research questions, the researcher carefully developed a series of questions in the survey questionnaire targeting companies and experts from the Maritime industry namely Ship Management, Ship Operators, Fleet Management, Ship Owners, Seafarers, Maritime System developers and others in general from the specified sector. Mostly closed ended questions were utilized, some using 5-Point Likert Scale was used for weighing and ranking the decision criteria, with choices "Strongly Agree", "Agree", "Not Sure/Neutral", "Disagree" and "Strongly Disagree" while few with suggestive multiple choices to select from. Some open-ended questions were also adopted on selected areas that sparked interest of triggering participants to share their expertise, knowledge, and experience in the research area.

3.6 Interviews.

Interviews refer to a set of expectations and awareness about situations that are normally not related to spontaneous conversations. They have been used to gather thorough information on specific topics and regularly whenever other study instruments are deemed inappropriate. It also indicates the level of importance of the study topic and are by far quite resource intensive, requires eliciting information on a one to one basis and are more insightful (Wilkinson, D., & Birmingham, 2003). Development and process of the interview were as per figure 5.

Figure 5. Development and process of the interview.



Draft interview questions were structured. The interview did not only mainly target Ship Management and Ship Operator Companies and professionals working there but, also, technology developers in the maritime industry. The purpose of doing so was to be able to support the survey findings with expert opinions as well as gather information from candidates having hands on experience following a careful selection made of the targeted interviewees. It was very unfortunate that the researcher despite communicating with numerous potential interviewees, non was willing to participate or backed down on the last-minute citing highest level of confidentiality on this topic and that no data or information could be disclosed. With no option, the research continued fully relying on the survey questionnaire.

3.7 Data Analysis.

Data analysis refers to a process of reducing huge amount of data and converting it to make sense of its use (Kawulich, 2015) and according to Berg, (2001) it involves reducing of data, displaying and evaluating it and, making conclusions from the results.

All questions from the survey questionnaire were categorized accordingly and the results from each finding were presented, sorted, and analysed with respect to each of the research questions. A qualitative descriptive analysis was deemed appropriate and used for the collected data.

According to Lambert & Lambert, (2012), the goal of a Qualitative Descriptive Analysis is to provide a comprehensive summary of specific events in every day terms and scenarios of specific events experienced. This can be by individuals or groups. It should be seen categorical as opposed to being non-categorical, a substitute for inquiry and is less analytical.

The data analysis commenced with providing demographics of the participants. Bbenchmarking questions as per table 3, and themes categorized as per figures 12, 13 & 14 were then developed for ease of conducting a qualitative descriptive analysis with the help of graphs and charts for each of the developed themes along with the benchmarking questions. Each of the questions from the benchmark and the respective themes were thoroughly studied and categorized in line with the Research questions and made ready for gathering final findings, discussions, recommendations, and conclusions.

3.8 Reliability and validity.

Reliability refers to trustworthiness while validity aims at measuring authenticity of data (Bryman, 2011). These are two very good concepts meant to ensure high research quality. The survey questionnaire was carefully and systematically structured and developed to provide answers to the research questions. During the process, it was subject to continuous scrutiny and adjustments guided by extensive expertise and wealth of knowledge by the Professor supervising this research. Finally, the questionnaire was reviewed and approved for use and distribution after was found appropriate and relevant to answer the research questions of this study by the WMU Research Ethnic Committee Protocol.

The data obtained was examined thoroughly, sorted, and properly analysed. The researcher targeted Companies and Individuals from the Maritime Industry who were well acquainted on this study topic and their contribution by participating in this survey provide wealth of experience and high value data with expectations that will lead to result outcomes that are valid and reliable.

3.9 Limitations.

Research limitations are undeniable and may vary from one to another. According to Price & Murnan, (2004), a research limitation is a systematic bias that could influence the outcome of a study, as a result of the researcher not having control over it and on the contrary delimitation is a systematic bias introduced deliberately by the researcher. Theofanidis & Fountouki, (1994) described it as an imposed restriction or a potential weakness as per Simon, (2011) that is out of the researcher's control that may affect and influence the results, study design and conclusions.

This research had its share of limitations; 1. Potential interviewees were not willing to participate and those who showed interest later backed down. Among the reasons shared were sensitivity of the topic and confidentiality clauses applicable to staff, non-familiarity to the technology investigated or concerned candidates were on either on summer holidays or out of workstations during this period of research, 2. Survey questionnaire attracted more personal communications. People reached out to inquire on concept and what was expected to be achieved rather than participating by filling it up, 3. accessibility to companies and experts was very challenging, 4. time allocated for this research was very minimal.

It was the opinion of the researcher that challenges were partly attributed to the covid 19 pandemic that made it difficult to have access to candidates and companies. Among others are the level of secrecy by companies who have adopted and working on enhancing those existing technologies or on the other hand non-disclosure policies by those who are developing to newly adopt, restricted candidates from participating and lastly shying of following non familiarity to such existing technologies.

4.0 Chapter 4: Data Analysis

4.1 Introduction

Results from of the survey carried out by use of questionnaires as explained in the previous chapter were revealed to determine the status quo, influential factors, extent of use, benefits and draw backs, and future of digital twin technology in monitoring marine fouling. To start, general demographic was illustrated from the data obtained. Then details from each of the questions were presented and structured in line with the research questions, detailed descriptive analysis conducted and finally findings were thoroughly discussed to answer the research questions.

4.2 Demographics of Research Respondents

Generalized Information and demographics of the participants from the survey questionnaire are reflected in the next paragraphs of this section, accordingly.

4.2.1 Survey Questionnaire

The survey questionnaire attracted a total of 52 participants from 18 countries. The results summaries of their nationalities, Professional Background, years of experience are shown in the following section.

4.2.2 Nationalities

A total of 18 nationalities participated in the survey questionnaire. Jordan stood the top with 8 participants (15%), followed by Kenya with 7 (13%), Philippines 7 participants (13%), India 5 participants (10%), Gambia and Japan with each 3 participants (6% each), Sweden, Tunisia, Hongkong, Trinidad and Tobago each with 2 participants (4% each) while Bahamas, Greece, Singapore, Pakistan, United Arab Emirates, German, Qatar, Egypt, Senegal, and Denmark each having 1 participant (2% each). One participant (2%) did not indicate nationality. Figures 6 & 7 depicts the number and percentage of participants from respective countries.

Figure 6. Nationality of respondents in percentage.

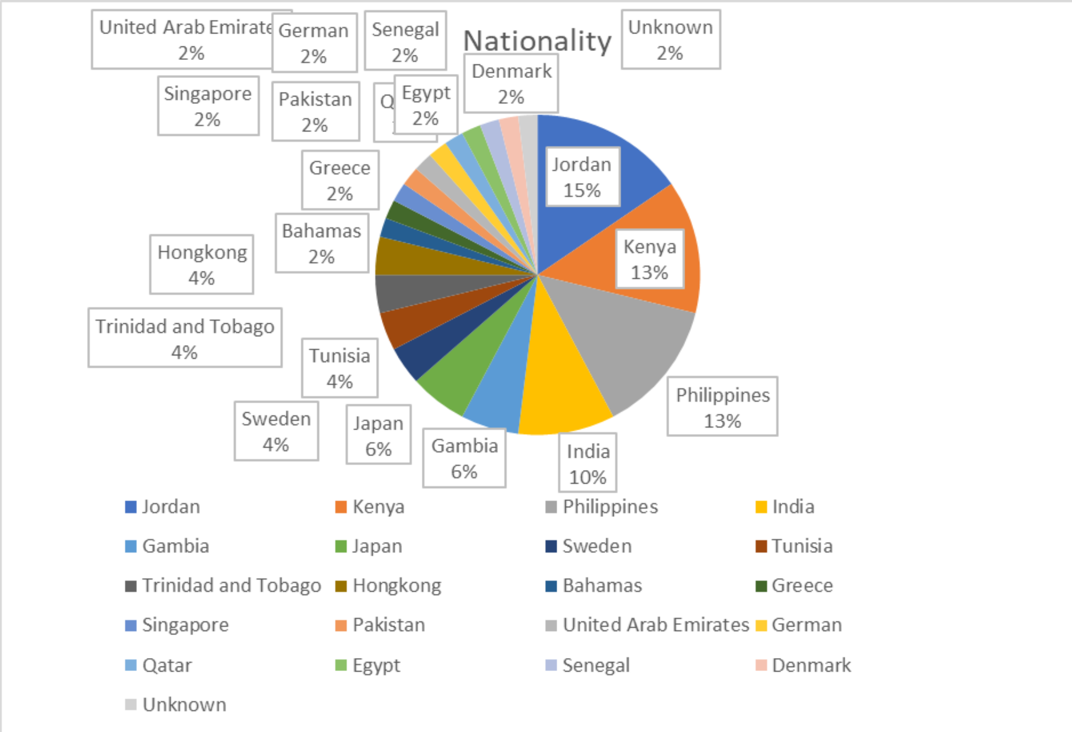
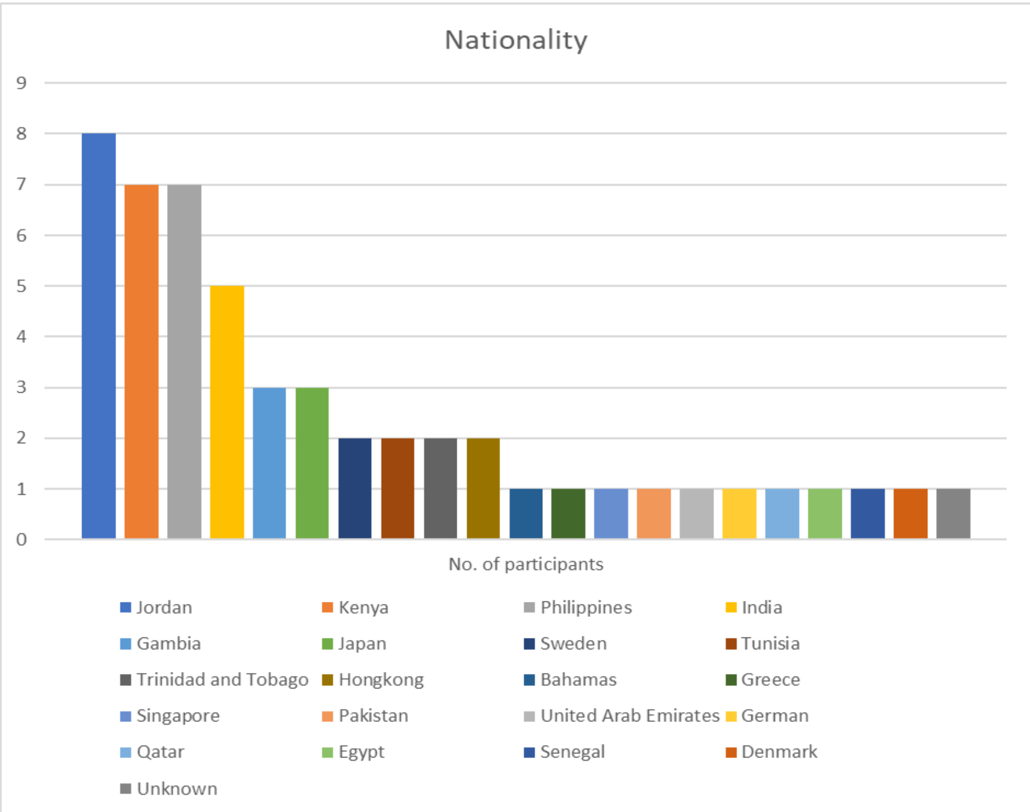


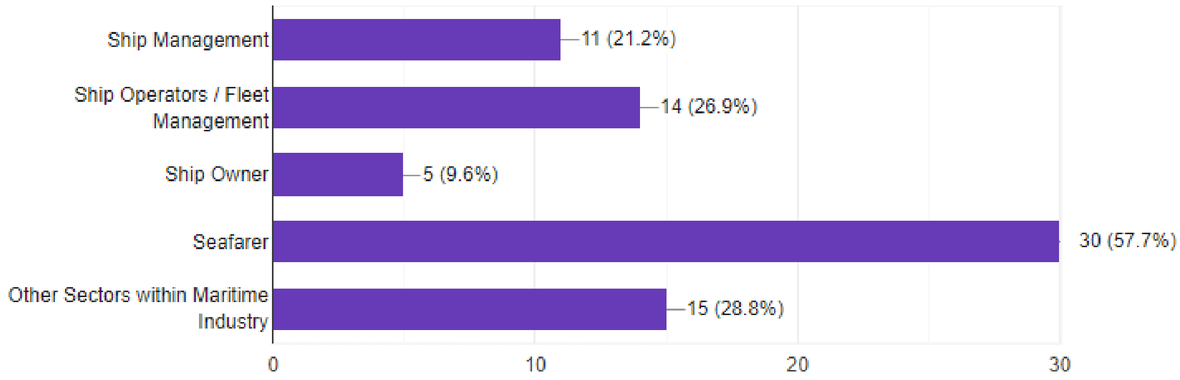
Figure 7. Nationality of respondents in numbers.



4.2.3 Professional Background

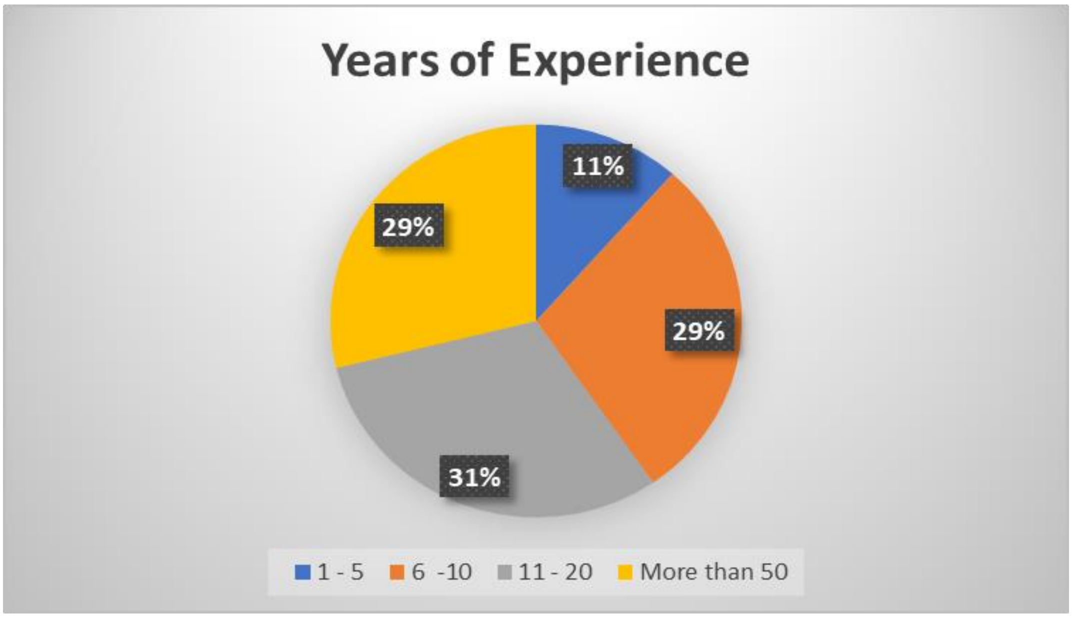
Out of the 52 participants from the survey questionnaire, a collection of multiple experiences with each participant from within the Maritime Industry sectors were noted. From the Multiple choices we had Ship Management with 11 participants depicting 21.2%, Ship Operators/Fleet Management with 14 Participants depicting 26.9%, Ship Owners with 5 Participants depicting 9.6%, Seafarers with 30 participants depicting 57.7% and 15 participants from other sectors within the Maritime Industry depicting 28.8%.

Figure 8. Professional Backgrounds.



4.2.4 Years of experience

Figure 9. Level of experience of participants.

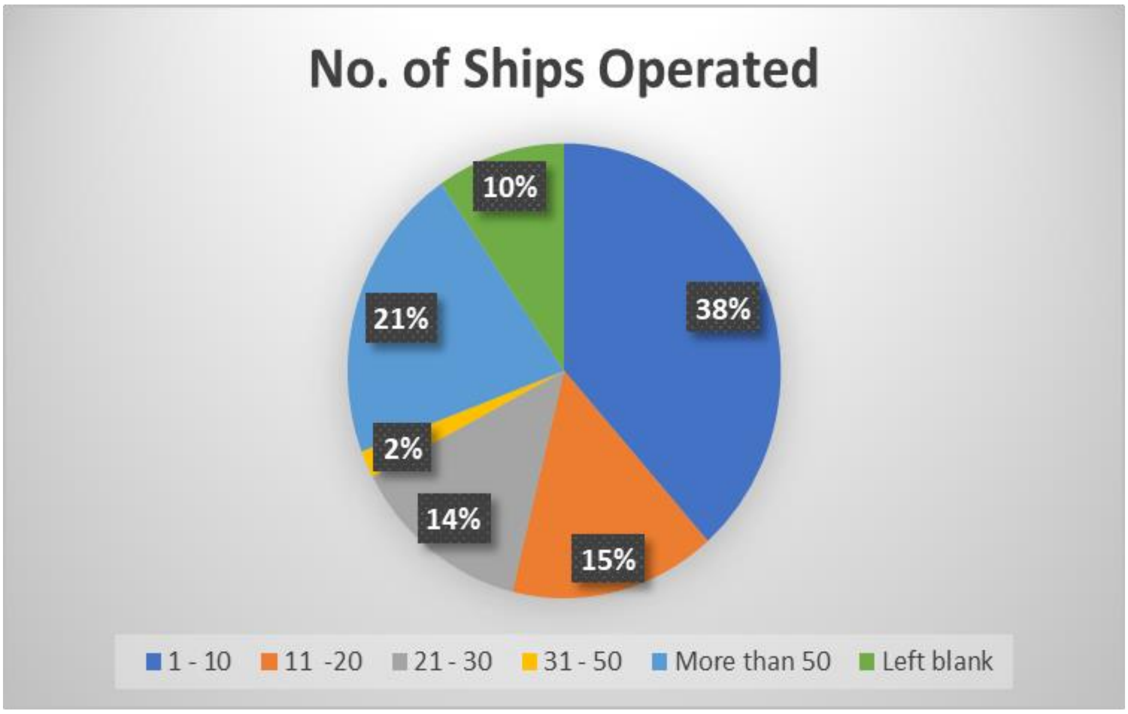


Six participants possessed professional background experience of between 1 – 5 years occupying 11%, followed by Fifteen participants with experience of between 6 – 10 years occupying 29%, Sixteen participants between 11 – 20 years occupying 31%, while 15 participants had more than 20 years of experience, occupying 29%.

4.2.5 No. of Ships operated/Managed

20 Participants are either operating or managing between 1 – 10 ships depicting 38%, 8 Participants between 11 – 20 ships depicting 15%, 7 Participants between 21 – 30 ships depicting 14%, 1 Participant between 31 – 50 ships depicting 2%, 11 Participants with more than 50 ships depicting 21%, while the remaining 5 participants (10%) did not disclose the number of ships they manage/operate.

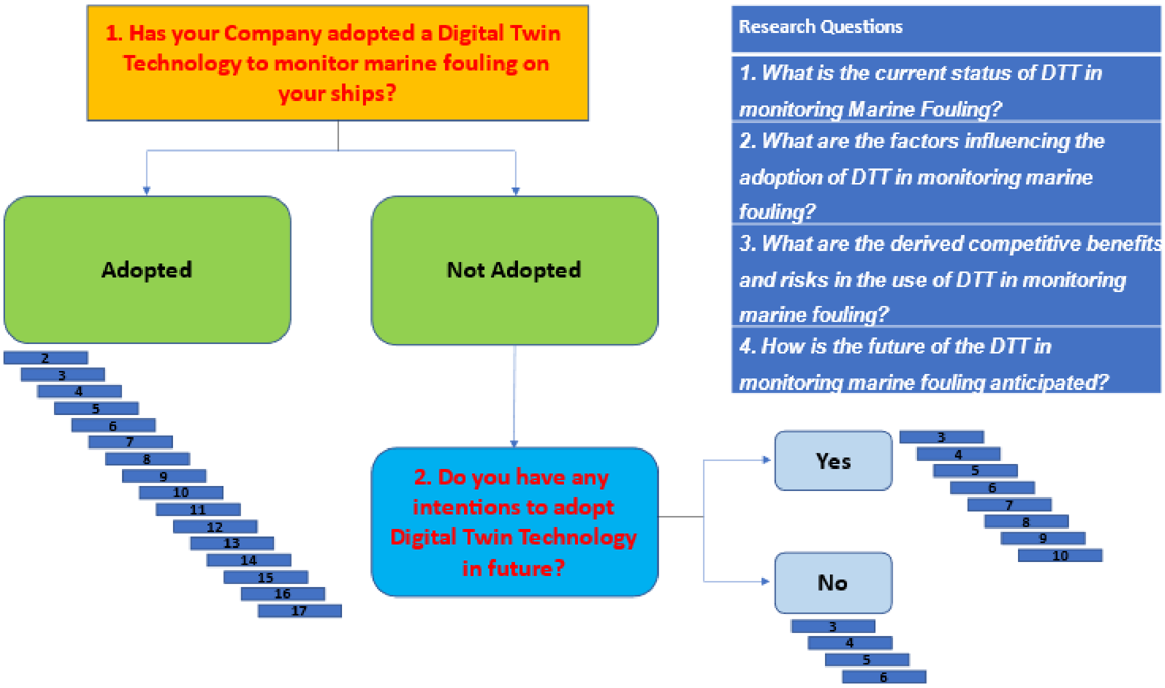
Figure 10. Number of ships operated.



4.3 Survey Questionnaire

After determining the details and demographics of participants, research questionnaire was structured into parts. First was to understand on whether the participants have adopted to the digital twin technology in monitoring marine fouling and the question asked was, “What is the current status of digital twin technology in monitoring marine fouling on your ships? A set of sixteen questions followed to those who confirmed adoption. For those who had not adopted, another question was asked “Do you have any intentions to adopt Digital Twin Technology in future?” this led to either “Yes” we intend to adopt or “No”, we have no intentions to adopt. For those who answered “Yes”, a set of eight questions followed and 4 questions to those who answered “No”. The structure is reflected on figure 11.

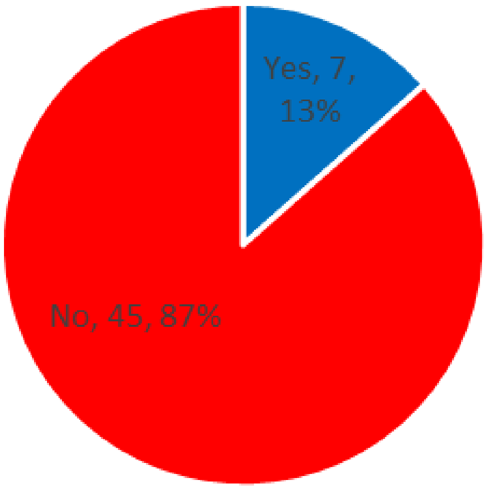
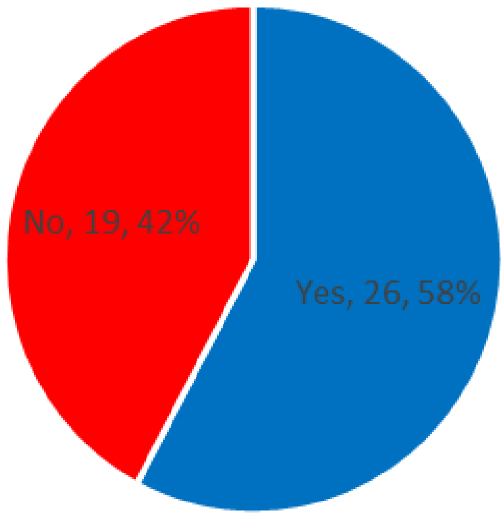
Figure 11. Structure of the survey questionnaire.



Question 1 and 2 (in red fonts) from the structure separates the themes and have been referred to as the benchmarking questions.

4.3.1 Benchmarking Questions

Table 3. Benchmarking questions.

Question 1	Question 2
Has your company adopted a Digital Twin Technology to monitor marine fouling on ships you operate?	Do you have any intentions to adopt Digital Twin Technology in future?
	

Out of the 52 participants, 7 participants have adopted to the digital twin technologies while 45 participants have not. Out of the 45 participants who have not adopted, 26 participants intend to adopt while 19 participants have no intention to so.

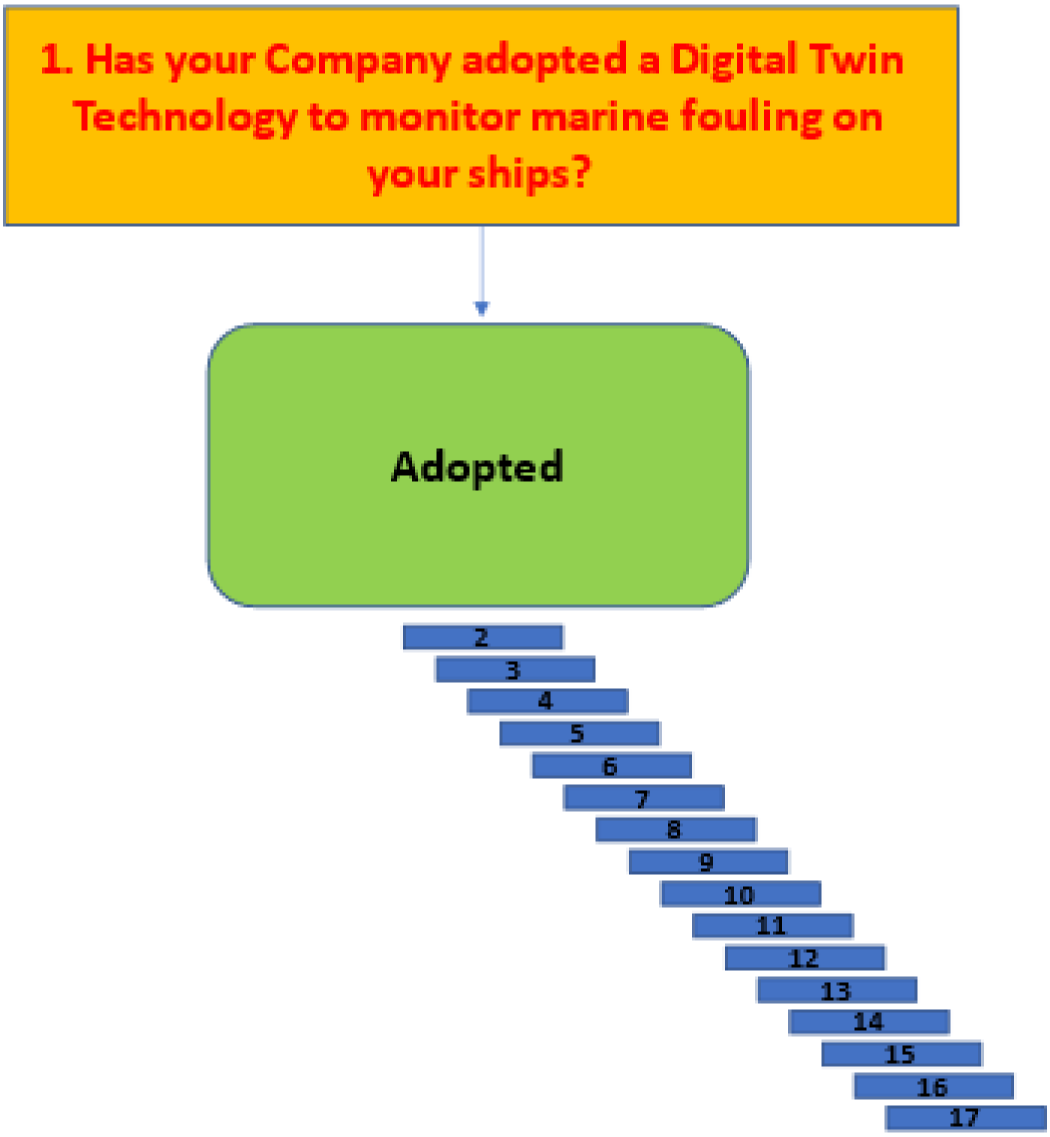
4.3.2 Themes

In order to analyse the questions, the structure was divided into three categories, namely; 1. Theme "Adopted" that will analyse the answers from those participants who have already adopted the digital twin technology in monitoring marine fouling, 2. Theme "To Embrace" for those who have not adopted but plan to do so and lastly 3. Theme "Analogue" for those who have neither adopted nor intend to embrace the digital twin technology in monitoring marine fouling now or in future.

Refer to table 4 for the survey questions related to the developed themes and numbered 2 – 17, 3 – 10 and 3 – 6 on figures 12, 13 and 14, respectively.

4.3.2.1 Theme "Adopted".

Figure 12. Theme "Adopted".



Seven participants representing six countries, five of which are seafarers with experience ranging from 1 to 20 years and having between 1 to 30 ships. One is a ship operator with 6 – 10 years professional experience operating more than 50 ships and lastly one with professional background in ship management, owning and operating for 11 – 20 years with more than 50 ships. Ref to appendix 1.

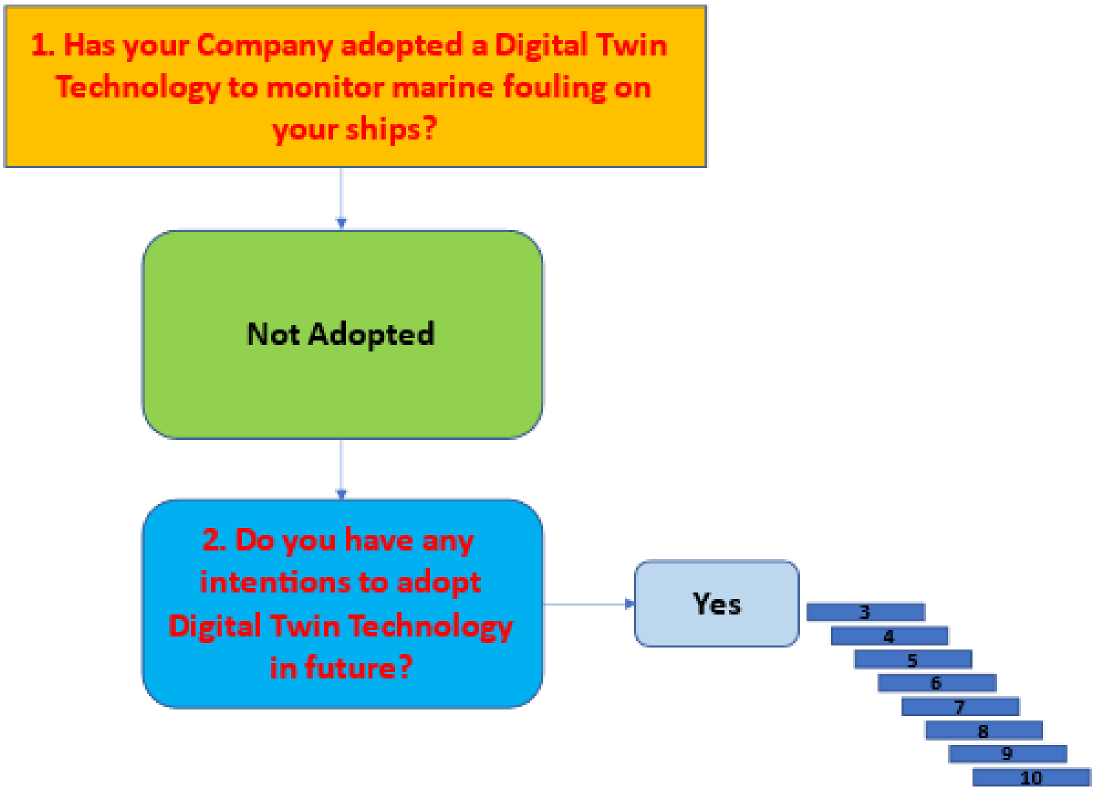
Out of the 7 particpants,

- 3 felt DTT has “Greatly” assisted them in monitoring changes to to the hull and propeller of their ships while“Fairly” by two particpinats and remaining two “Least” assisted (Appendix 2).
- 6 “Agree” that Digital Twin technology has “Greatly” assisted in monitoring marine fouling againt one participant who was “uncertain” (Appendix 3).
- 3 collected data, basis fully automated from the DTT for monitoring marine fouling while semi automated by the remaining 4 participants (Figure 15).
- 5 agree to the “Reliability” of information on changes to the hull and propeller on marine growth while the remaining 2 participants were not sure (Figure 16).
- 5 agree to the “Effectivity” of information on changes to the hull and propeller on marine growth while the remaining 2 participants were not sure (Figure 16).
- 3 agree to the “Accuracy” of information on changes to the hull and propeller on marine growth while 3 participants were not sure and remaining one participant disagreed. (Figure 16).
- 1 participant “Strongly Agree” that Digital Twin Technology in its implementation, is associated with high risks and uncertainties on sensor reliability, model failures and wrong decision making as an output to data processing while 4 “Agree”, One “Disagree” and One “Unsure” (Appendix 4).
- 6 times “Information Sharing” and “Real Time Data Analysis” was selected as the technological factors that influence the adoption of Digital, followed by “Perceived benefits” 4 times, “Data Security and Privacy” 3 times, “Compatibility” twice, then by “Complexity” once (Figure 17).
- 7 times “Cost of Operation” was selected as the economic factor that influence the adoption of Digital Twin Technology, followed by “Preventive Planning” 3 times, “Cost of Investment” and “Competitive Pressure” twice then by “Stakeholder Pressure” once (Figure 19).
- 6 times “Emissions Reduction” was selected as the environmental factors that influence the adoption of Digital Twin Technology, followed by “Regulatory Pressure” 5 times (Figure 21).

- 1 participant “Strongly Agreed” that use of Digital Twin Technology is cost effective, 4 “Agreed”, while for the remaining 2, One “Disagreed” and One was unsure (Appendix 6).
- For the factors the digital twin has given participants a competitive advantage over their competitors in decision making. “Reduction of Fuel Consumption” and “Reduction of CO_2 Emissions” were selected 4 times each, then “Preventive Maintenance”, “Periodic Maintenance Scheduling” and “Maintaining Ship Speed” were each selected thrice, followed by “Mitigating maintenance cost” twice and lastly “Building and or retaining reputation” selected once (Appendix 7).
- 1 participants “Stronly Agree” that accurate data collected on marine fouling enables timely antifouling, and propeller cleaning while the remaining 6 participants “Agree” (Appendix 8).
- 2 participants “Strongly Agree” that the Maritime Industry should focus on developing and improving the Digital Twin Technology for monitoring the hull and marine growth while 4 “Agreed”, and the remaining one participant “Disagreed” (Appendix 9).
- 1 participant “Strongly Agreed” that reliable vessel performance monitoring systems are vital in detecting underperformance of ships while 6 participants “Agreed” (Appendix 10).
- 1 participant “Strongly Agree” that Digital Twin Technology is the future for monitoring marine fouling, while 4 “Agreed” and the remaining 2, one “Disagreed” and one “Unsure” (Figure 23).

4.3.2.2 Theme "To Embrace".

Figure 13. Theme "To embrace".



26 participants, ranging from Shipowners, Ship Management, Ship Operators and Fleet Management to seafareres and other professionals from within the Maritime Industry participated. Years of experienced ranged from 1 – 5 to more than 20 years and ships operated or managed ranged between lowest 1 – 10 to More than 50 ships (Appendix 12).

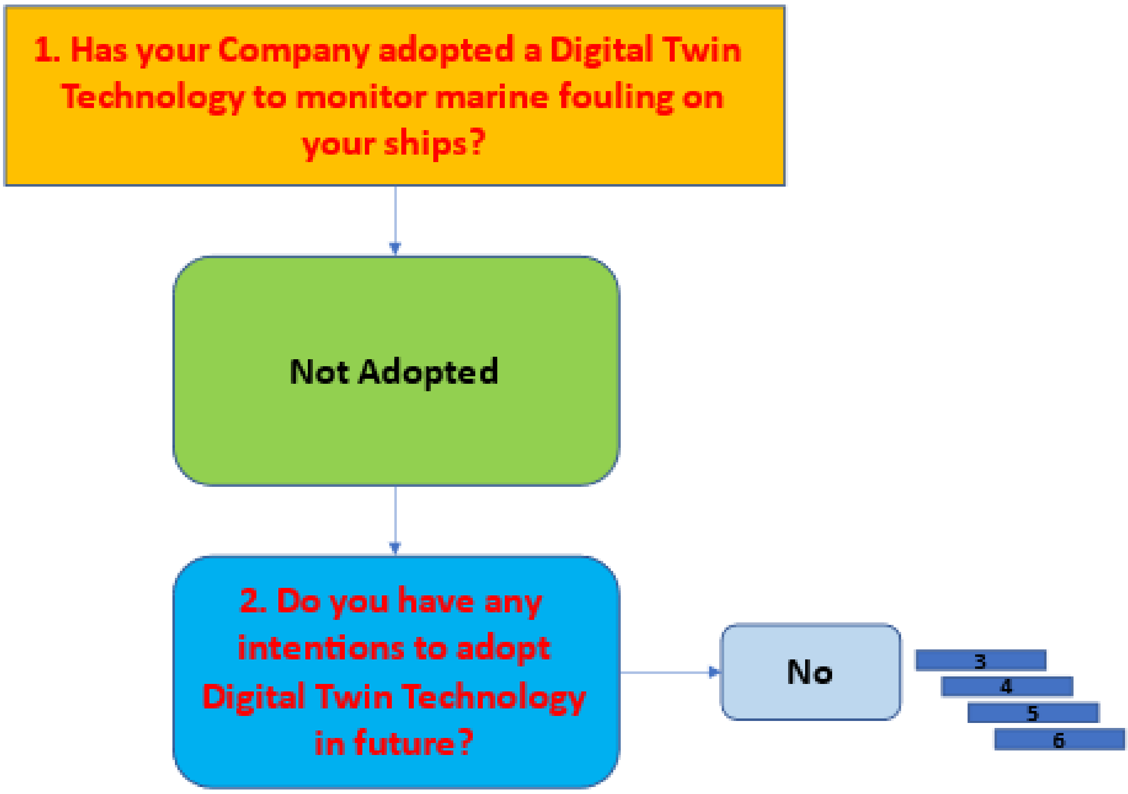
Out of the 26 particpants,

- 6 participants "Strongly Agreed" to have already taken necessary initiatives to adopt and develop a digital twin technology, while 7 "Agree". Three participants "Disagree" while 10 are "Not Sure" (Appendix 13).

- 13 times “Real Time Data Analysis” was selected as the technological factor that influenced them to adopt to the Digital Twin, followed by “Perceived benefits” that was selected 11 times, “Data Security and Privacy” 10 times, “Information Sharing”, “Compatibility” and Complexity” 8 times each and finally “Maintaining Its operability upon its implementation” once (Figure 18).
- 19 times “Cost of Investment” and “Cost of Operations” were selected as the economic factors that influenced them to adopt to the Digital Twin, followed by “Preventive Planning” 12 times, “Stakeholder pressure” 7 times, “Competitive Pressure” 5 times, and lastly “Reduce Cost for physical or actual survey for monitoring foul density on ships hull” once (Figure 20).
- 15 times “Regulations Pressure” and “Risk Mitigating Strategies” was selected as the environmental factors that influenced them to adopt to the Digital Twin, followed by “Emissions reduction” 14 times, then one suggested “Adequate study to be performed in case of possible harm to marine environment” another participant not accepting any of the multiple choices by selecting none of the above (Figure 22).
- 19 times “Reduction of Fuel Consumption” and “Reduction of CO_2 Emissions” was selected as the factors the digital twin has given them a competitive advantage over their competitors in decision making, followed by “Periodic Maintenance Scheduling” 16 times, then by “Maintaining ship speed” and “Mitigating Maintenance costs”, 15 times each, and lastly “Preventive Maintenance” was selected 13 (Appendix 14).
- 20 times “Data Quality” was selected as a foreseen risk and uncertainty in adoption and implementation of Digital Twin Technology as an output to data processing while “System compatibility” was selected 8 times, “Sensor Reliability” 15 times and Model Failures 12 times (Appendix 15).
- 5 participants “Strongly Agreed” that use of Digital Twin Technology is cost effective depicting while 13 “Agreed” and the remaining 8 were unsure (Appendix 16).

4.3.2.3 Theme “Analogue”.

Figure 14. Theme “Analogue”.



19 participants, ranging from Shipowners, Ship Management, Ship Operators and Fleet Management to seafareres and other professionals from within the Maritime Industry participated. Years of experienced ranged from 1 – 5 to more than 20 years and ships operated or managed ranged between lowest 1 – 10 to More than 50 ships as per appendix 18.

- Reasons behind deciding not to embrace the Digital Twin Technology were selected as follows, “Cost of Investment” was selected 11 times, followed by “Complexity” and “Strategic Decision” 6 times each, then “Data Security and Privacy” and “Perceived benefits” 2 times each, then “Compatibility” that was selected only once, and finally, “Maintaining Its operability upon its implementation” once (Appendix 19).
- 5 out of the 19 participants felt that the use of digital twin tecnology can give you an advantage over competitors while 13 were not sure and remaining one particpant felt there are no advantages (Appendix 21).

4.4 Findings

The Association for Qualitative Research, referred to ***findings*** as “The principal outcomes of a research project; what the project suggested, revealed or indicated. This usually refers to the totality of outcomes, rather than the conclusions or recommendations drawn from them” (AQR, 2021). The findings provided in this research therefore refer to the results of the analysis or discoveries made from collecting, analyzing, organizing, and data interpretation (Asogwa et al., 2016).

Careful selection of specific survey questions from each of the categorized themes and benchmarking questions was made. Their findings presented in the most systematic manner to both relate and concurrently answer the respective research questions and meet the research objective as guided by table 4.

Table 4. Guiding survey questions to answer the research question.

Research Objective	**Research Questions**	**Benchmarking Questions**	**Theme “Adoption”**	**Theme “To Embrace”**	**Theme “Analogue”**	
1. To evaluate the status quo of digital twin technology in monitoring marine fouling.	***1. What is the current status of DTT in monitoring Marine Fouling?***	Q1. Has your company adopted a Digital Twin Technology to monitor marine fouling on?	Q2. To what extent has Digital Twin Technology assisted you in monitoring changes to? Q3. Digital Twin Technology	Q3. We have taken necessary initiatives to adopt and develop a digital twin technology	Q3. Please elaborate on your reason behind such a decision not to adopt to the Digital	

		Q2. Do you have any intentions to adopt Digital Twin Technology in future?	has greatly assisted in monitoring vessel performance Q4. How is data collected? Q5. Digital Twin Technologies have so far proven to be reliable, effective and offer accurate information on changes to the hull and propellers on marine growth.		Twin Technology	
2. To identify the factors that influence the adoption of digital twin technology in monitoring marine fouling.	***2. What are the factors influencing the adoption of DTT in monitoring marine fouling?***		Q8. What are the technological factors that influenced the adoption of Digital Twin Technology? Q9. What are the economic factors that influenced the adoption of Digital Twin Technology? Q10. What are the environmental factors that influenced the adoption of Digital Twin Technology?	Q4. What are the technological factors that influenced the adoption of Digital Twin Technology? Q5. What are the economic factors that influenced the adoption of Digital Twin Technology? Q6. What are the environmental factors that influenced the adoption of Digital Twin Technology		Overall Professional Opinions and views of Companies on the Use of Digital Twin Technology

				?		
3. To establish the competitive advantages and shortcomings in use of digital twin technology in monitoring marine fouling.	***3. What are the derived competitive benefits and risks in the use of DTT in monitoring marine fouling?***		Q6. Despite advantages of Digital Twin Technology in its implementation, it is still associated with high risks and uncertainties on sensor reliability, model failures and wrong decision making as an output to data processing. Q7. What are the challenges encountered in using Digital Twin Technology? Q11. Use of Digital Twin Technology is cost effective Q12. Use of digital twin technology has given us an advantage over our competitors in making timely decisions towards: -	Q7. Use of digital twin technology can give us an advantage over our competitors in making timely decisions towards Q8. As an output to data processing, we foresee risks and uncertainties in adopting and implementation such as Q9. Use of Digital Twin Technology would be cost effective	4. Do you think Use of digital twin technology can give you any advantage over your competitors? 5. What are the challenges you foresee to encounter in case you choose to adopt and implement the Digital Twin Technology?	
4. To determine the future of digital twin technology in monitoring	***4. How is the future of the DTT in monitoring marine fouling anticipate***	Q2. Do you have any intentions to adopt Digital Twin Technology in future?	Q13. Accurate data on marine fouling enables timely antifouling, and propeller cleaning.			

marine fouling.	***d?***		Q14. Maritime industry should focus on developing and improving digital twin technologies for monitoring the hull and marine growth Q15. Reliable vessel performance monitoring systems are vital in detecting underperformance of ships Q16. Digital Twin Technology is the future for monitoring marine fouling.			

4.4.1 What is the current status of DTT in monitoring Marine Fouling?

Findings from the analysis show that the DTT for monitoring marine fouling has been adopted, though so far not widely but continuously gaining confidence and popularity as many intend to soon adopt based on perceived benefits and influential factors that are further mentioned in detail on the next unit. Refer to table 3. The use is also in monitoring overall changes to the hull, propeller, and ships performance. Data collected for those purposes is currently either semi-automated or fully automated but no longer gathered manually (Figure 15). Information acquired on the underwater condition has been found to be reliable and effective but not as accurate as required to be (Figure 16).

While some players indicated having plans in place to adopt and acknowledged the role such a technology can play in decision making and timely maintenance scheduling, others felt otherwise and found comfort in the traditional methods of maintaining frequent under water inspections and most current methods of anti-fouling coatings. Among other main reasons or concerns revealed were the related costs of the technology, its complexity, strategic decisions required, fear on data privacy and security, perceived benefits, and compatibility challenges. Some felt the number and size of fleet played a big role in adoption.

Figure 15. How respondents collect data.

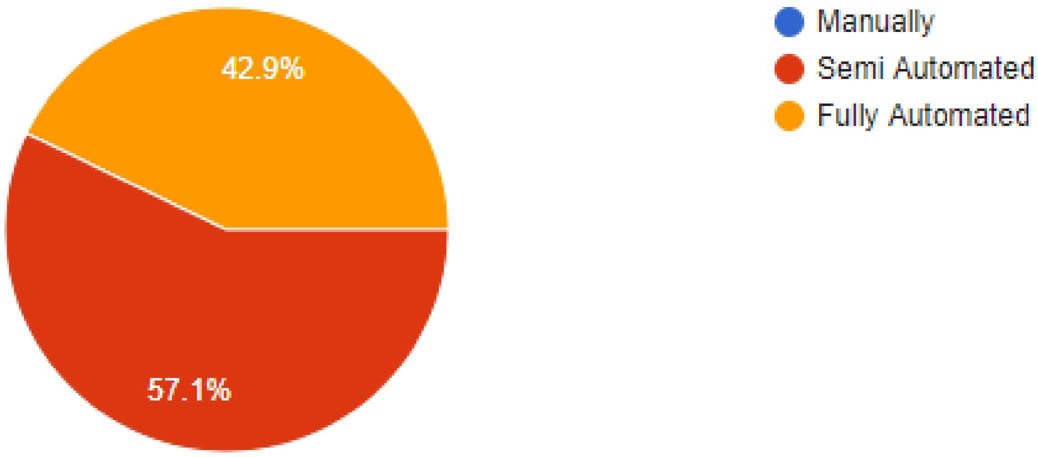
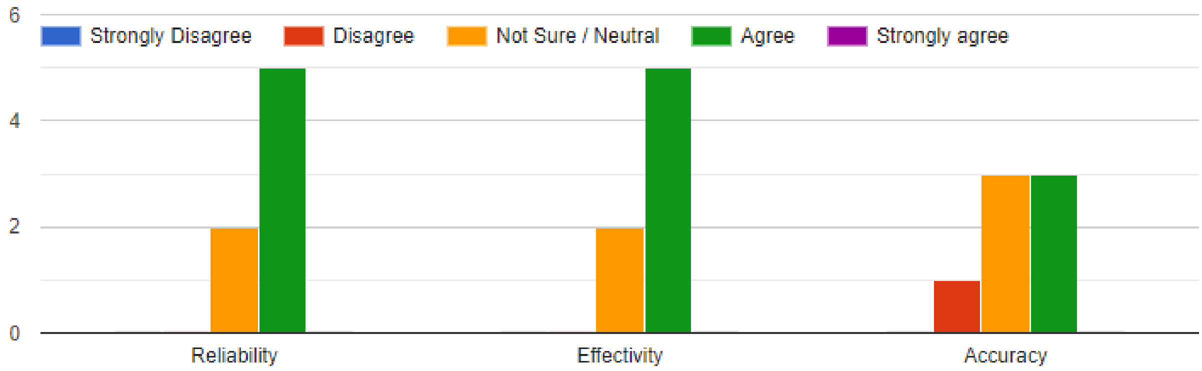


Figure 16. Reliability, Effectivity, and accuracy of data.



4.4.2 What are the factors influencing the adoption of DTT in monitoring marine fouling?

Relating and learning from other sectors and their choice of technologies, the research also aimed at understanding the factors that influenced the use and development of DTT in monitoring marine fouling to the industry players currently using it and to ascertain what would or is motivating the rest to follow soon in doing so. The analysis revealed the existence of technological, economic, and environmental factors influencing the adoption. Refer to figures 17 to 22.

Technological factors: uninterrupted smooth flow and receipt of data in good time to users was a key aspect with consistency and compatibility being of paramount importance, followed by their regarded values from different perspectives and affirmation towards data protection and confidentiality. Technologies should not be complicated but rather easy and friendly to use.

One cannot argue that Maritime Industry especially the Ship Management and operations sector, data flow, data quality and integrity, time such data is sent out or received and to/by whom may have different consequences, impacts and gravity, because of its usefulness and value to different users, may be for various needs and holds numerous levels of sensitivity in them. Respondents, without fail uniformly made that clear by indication of them being influenced by technologies for monitoring marine fouling. The growth in the industry has seen a rise in data that needs proper management and transformation in different forms suitable to suit different needs hence the need to embrace technologies.

DTT by use of sensors sending signals and data to a central location or being accessed by multiple parties on marine growth will trigger various decisions and actions. Rate of fouling can provide predictions on how soon or later an underwater cleaning or dry docking may be required hence proper commercial planning can be kept in place in readiness for the anticipated extent of works to be done and idle period as may professionally and timely be suggested by Ship Managers who would be monitoring such data. On the other hand, Ship operators are more concerned on the performance of the ship to make maximum voyages. Proper voyage costs need to be accurate in order to be able to make desirable financial gains hence anticipation of speed loss and additional fuel consumption will assist them in determining and adjusting voyage costs and sailing schedules in line with the forecasted costs to be incurred because of the accumulation of fouling and its repercussions to performance and operational costs. For example, such data may not be useful to documentation, imports or export departments but will definitely affect their swift work roles in timely preparing ships documentations, advise of estimated time of arrival (ETA) of ships to interested parties, arrange for berth and many others as a result of an operator being able to be accurate in advising all concerned on the ETA of a ship from an informed angle rather than assuming from vessel speeds in normal circumstances.

Digitalization has resulted to major transformation and has revolutionized industries and ways of conducting businesses. Developing, enhancing existing technologies or innovating better ones cannot be emphasized enough. Technologies, despite having different glitches, come with numerous advantages. They offer efficiency, effectiveness, reliability, accuracy of reporting and can process and generate customized huge data and provides reports at a click of a button, with ease of access from multiple places or devices around the clock. This allows Ship Managers and Operators to have fast hand information, anticipate the future and be able to plan ahead. One thing that such an industry cannot afford is to work with uncertainties and this can be achieved by adopting to technologies such as DTT.

Figure 17. Technological factors influencing “theme adopted” respondents to use DTT.

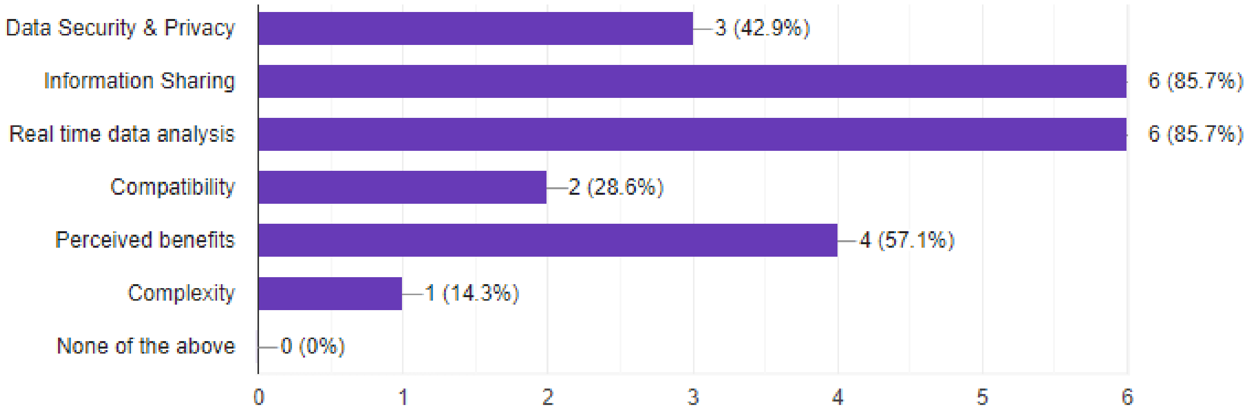
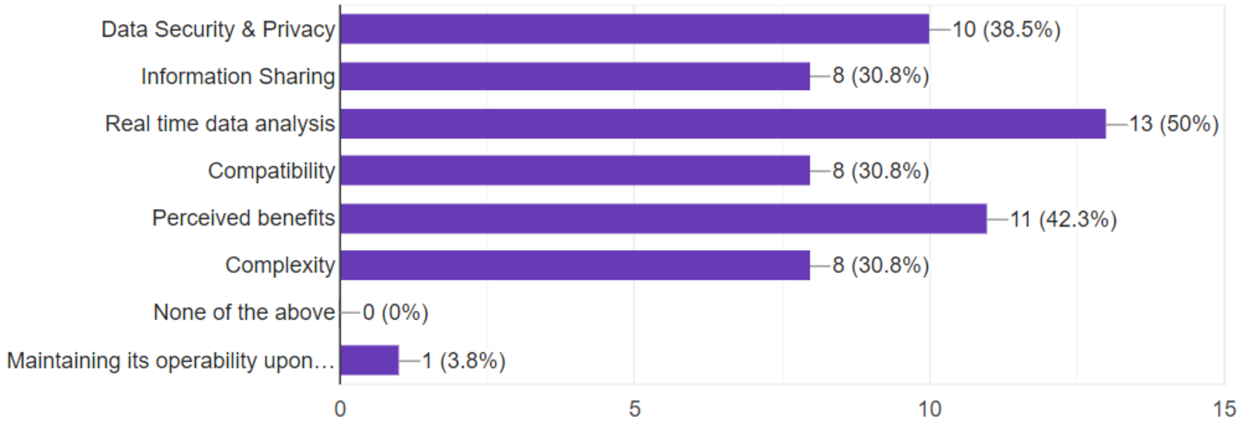


Figure 18. Technological factors influencing “theme to embrace” respondents to use DTT.



Economic factors: technologies and systems are costly to purchase, develop or maintain. Respondents perceived the related cost of operations to be the main driver, followed by precautionary planning which are already in addition to the initial cost of investment. Level of competition around may as well influence adoption and pressures from the involved stakeholders. Lastly, consideration basis affirmation of savings that could be made by dodging physical inspections and surveys.

Managing and operating ships is expensive hence options to adopt to digitalization platforms and automated instruments reduce the applicable costs. Respondents looked at such technologies as opportunity costs rather than additional costs. There is an English proverb from Cambridge Advanced Learner's Dictionary & Thesaurus, that says: “*prevention is better that cure*”. For ship managers and operators, preventive maintenance strategy is the proactive way to efficiently maintain and operate a ship. DTT by the virtue of providing data that can be utilized to plan against negative eventualities is considered to be a proactive move and provides an upper hand for proper decisions and timely action to be taken to ensure vessel performance and its commercial operations are not compromised and costs in ensuring that are mitigated if not avoided i.e. increase of fuel cost and loss of speed as a result of marine growth that was not well monitored or impact not timely anticipated.

In the long run the savings made from additional bunkers consumed and power for maintaining ship speed are huge as compared to the costs of investment in buying, developing, or maintaining a DTT hence bringing the aspect of opportunity costs. It also saves time and huge costs related to underwater inspection, cleaning, and dry docking which could be minimized if not dodged. This is complemented by the fact that ROV's introduced can help cleaning the hull while cargo operations are ongoing to avoid unnecessary huge costs related to underwater surveyors and drydocking.

Competition as well can be seen as an influential driver that sets momentum in people adopting and behaving in certain ways. Evidently, for respondents who have adopted and presently enhancing their technologies is more than a prove that there exist benefits from utilization of technologies, and they are deemed useful, practical, reliable, and worth investing on. Where a competitor is able to timely make decisions to save costs as a result of a potential impact and that too without engagement of additional manpower may trigger competitors to adopt similar technologies so that they can enjoy equal playing grounds. To give strength to such findings, we can draw from different sectors including the maritime industry how fast digitalization is been given priority not only in performance and productivity benefits but as well in keeping costs of operations low i.e ship automation.

Figure 19. Economic factors influencing "theme adopted" respondents to use DTT.

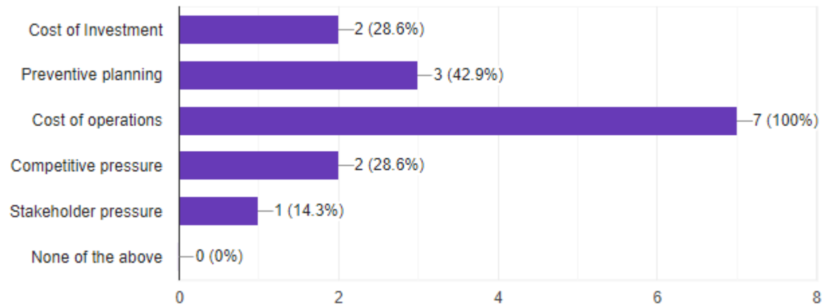
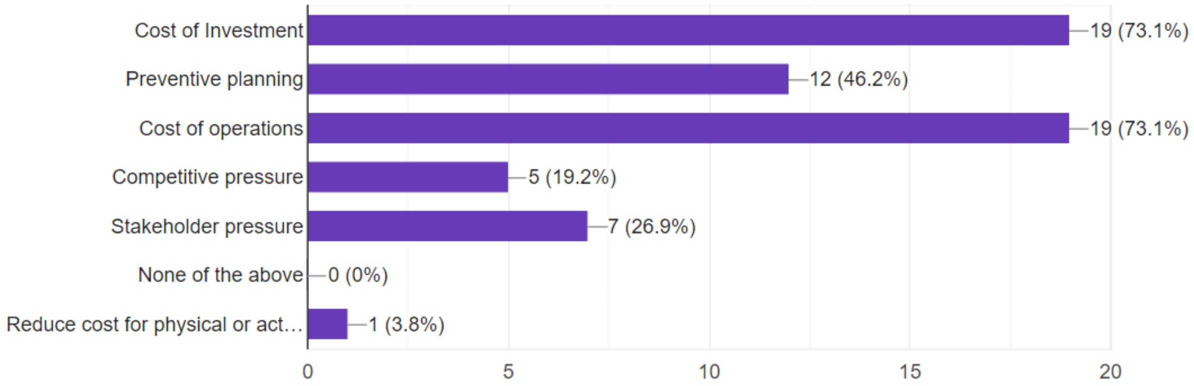


Figure 20. Economic factors influencing "theme to embrace" respondents to use DTT.



Environmental factors: reduction of emissions to the lowest possible level was regarded imperative along with the related regulations being enforced and the pressure exerted by respective bodies like the IMO. This implied the gravity of risk management strategy also being considered as an influential factor.

Above findings are from the point of view of those who have already adopted DTT. As with regards to those who intend to embrace, similar views were shared though level of scaling their respective importance was slightly different.

A lot of emphasis, attention and focus has now been directed to climate change to which related realities have been acknowledged and impacts are witnessed across the world. Research and solutions to energy efficiency, reduction of emissions and keeping the environment clean and conducive have seen rise with a lot of sensitization programs seeking to keep awareness and teach us how to be environmental conscious and responsible for a better future. This is happening across the world and at different levels. On the other hand, policies and regulations are as well keeping up to speed to ensure proper guidelines are in place including rules and regulations for all to adhere to from national and international capacities.

Many Companies including Maritime Sector are fully promoting and looking for solutions to energy efficiency, and in keeping our environment cleaner and safer. A lot of initiatives have been taken including research and development, technological innovation, and advancement and in policies. Ship Managers and Operators have not lost track but totally committed to the environment and compliance to the respective regulations towards achieving the Sustainable Development Goals (SDG).

Figure 21. Environmental factors influencing "theme adopted" respondents to use DTT.

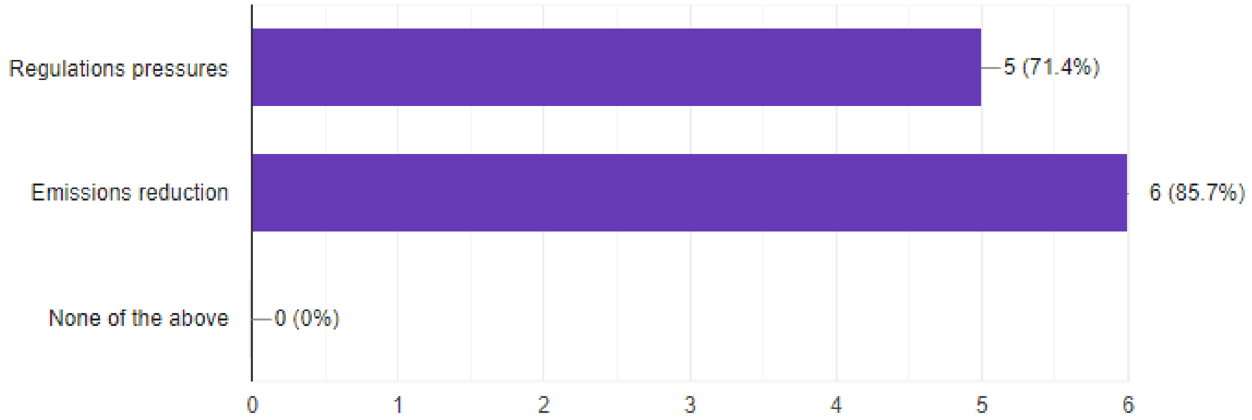
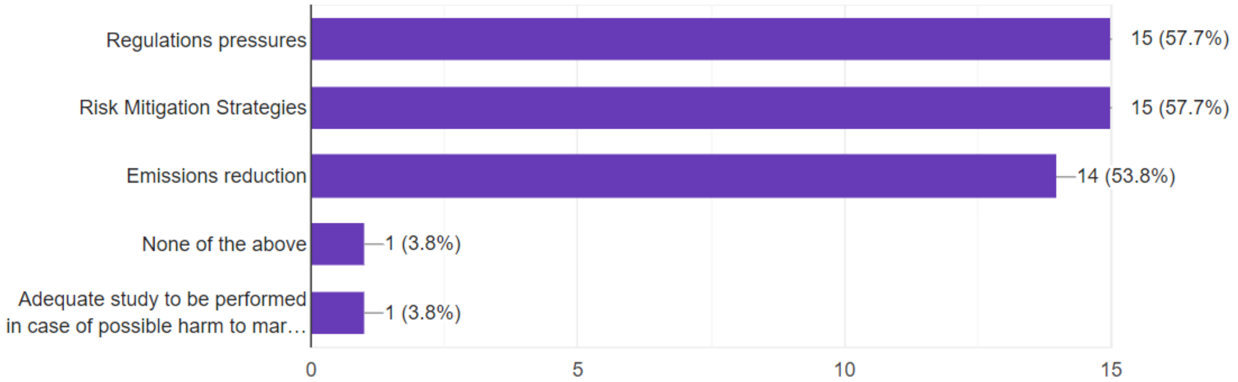


Figure 22. Environmental factors influencing "theme to embrace" respondents to use DTT.



4.4.3 What are the derived competitive benefits and risks in the use of DTT in monitoring marine fouling?

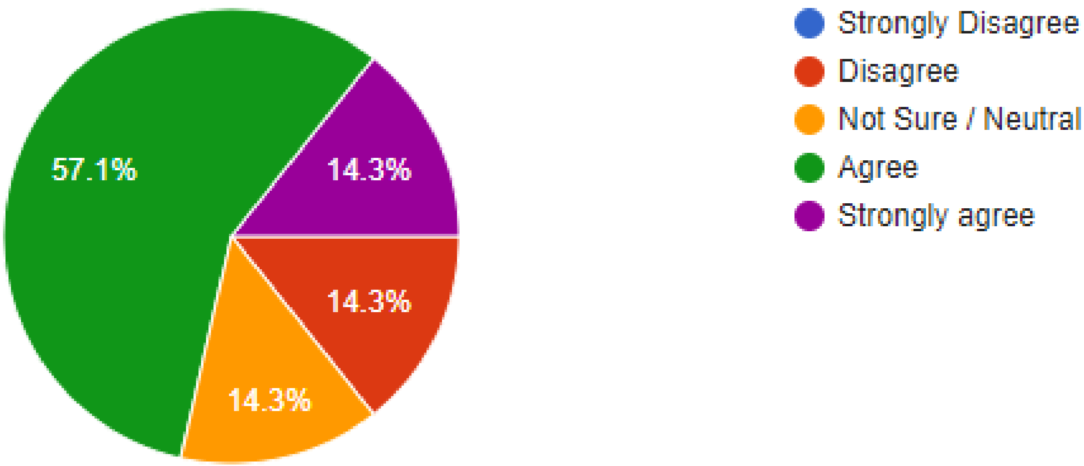
Respondents using DTT are able to keep a close eye to the hull and make informed decisions towards reducing fuel consumption and CO_2 emissions. It allows them to place proper maintenance schedules and where appropriate conduct timely preventive maintenances to avoid greater harms to ships. This leads to ensuring ships performance efficiency and ship speed is preserved. In the long run maintenance and operations costs are kept to the lowest. As a result, respondents also argued that they can retain their image and reputation and generally DTT has proven, through their experiences to be cost effective and an opportunity cost.
It was also noted that despite the benefits brought using DTT there were existing risks and shortcomings associated to them. Among the concerns were on sensor reliability and model failures that can lead to inaccurate data collection, discrepancies or affect the data quality and integrity. Data security was another concern on its safety and confidentiality, followed by model failures during engineering, inception, while in use or developments stages as well as the complications from system compatibilities and complexity. Refer to appendixes 13, 24 and 31.

Ship Managers and operators will strive to enhance technologies in use to safeguard their interests so long as benefits over run shortcomings and will keep on improving and customizing them to suit individual needs and priorities. As a result, this study realized how much time is spent by system developers before implementation during the test and error period, piloting and simulations from system developers and the classification societies in the market.

4.4.4 How is the future of the DTT in monitoring marine fouling anticipated?

It was overall agreed that accurate data for monitoring the underwater growth is of essence and that would lead to timely antifouling and propeller cleaning. Reliable technologies for monitoring such growths and ship performance were therefore vital. Apart from those who had already embraced DTT for that purpose, more respondents intended to adopt, reference to table 3, and as well felt it is the way forward, a step towards the right direction and is the future in monitoring the marine fouling, the hull and ships performance and has a significant impact in increasing ship efficiency (Refer to figure 23).

Figure 23. DTT is the future in monitoring marine fouling.



For the few who disagreed, they raised questions on the maturity of DTT, whether it was too early to adopt and were more comfortable with using the traditional method of monitoring using daily ships report, ships speed, consumption and maintaining the regular underwater inspection, dry docking, and the use of latest anti-fouling methods hence DTT is not required.

It would go without saying that DTT is gaining popularity, and good momentum, has a great future and potential because of many intending to embrace and will see increase in adoption, improvement in enhancing and developing and also in its implementation.

To mention a few, a *digital solutions company* that we had a chance to exchange email communications, confirmed that they were in the process of building a multi-tech digital product that was intended to optimize voyage performance of ships. One of the happy spin-offs mentioned of that project was the reduction of carbon footprint.

Among the technologies they use is a virtual simulation software that accurately recreates a ship form, hydro-static and hydro-dynamic environments of choice to digitally ‘twin’ a ship’s motion through water including the 6 degrees of freedom of motion. The output of such ‘twinning’ simulation is the fuel ~ speed ratio in different conditions. The technology is then able to pick the most optimal template and give you the most efficient voyage in terms of fuel & time for a given set of conditions. The conditions include quantifying hull roughness caused by marine growth on hull, among other things.

Since their work was in progress on actual ship models for their clients, they were constrained in sharing details or results. But broadly, thereafter mentioned that not much work has been done in this aspect around the world to their knowledge.

Chapter 5: Discussions, Recommendations, Summary, and conclusion

5.1 Discussions

The Maritime Industry has witnessed a great impact and exposed to major transformations brought about by digitalization. No doubt all discussions are now made around it at different forums and levels as changes keep on being witnessed and more expected to alter our traditional ways of conducting business and in carrying out our day-to-day activities. As a result, competition levels and pressures have risen and brought a sense of having to keep up with the pace with the various digital technologies being introduced, developed, implemented, and maintained.

We can easily say that digitalization has become increasingly of relevance especially in the maritime industry as it keeps on reshaping and restructuring, and assisting in optimizing the processes in place, creating more opportunities, and transforming trade and supply chain. A policy brief report by United Nations Conference on Trade of June 2019, No. 75 on "Digitalization in Maritime Transport: Ensuring opportunities for development" discussed the importance of advocating to technological innovations and urged on the importance of realizing and promoting the potential of digitalization and to ensure that digitalization in the maritime industry is driven towards achieving the Sustainable Development Goals (SDG) (UNCTAD, 2019).

Technologies are meant to save cost and time, bring efficiency and improved performance, promote accuracy and transparency and ability to process volumes of data at ease, generate different detailed reports and analysis within split of seconds, speed up processes and productivity and many more sparks. And for that reason, the concept of DTT has captured the eyes and attention of many players in the industry with its potential to assist them in various and numerous ways.

This is clear from the findings illustrating the positivity of adopting the technology and level of acceptance by those who are looking forward to embracing it. From the sample data collected it is evident that the adoption is still at its infancy with not many stakeholders using it but there is a lot of potential shown to do so. Logically, one may argue that the background plays a role, for example, a ship owner or an operator with a fleet of ships may consider depending on technologies for better results and in business operations and the fleet size may have an impact to such an extent and make a great deal of sense. This however has not been the case in the findings though generally fleet size matters according to the individual respondents. The number of respondents, specific targeting ship owners and operators for future research would be ideal. References were made from other industries that have adopted to similar technologies and the factors influencing their decision to adopt were also evaluated if they could also be of impact in the case of DTT for monitoring Marine fouling. All the three factors received support from the respondents i.e., technological, economic, and environmental as mentioned earlier.

With every new technology and despite their benefits or perceived advantages, they are always subject to drawbacks and associated with variety of risks depending on the quality and advancement of the technology, duration of testing and use and how much developments have been made on them. Maritime industry players were looking at the use of DTT to gauge the marine growth and assist in decision making to reduce any potential damage and in mitigating operations costs. In monitoring the hull, players can be able to execute decisions towards preventive maintenance, scheduling drydocking and underwater cleaning, be able to minimize fuel consumption which takes a bigger share of the ships operating costs and in turn reduce the emissions and maintain engine powers with the ships speed hence ensuring good performance of the ship, efficiency, and its safety. This would be a wish to any owner, operator, or manager, however, DTT depends on reliability of its sensors to provide accurate data in real time and any failure to that would jeopardize the ships performance and keep expenses higher because of taking decisions based on inaccurate or wrong data that does not twin the real changes to the hull. It would be a disaster to invest in a technology that is unreliable, and inaccurate or when it is found not to be compatible, complex to use with model failures. Piloting phase is of great importance and implementation should be only after proper trials have proven good to go.

Across the board, it has been acceptable that digitalization is the way to go and future in maritime industry and Digital twin accepted to be having the potential to assist Ship Managers and operators in monitoring marine fouling and the hull condition in general.

We cannot resist the fact that the Maritime Industry will remain relevant as a result of its nature and ability to move huge quantity of cargoes at ease and at low costs. There is a local say that goes "Without Shipping, there is no shopping". This phrase continued to be shared in the social media during the covid 19 pandemic as a statement that confirms the relevancy of shipping transportation in the world. Statistics from the UNCTAD proved this and showed that at least 80% of cargo is moved by sea as a result of the imbalance of natural resources and other factors across the world and that no one state can be able at any time to claim self-sustenance. This brings in the element of globalization and elaborated how much states depend on one another.

In order to keep the balance, shipping investments remain a reality and certainly are of capital intensive. It is therefore of great importance for ship managers and operators to look for all possible options in place to ensure sustainability in operations and keeping respective cost as minimal as possible and at the same time adhere to the national or international regulations that apply.

It is important for voyage or operations costs to be kept low and managed well, in order for ships to commercially operate and keep business afloat. Main expense that takes a big portion of the operations cost is fuel that can go over and beyond 50% or more in case of any ship drag experience as a result of marine fouling. This will also reduce the speed and increase the engine propeller power and also increase emissions. Ship Mangers and operators consider that as a disaster and have no choice but to ensure proper measures are kept in place to overcome them. Marine fouling being the course requires close and frequent monitoring. Followed by timely decisions and actions on preventive maintenance and maintenance scheduling.

Among the options, is use of technologies that will assist in running business at ease, efficiently and effectively. As the study implies, DTT has come in as a solution to help in monitoring the marine growth and assist in keeping a closer eye in gauging the fouling and offer to predict future and performance of the ship hence allowing ship managers and operators to foresee and plan ahead in time and in the process save time, energy, keep costs low and ensure vessel is operating and performing efficiently.

Other than monitoring marine fouling, questions that can arise are on the potential ability of DTT or similar technologies to be developed or enhanced to offer more solutions. For example, possibility of sensing and avoiding coalitions, assisting in self-maneuvering, and berthing to save from use of tug assistance, measure and monitor the adverse weather conditions and ships surroundings, ship machinery monitoring and diagnosis. These and many can become a reality and provide tools and solutions to avoid damages and expenses and probably even enable classification societies change on how they view things and loosen up on compliance requirements and help owners with reduced insurance covers as a result of having such technologies in place. In essence, underwater surveys are too expensive and should be avoided and accepted to be replaced by classification societies with monitoring technologies and to base further decisions from them. Travel expenses for surveyors for the hull and machinery and P&I cover can be avoided and in turn DTT can be relied on for inspection and quotation of premiums and cover requirements. Extent of accidents, damages to ship and cargo and, coalitions can be assessed, and timely decisions made and coordinated as a result of development of such relevant and suitable technologies and systems.

Ship Managers and Operators have no choice but to embrace technologies and encourage on research and developments of technologies in order to provide solutions to the numerous challenges facing the management and operations of the ships safely, efficiently and at minimal costs.

5.2 Recommendations

The research purpose was to understand the level of use of DTT in monitoring marine fouling from the Maritime Industrial players who are fully engaged in to Ship Management and operations and or the development and implementation activities of such technologies meant to observe changes to the hull condition and ships performance. Their hands on experience in developing, implementing, use and managing the technology was considered valuable as it would allow researcher to engage directly and be able to access how much has DTT impacted its users, how beneficial it is and the kind of value it has added to their companies and operations, what are the shortcomings and challenges they faced during the process and their individual professional views on its adoption and future based on their practical experiences.

Hundreds of potential participants in this research were reached out by email, thousands over professional platforms and numerous more by telephone calls. However, survey questionnaire only attracted 52 respondents while none for the interviews. At least 30 reached back over the phone and a couple by email inquiring more on the scope of the study. They seemed to have been impressed by the research topic but were limited from their company policies under respective confidentiality clauses in sharing any data or information hence could not further engage or participate.

A case study would have been ideal and very much encouraged in future with a careful selection of DTT users and developer’s companies from the maritime industry. Time allocated for such a study was very less and complemented subsequently with the difficult times of the covid 19 pandemic, that unfortunately limited movement and access to potential targeted companies and professionals on a one-to-one basis hence not allowed researcher the flexibility to move and reach out to companies that may have been able to participate provided enough notice was granted and circumstances allowed.

Digitalization is the future, and we have no option but to accept its transformation and changes coming along with it. Companies and professionals should be encouraged to willingly extend their hands to researchers and offer necessary support, collaboration and cooperation as their inputs will help understand where we are, how well are we preparing, to where we are heading and how best we would venture and be ready for the future of digitalization.

5.3 Summary and conclusion.

The purpose of this study was to understand the extent of use of digital twin technology in gauging marine fouling. It aimed at 1. evaluating the status and level of its acceptability and adoption, respectively, in the Maritime Industry, 2. identify the influential factors to embracing it, 3. establish its pros and cons and lastly 4. to anticipate its future on ships for the Ship Management and Operations companies.

Digitalization has been in the middle of discussions on different tables across all sectors and specially in the Maritime Industry where, though still lagging, has been considered a key aspect for research, development and adoption, and its imperativeness emphasised with all related technologies that are in use at different capacities and level of interests.

IMO identified Marine fouling as a threat following the transfers of invasive aquatic species between regions and undermining hydrodynamic performance of ships. It also leads to unnecessary maintenance operations, increase in fuel consumption and emissions and reducing ship speed and efficiency. These come at a heavy cost in Ship Management and operations.

Digital Twin Technology, “a virtual replica of physical items”, originating from the aerospace sector, is among the technologies being embraced in the Maritime Industry and has specifically been selected as a choice of technology for study in this research. This is in line with monitoring Marine fouling and determining how much it assists the Ship Managers and Operators to keep a close eye to changes in marine growth and condition of the ship’s hull and enabling them to timely and proactively act when necessary, and at minimal costs.

Numerous lliteratures within the scope and in relation to this research were reviewed in line with the research design and framework. Survey questionnaire was solely made accessible for potential respondents to participate after many attempts failed to attract professionals and companies experienced in the subject topic to participate in interviews whom either did not show interest or were unwilling to participate citing sensitivity of the topic and level of confidentiality policies they are complying.

A qualitative descriptive analysis was used, subsequently, findings followed and discussed.

Digital Twin Technology though still at infancy stage, is gaining popularity for monitoring marine fouling and the hull condition with encouragement from various technological, economic, and environmental factors influencing its adoption. DTT provide users with an upper hand in having access to real time data that allows timely and well-informed decisions to be made. In turn ships performance and efficiency is ensured and maintenance costs are kept to minimal. DTT has been considered cost effective and an opportunity cost. Shortcomings were also noted that included sensor reliability and model failures that can create anomalies in the quality and integrity of data collected, system compatibilities and complexity, data security and absence of guiding regulations.

This study concludes with the statement ***"Digital Twin Technology is the way to go, a step towards the right direction and is the future in monitoring marine fouling and condition of the ships hull"***.

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Appendices

A. Theme "adopted" – Appendixes 1 – 11.

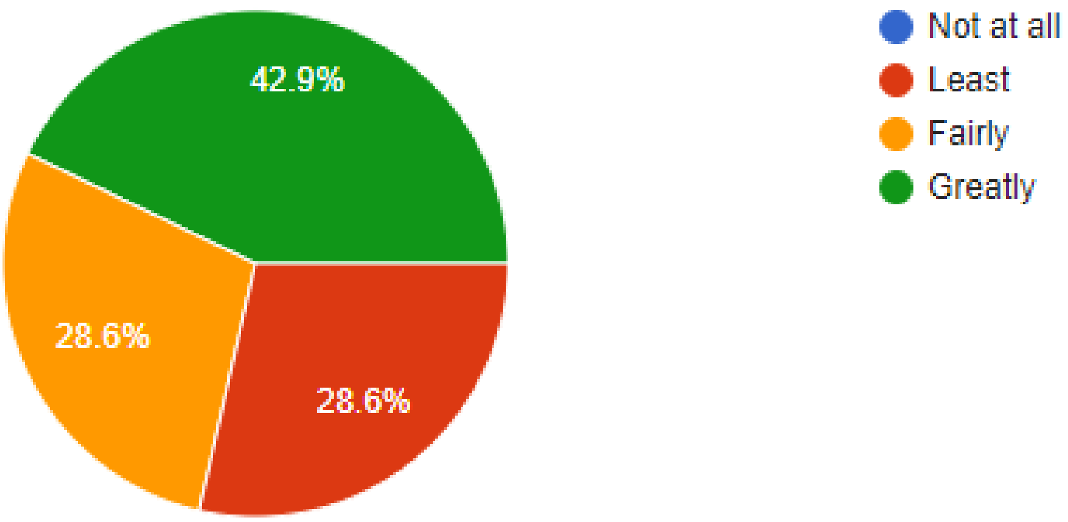
Appendix 1.

Background of participants who have adopted DTT.

Participants No.	**Country**	**Background**	**Years of Experience**	**No. of Ships Operated / Managed**
5	Denmark	Seafarer	1 – 5	1 - 10
6	Kenya	Ship Operator	6 - 10	More than 50
7	Jordan	Seafarer	11 - 20	21 – 30
24	Japan	Ship Owner / Operator / Manager	11 - 20	More than 50
42	Phillippines	Seafarer	11 - 20	11 - 20
46	Phillippines	Seafarer	11 - 20	21 – 30
48	Bahamas	Seafarer	6 - 10	1 - 10

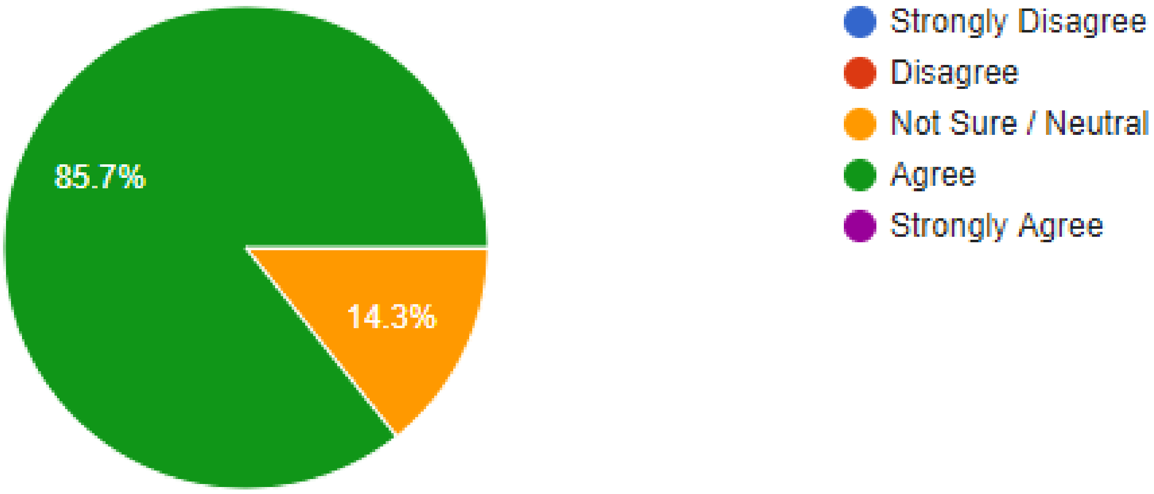
Appendix 2.

Question 2 : To what extent has Digital Twin Technology assisted you in monitoring changes to the hull and propeller of your ships?



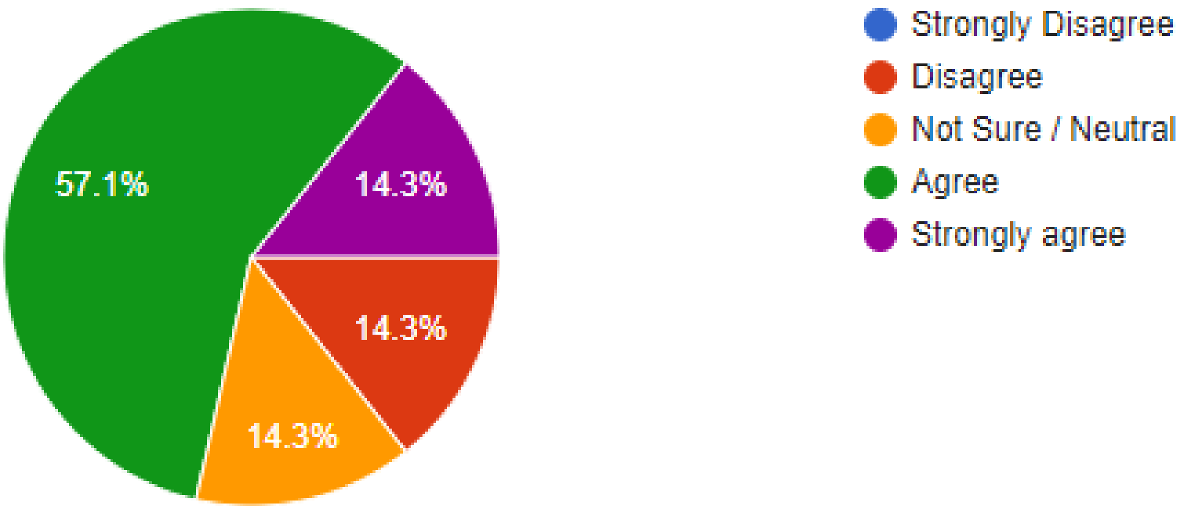
Appendix 3.

Question 3 : Digital Twin Technology has greatly assisted in monitoring vessel performance.



Appendix 4.

Question 6 : Despite advantages of Digital Twin Technology in its implementation, it is still associated with high risks and uncertainties on sensor reliability, model failures and wrong decision making as an output to data processing.



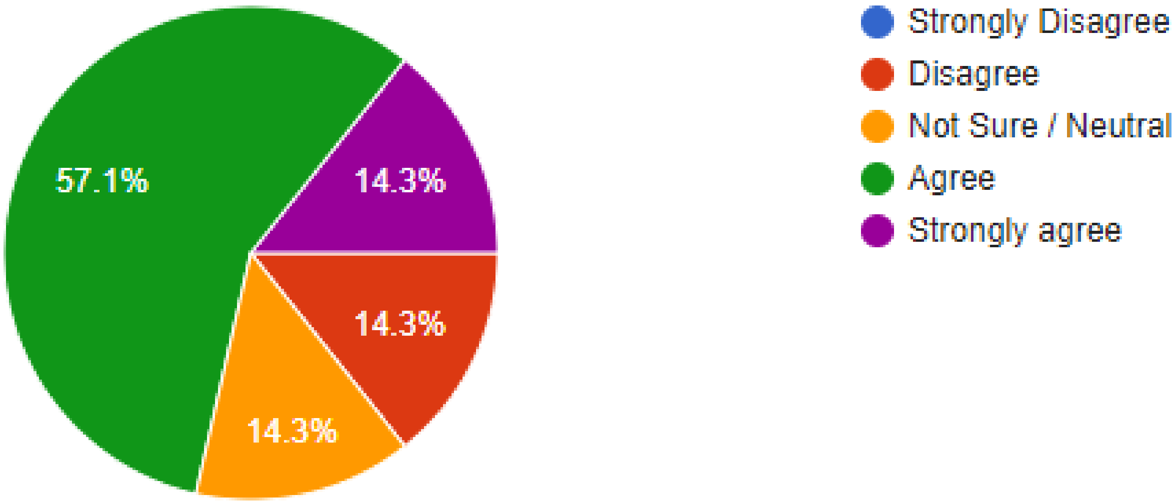
Appendix 5.

Question 7 : What are the challenges encountered in using Digital Twin Technology?

Participants	**Challenges encountered by each participant**
1	Data collection onboard process
2	Obtaining accuracy reports in times of technical glitches.
3	Based on my experience I believe it's useful technology, assisting shipping companies, ships master, officers and engineers to ensure optimal fuel efficiency
4	Accuracy of data
5	Automatic update in real time.
6	Sensor information differentiating from manual information and discrepancies not being accounted for.

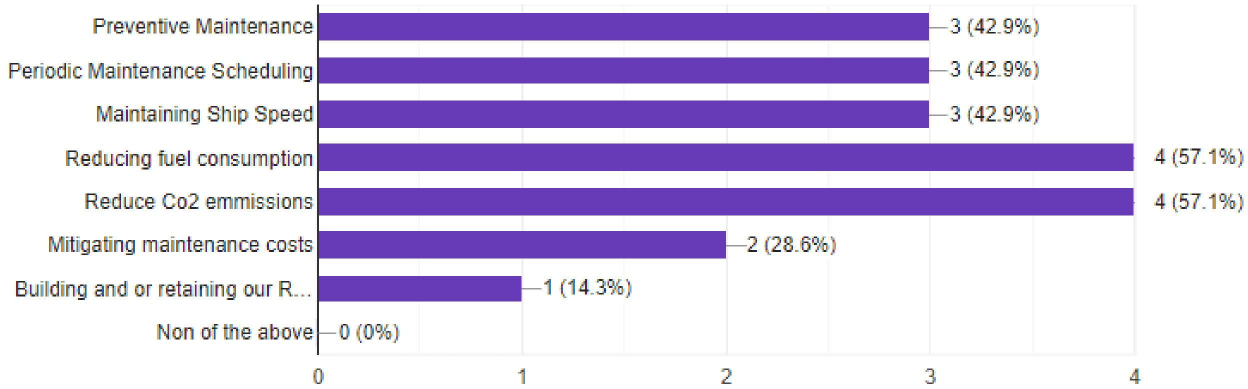
Appendix 6.

Question 11 : Use of Digital Twin Technology is cost effective.



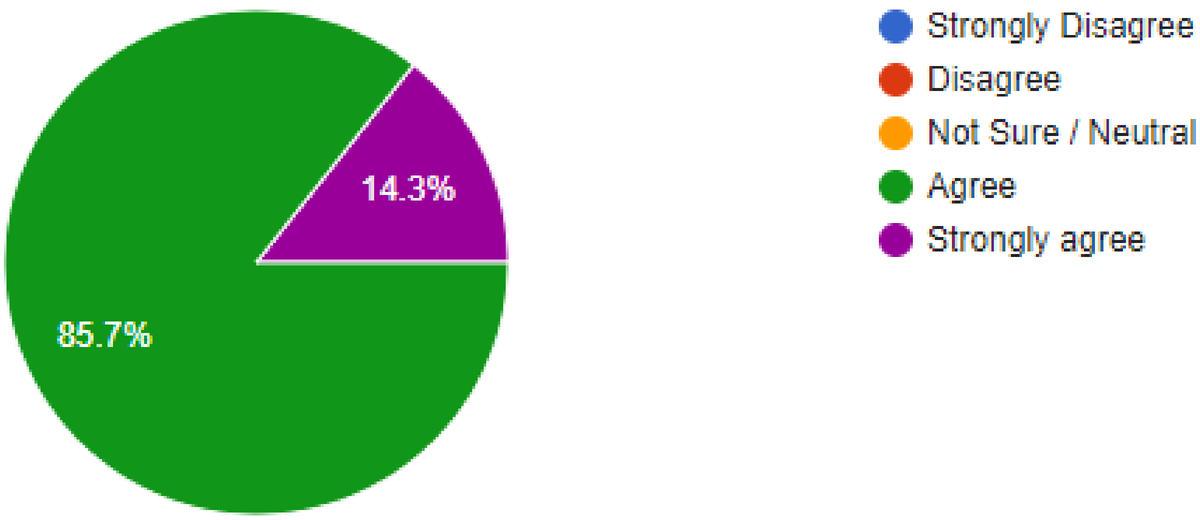
Appendix 7.

Question 12 : Use of digital twin technology has given us an advantage over our competitors in making timely decisions towards:-



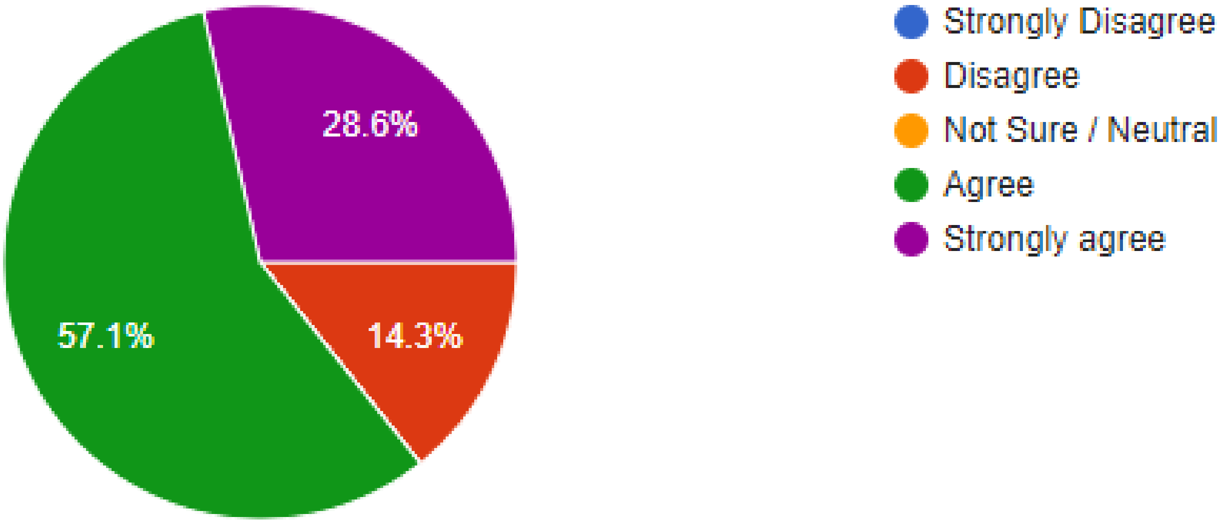
Appendix 8.

Question 13 : Accurate data on marine fouling enables timely antifouling, and propeller cleaning.



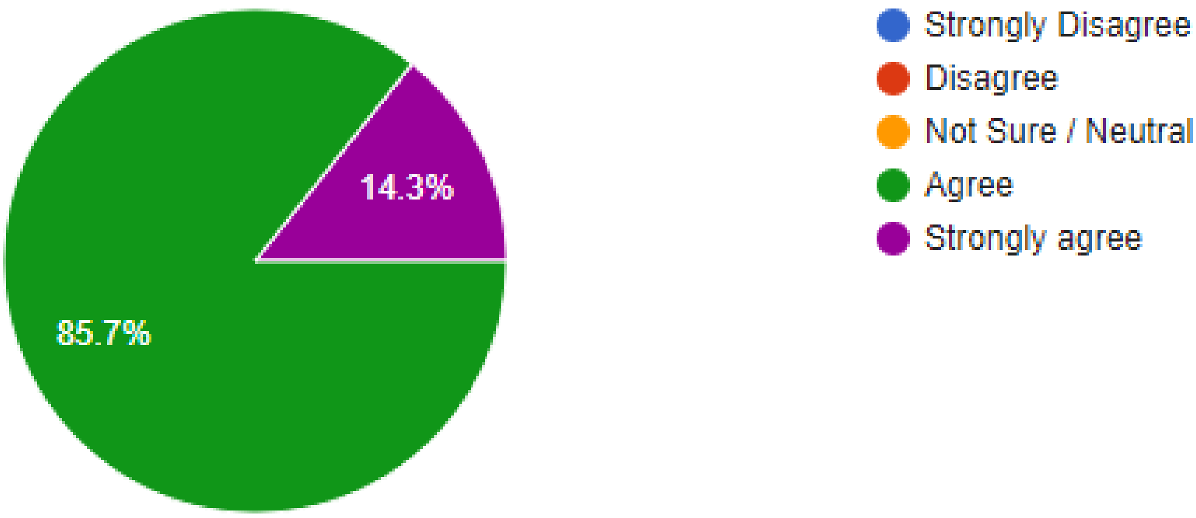
Appendix 9.

Question 14 : Maritime industry should focus on developing and improving digital twin technologies for monitoring the hull and marine growth.



Appendix 10.

Question 15 : Reliable vessel performance monitoring systems are vital in detecting underperformance of ships



Appendix 11.

Question 17 : My overall Professional Opinion and view of my Company on the Use of Digital Twin Technology.

Participant	Comments
1	Transparency and timely info sharing which in turns ensure proper management of fleet, time, maintenance, and cost.
2	Have been able to save costs in fuel consumption and reduced the amount of emissions generated by the fleet due to practices implemented based on data obtained.

B. Theme “To embrace” – Appendixes 12 – 17.

Appendix 12.

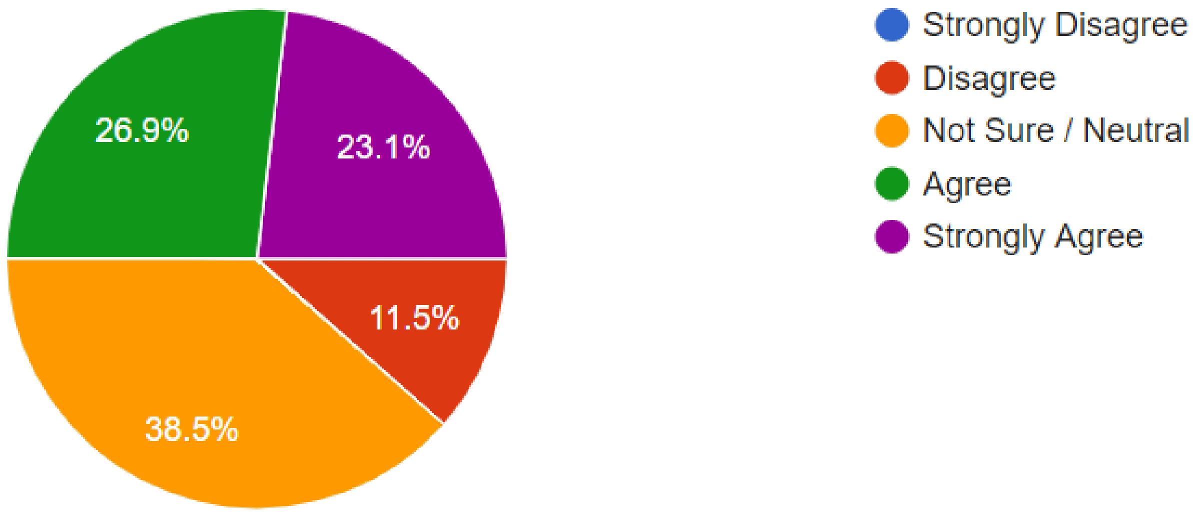
Background of participants who have not adopted DTT but intend to do so.

Participants No.	Country	Background	Years of Experience	No. of Ships Operated / Managed
1	Qatar	Ship Owner / Operator / Manager / Others	More than 20	21 - 30
3	Sweden	Ship Operator / Fleet Management	6 - 10	1 – 10
4	Pakistan	Ship Operator / Fleet Management	6 - 10	More than 50
9	Kenya	Seafarer	6 - 10	1 – 10
10	Kenya	Ship Management / Ship Operator / Fleet Management	11 - 20	1 - 10
11	Trinidad and Tobago	Others within Maritime Industry	11 - 20	11 – 20
13	Kenya	Ship Management / Ship Operator / Fleet Management	More than 20	1 - 10
14	HongKong	Others within Maritime Industry	More than 20	11 – 20
15	Kenya	Others within Maritime Industry	More than 20	More than 50
16	Jordan	Seafarer	6 - 10	1 – 10
18	Jordan	Seafarer	1 - 5	1 – 10
23	Kenya	Others within Maritime Industry	More than 20	More than 50
27	Egypt	Ship Operator / Fleet Management /	More than 20	21 - 30

		Seafarer		
29	Sweden	Ship Management	1 – 5	More than 50
30	Senegal	Seafarer	11 - 20	1 – 10
32	India	Seafarer	More than 20	21 – 30
33	Gambia	Others within Maritime Industry	More than 20	1 – 10
38	India	Ship Operator / Fleet Management / Ship Management / Seafarer / Others	More than 20	More than 50
39	Japan	Ship Operator / Fleet Management	1 – 5	More than 50
40	Tunisia	Seafarer	6 - 10	1 - 10
41	Gambia	Ship Operator / Fleet Management	11 - 20	1 – 10
43	Phillippines	Seafarer	More than 20	21 – 30
44	Phillippines	Seafarer	11 - 20	11 - 20
47	Phillippines	Seafarer	More than 20	31 - 50
51	Japan	Ship Management	More than 20	More than 50
52	Phillippines	Seafarer	11 – 20	21 - 30

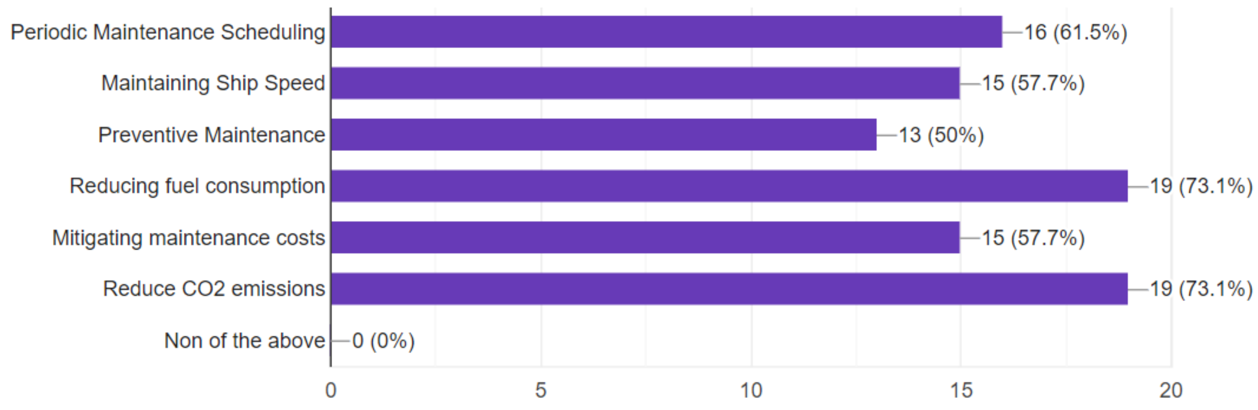
Appendix 13.

Question 3 : We have taken necessary initiatives to adopt and develop a digital twin technology



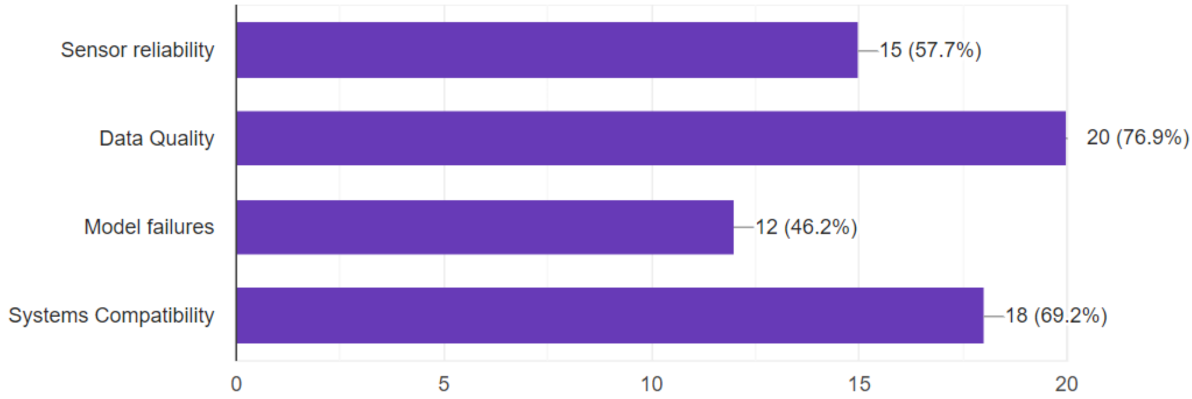
Appendix 14.

Question 7 : Use of digital twin technology can give us an advantage over our competitors in making timely decisions towards:-



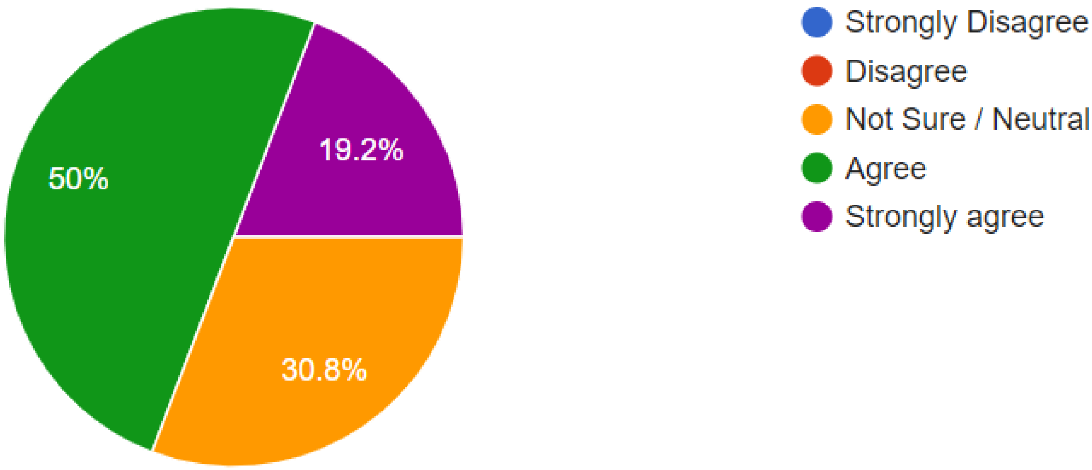
Appendix 15.

Questions 8 : As an output to data processing, we foresee risks and uncertainties in adopting and implementation such as:-



Appendix 16.

Questions 9 : Use of Digital Twin Technology would be cost effective.



Appendix 17.

Question 10 : My overall Professional Opinion and view of my Company on the Use of Digital Twin Technology.

Participant	Comments
1	Any new development is welcome but should remain sustainable and affect positive changes commercially.
2	Adoption of digital twin technology is a hot topic currently in the industry, I believe that is will take the lead it organizational innovation and provide competitive edge for entities that adopt it earlier and continue to maintain and upgrade to highly advanced version of digital twin technology in interoperable with other technologies
3	GOOD
4	I think once adapted by IMO it can reduce emission by operating ship at optimum parameters and reduce maintance cost by extending drydock periods..
5	While it presents an opportunity cost, data integrity is a key factor in realizing the cost benefit.
6	The future of shipping is technology innovation
7	Positive
8	It is the way forward for sustainability
9	As a seafarer cannot comment on shipowners behalf
10	Is step in the right direction in our efforts to technological innovations
11	Big significant impacts on the environment and able to increase the ship efficiency.
12	Data compiled from the use of technology can be used in decisions making and help in planning maintenance work
13	My company nor charterers does not adopt digital twin technology but rather have the vessel's hull and propeller regularly clean and polished annually and periodic drydocks and antifouling paints

	applied.
14	There are ways in monitoring ship's fouling in order to optimize fuel and reduce emmission which is proven effective such daily data analysis and ship performances sent by individual vessel daily. If the digital twin antifouling monitoring will be proven more cost effective and reliability is proven in all aspects, ship owners will definitely embrace the technology.
15	Digital Twin Technology is very use full specially for shipbuilding and ship management companies. A real-time data collection and analysis has been a adopted to some of our managed vessels and found it cost effective preventing bigger trouble. This system has saved operation cost for the ship owners.

C. Theme "Analogue" – Appendixes 18 – 24.

Appendix 18.

Background of participants who have not adopted DTT with no intention to do so.

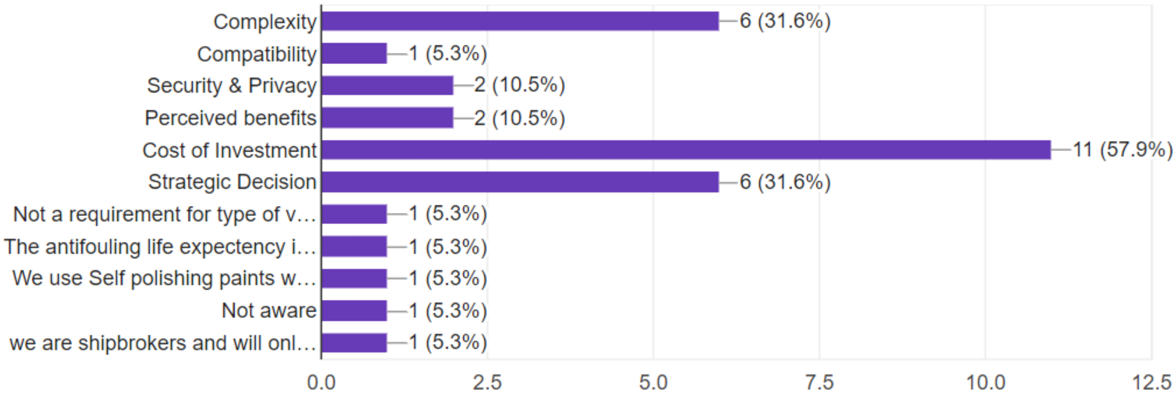
Participants No.	Country	Background	Years of Experience	No. of Ships Operated / Managed
2	Trinidad and Tobago	Ship Operator / Fleet Management	6 – 10	11 - 20
8	Jordan	Others within Maritime Industry	11 - 20	1 – 10
12	Tunisia	Seafarer / Others within Maritime Industry	6 – 10	-
17	Jordan	Seafarer	1 – 5	1 – 10
19	Jordan	Ship Management / Seafarer	6 – 10	1 – 10
20	Jordan	Ship Management / Seafarer	6 - 10	1 – 10
21	Unknown	Seafarer	6 - 10	-
22	Jordan	Seafarer	1 – 5	1 – 10
25	German	Ship Management / Seafarer	More than 20	1 – 10
26	United Arab Emirates	Ship Management	11 – 20	11 – 20
28	India	Seafarer	11 – 20	-

31	India	Others within Maritime Industry	More than 20	11 – 20
34	Kenya	Seafarer / Others within Maritime Industry	6 - 10	1 – 10
35	India	Ship Owner	11 - 20	More than 50
36	Hongkong	Ship Owner / Seafarer	Motr than 20	11 – 20
37	Gambia	Ship Operator / Fleet Management	11 - 20	1 – 10
45	Phillipines	Others within Maritime Industry	6 - 10	More than 50
49	Singapore	Others within Maritime Industry	11 – 20	-
50	Greece	Others within Maritime Industry	1 – 5	1 - 10

Appendix 19.

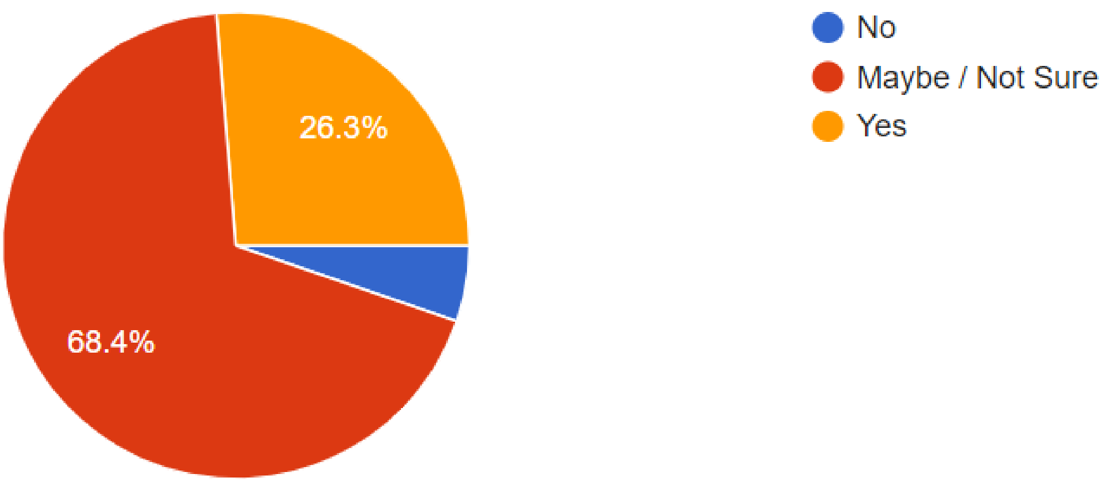
Question 3 : Please elaborate on your reason behind such a decision not to

adopt to the Digital Twin Technology.



Appendix 20.

Question 4 : Do you think Use of digital twin technology can give you any advantage over your competitors?



Appendix 21.

Challenges foreseen to encounter on adoption and implementation of DTT.

Participants	Comments
1	Security of data, competition issues, technical staff (modeling, software engineering) are required, which overall increase costs vis a vis aspired benefits
2	Cost of Investment and Compatibility
3	Understanding.
4	Slow companies adaption to technology if not proven 100% effective
5	Cost
6	Training on use of the technology
7	This technology has more advantages however getting the telemetric data is a challenge from the existing ships as retrofitting sensors is quite a challenge fo the existing ships. Much more easy to install on newbuild ship by collabroting with companies who provide Integrated centralised system.
8	Trust and verification
9	The complexity of the technology will pose implementation difficulties as we are not yet prepared for such in terms of materials and human resources.
10	cost

Appendix 22.

Question 6 : My Overall Professional Opinion and view of my Company on the Use of Digital Twin Technology.

Participants	Comments
1	Excellent (is it mature enough and verifiable in the shipping domain - a question i would raise)
2	This technology can be beneficial for vessels above a certain GT

	and ship owners with a large fleet of ocean going vessels engaged in international trade. Companies with vessels of smaller sizes eg below 1000GT engaged in trade in the national's territorial zones may not benefit from this technology.
3	May be it is too early to adopt.
4	5 years change of antifouling coat and almost no fouling found-vessel inspected every 2.5 years So mirror simulation benefits will not be needed
5	Not relevant
6	Company may not embrace Digital Twin Technology soon for the for the reasons given in part 4 above
7	Digital Twin technology is useful on ship and in Maritime industry. monitoring the enginer parameters, Navigation control system has much more effective usage. Digital Twin can be used to check the performance of various machineries which are operated in a closed environment or in a specific parameter. For machineries which are in overhauled and maintained as per condition-based monitoring can utilise this technology.
8	It has good room to add benefits
9	We as at now don't see the need to invest in the technology because we are operating in inland waters.
10	not at this stage