

Digital Twin in Maritime Industry

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Abstract - The maritime sector is witnessing an accelerated shift toward digitalization as it seeks higher levels of operational efficiency, increased safety, lower fuel consumption, and environmentally-friendly shipping. As one of the new technologies being explored in this rapidly evolving environment, Digital Twin is becoming increasingly popular. It creates real-time virtual replicas of ships or their components through onboard sensor-collected data. Through integration with IoT, AI, ML, cloud computing, and physics-based simulation, Digital Twin continually evaluates equipment health, forecasts potential machinery failures, optimizes maintenance schedules, and increases vessel performance. Maritime applications for Digital Twins include ship performance analysis; predictive maintenance; optimizing vessel fuel efficiency; managing fleets; improving vessel safety; and training vessel crews. Through the provision of real-time data to support data-driven decision making for both onboard engineers and shore-based technical experts, the technology provides benefits such as improved reliability of machinery, fewer instances of unplanned down time, decreased operational costs, and compliance with environmental regulatory requirements.

Key Words: Digital Twin, Marine Engineering, Smart Shipping, Predictive Maintenance, Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Ship Performance Monitoring.

1. INTRODUCTION

The Maritime Industry represents the backbone of Global Trade; approximately 90% of all global commerce is transported via the Sea by Volume. Modern Ships represent Complex Engineering Systems consisting of Propulsion Machinery, Auxiliary Equipment, Automation Systems, Navigation Technologies and many other components operating under extreme Environmental Conditions continuously. With increasing demands for operational Reliability, Fuel Efficiency, Compliance to Environmental Regulations, Cost Effective Maintenance, the use of Advanced Digital Technologies within Marine Engineering continues to accelerate. Of those digital technologies; Digital Twin represents one of the leading innovations towards Intelligent Ship Operations.

A Digital Twin represents an exact replica of a Physical Ship or one of its Machinery which continually receives Real-Time Data from Onboard Sensors. Through the integration of Internet of Things (IoT); Artificial Intelligence (AI); Cloud Computing; and Data Analytics; a Digital Twin provides Real-Time Condition Monitoring; Predictive Maintenance;

Performance Optimization; and Data Driven Decision Making. As the Maritime Industry transitions into Smart Shipping and Autonomous Vessel Operations; Digital Twin Technology will be critical in enhancing Safety; Operational Efficiency and Lifecycle Management. Today, Digital Twin Technology is considered one of the most important Components of the Industry 4.0 Revolution and is becoming widely accepted across the Maritime Industry. Modern Ships Equipped with Thousands of Sensors Continually Transmit Operational Data to Digital Twin Platforms, Allowing Engineers to Monitor Vessel Performance, Predict Machinery Failures, Fuel Consumption and Enhance Maintenance Planning

2. HISTORY AND EVOLUTION OF DIGITAL TWIN TECHNOLOGY

The history of Digital Twin Technology began in 2002 when Dr. Michael Grieves first developed the idea for Digital Twins as an integral component of Product Lifecycle Management (PLM) a system which uses a virtual model of a product to simulate the entire life cycle of the product. The original application of this concept were within manufacturing for the purposes of improving product design, product testing, and managing products over their lifecycle. Advances in technologies such as sensor devices, IoT, Cloud Computing, and Industrial Automation have furthered the development of Digital Twin Technology and transformed it from traditional reactive/Preventative Maintenance to Condition-Based Monitoring and now to the continuous collection of data related to operations via onboard sensors.

The creation of Digital Twin's technological basis for Real-Time Digital Asset Monitoring was made possible. With advances in AI, ML and BDAs; Digital Twins transitioned from being simply monitoring tools, but also became intelligent Decision-Support Systems. Through high-fidelity simulations and integrating with Real-Time Sensor Data, Digital Twins can predict how equipment will behave, diagnose faults and optimize performance. This rapid growth in adoption has resulted in the Digital Twin Technology being used today across multiple sectors including Aerospace, Automotive Manufacturing and Energy. The Maritime Sector is currently using Digital Twin Technology to create Virtual Models of Ships and Marine Machinery. Additionally, they integrate Real-Time Operational Data from On-Board Sensors with Simulation and Analytics for Predictive Maintenance, Fuel Optimization, Structural Health Monitoring and Fleet Management. With the advancement of Smart Shipping and Autonomous Vessels continuing to grow, Digital Twins are

anticipated to be one of the core Technologies in Future Marine Engineering Systems.

3. DIGITAL TWIN IN MARINE

In Marine Engineering, a Digital Twin is a virtual, real-time replication of a ship, its mechanical components, or onboard systems. The Digital Twin provides a continuous reflection of the physical assets based on current operational information. The Digital Twins integrate sensor data from various sources, automation systems, communication networks, and simulation models to create an accurate digital version of the vessel. The Digital Twins can monitor aspects of the vessel including temperature, pressure, vibration, fuel consumption, and the condition and performance of the machinery. This allows marine engineers to assess equipment health and operation at all stages of the vessel's lifecycle.

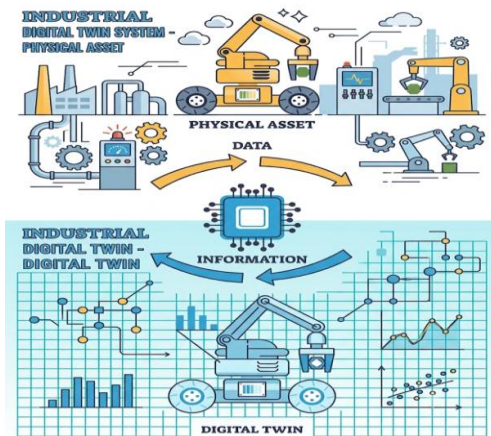


Fig -1: Digital twin

Digital twins are enhanced through advanced technologies such as Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), cloud computing, and big data analytics. These technologies enable real-time and historical analysis of data for early fault detection and informed decision making. Through their use in the maritime sector, Digital Twinned vessels will be able to achieve improved vessel reliability; lower maintenance costs; better operational safety; and contribute to the future of smart autonomous shipping.

3.1 Importance in the Maritime Industry

The maritime industry has many demands when it comes to the design, construction, and operations of modern ships. Safety is paramount because there is always a risk of damage, loss, and even loss of life. Reliability and fuel efficiency are also critical. The ability of a ship to operate safely and efficiently depends largely on the condition and performance of the shipboard systems. The complexity of these systems means they produce vast amounts of operational data which can be used to create a Digital Twin.

The Digital Twin technology uses this data to give insight into how well each system is performing and when they need to be maintained. Therefore, it can help improve maintenance planning; machinery reliability; voyage efficiency. With AI capabilities integrated into a Digital Twin, they can support predictive maintenance; identify faults before they become major problems; optimize fuel consumption; and allow remote monitoring by shore-based technical teams.

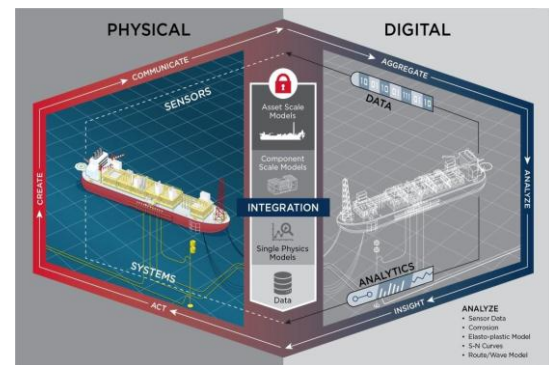


Fig -2: Digital twin in marine

The adoption of Digital Twin technology also supports the maritime industry's transition toward smart shipping and sustainable operations. It assists shipping companies in reducing operational costs, minimizing unplanned downtime, improving asset utilization, and complying with international regulations related to safety and emissions. As autonomous vessels, smart ports, and digital fleet management continue to evolve, Digital Twin is expected to become a fundamental technology in future marine engineering and vessel lifecycle management.

4. CURRENT MAINTENANCE PRACTICES IN MARINE ENGINEERING

Current maintenance practices employed within Marine Engineering consist primarily of Breakdown Maintenance, Planned Preventative Maintenance (PMS), and Condition Based Monitoring (CBM). Breakdown Maintenance is conducted subsequent to failure of an item of equipment, whereas PMS follows manufacturer recommendations and operating time for a set of pre-defined scheduled maintenance. CBM utilizes continuous monitoring through sensors of equipment parameters (i.e., temperature, pressure, vibration, etc.) that enable maintenance decisions based upon equipment health. The aforementioned maintenance methods have significantly improved the reliability and operational safety of vessels; however, as the complexity of modern ships increases along with the magnitude of operational data collected during their operation, there has been a corresponding increase in the application of advanced digital technologies such as Digital Twins for monitoring, predictive maintenance, and optimizing operations.

4.1 Breakdown Maintenance

Breakdown Maintenance, also referred to as reactive maintenance, is one of the first forms of maintenance utilized in the maritime industry. Under this type of maintenance, activities do not occur until a part or piece of equipment fails. Historically, ship engineers relied on routine inspections, knowledge gained from past experiences with equipment failure, and manual log books to determine when equipment had failed. While little planning was involved with this form of maintenance, many times unforeseen equipment failures occurred during a voyage. Disadvantages associated with Breakdown Maintenance include increased downtime, greater cost for repairs than planned preventative maintenance would incur, loss of revenue due to delayed voyages, and potential risks to crew members and passengers.

Furthermore, critical failures in propulsion or auxiliary systems can impact the availability of a vessel and its overall operational efficiency. Therefore, Breakdown Maintenance is typically applied to non-critical pieces of equipment only; modern vessels utilize more sophisticated maintenance techniques for all essential equipment.

4.2 Planned Preventive Maintenance (PMS)

Planned Preventative Maintenance (PMS) was introduced into the marine industry to increase the reliability of machinery through planned routine maintenance at predetermined times (usually based upon operational hours, calendar schedules, or manufacturer recommendations). Most modern vessels now employ computerised Planned Maintenance Systems for scheduling inspections, lubrications, replacement parts, etc. and overhauls.

These planned maintenance systems help ensure that vessels comply with all applicable regulations and Classification Society requirements. Although PMS will reduce unplanned downtime considerably compared to traditional Reactive Maintenance; it does not account for the actual condition of machinery. Components can be removed/replaced whilst still being in excellent working order which can lead to increased maintenance costs and usage of spares.

4.3 Condition-Based Monitoring (CBM)

Condition-Based Monitoring (CBM) is a type of maintenance strategy where ongoing monitoring of operating parameters provides a continuous assessment of the health of machinery onboard. Sensors are installed throughout vessels' mechanical systems to monitor temperature, pressure, vibration, lubricant quality, shaft speed etc. Based upon this data; maintenance activities are scheduled when necessary (i.e., when required due to a specific condition of the equipment); rather than scheduled at pre-determined time-based intervals.

The benefits associated with CBM include improved efficiency of maintenance activities by allowing for earlier identification of potential equipment failure and reduced unnecessary maintenance. However, conventional CBM systems provide no information regarding the likelihood of future equipment failures nor do they provide an ability to simulate how a particular piece of equipment will perform under various operational conditions.

4.4 Evolution Towards Digital Twin

Due to the rapid technological advancements and complex nature of modern shipping operations; advances in digital technology have driven developments beyond those offered by conventional condition monitoring systems. Advances in the application of IoT and Cloud Computing along with AI and advanced communications systems allow vessel operators to continuously collect and transmit real-time operational data from shipboard machinery.

Beginning with the use of real-time sensors to gather information from the actual vessel or ship component and combine this data with sophisticated computer simulations based on principles of physics (and artificial intelligence) digital twin technology takes the next step in this progression. A digital twin is different from traditional monitoring systems because it will constantly update an electronic representation of the actual vessel or ship component. The information generated can be used for predictive maintenance, performance enhancement, diagnosis of faults, and making informed decisions about operational conditions. The evolution towards digital twin technology has enabled ship operators to move from reactive and preventive maintenance towards a more predictive and data-driven approach. By continuously comparing real-time operating data with the digital model, abnormal conditions, performance deviations, and potential equipment failures can be identified at an early stage. This allows marine engineers to take corrective action before a major breakdown occurs, thereby reducing unplanned downtime, maintenance costs, fuel consumption, and operational risks. As digital twin technology continues to integrate with machine learning, advanced analytics, and autonomous systems, it is becoming an important tool for improving the safety, reliability, efficiency, and overall sustainability of modern ships.

5. KEY COMPONENTS OF A MARINE DIGITAL TWIN

The various digital twin components are interconnected to create an on-going, real-time, virtual model of a vessel or its associated equipment. The "Physical Asset" is the base layer of this system and represents the vessel itself including propulsion engines; auxiliary equipment; pumps; compressors; boilers; etc. All these physical assets are being continuously monitored with sensors and IoT devices to obtain real-time information about the operation parameters of each piece of equipment including but not limited to:

Temperature; Pressure; Vibration; Fuel Consumption; Shaft Speed; Oil Quality; Equipment Status.

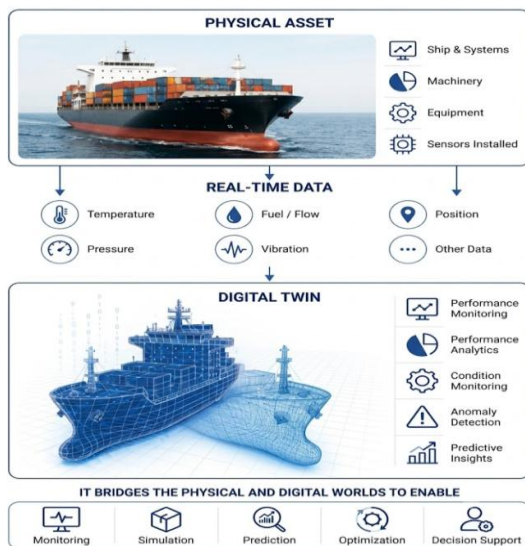


Fig -3: Key components

The data collected from all of the sensors will be a true reflection of the current operating conditions of the physical asset. Once the sensor data has been received it can be transmitted via a Communication Network that can include a variety of protocols such as industrial communications; Onboard Ethernet Networks; IoT Gateways; Satellite Communications Systems. These networks enable secure and uninterrupted communication between the vessel and the Digital Twin platform for purposes of updating the Digital Model. The Digital Model is essentially a virtual representation of the physical asset. As the physical asset continues to operate, the Digital Model continues to reflect the same operating conditions of the equipment thereby providing engineers with real time visualizations of how the systems behave and assessments of how well they are performing.

The operating information obtained by the Digital Model is analyzed utilizing Data Processing and Analysis techniques including artificial intelligence (AI); machine learning (ML) and sophisticated algorithmic approaches to analyze the behavior of the equipment; identify anomalies; determine when failures may occur; and optimize overall performance of the systems. Finally, the results of the analysis are presented through a User Interface typically represented as dashboards, charts, alarms and performance reports. This interface allows onboard engineering personnel; fleet managers; shore based technical professionals to track the health of the equipment; measure the operational efficiency of their vessels; make informed maintenance/operational decisions; improve the reliability/safety/lifecycle management of their vessels.

6. WORKING PRINCIPLE OF A DIGITAL TWIN

In order for a Digital Twin to work effectively, there needs to be a base in a physical form. For example this could be a ship, marine engine, pump, or auxiliary piece of machinery. There are many different types of sensors which can be fitted onto an item of equipment and will collect various amounts of data relating to how it operates. Sensors will include; temperature, pressure, vibration, fuel usage, shaft speed, lubricating oil condition, and performance of the engine. All of these sensors will send the data they have recorded back to the digital twin platform from where the data has been sent via the use of industrial communication networks, IoT gateways, onboard automation systems and satellite communications.

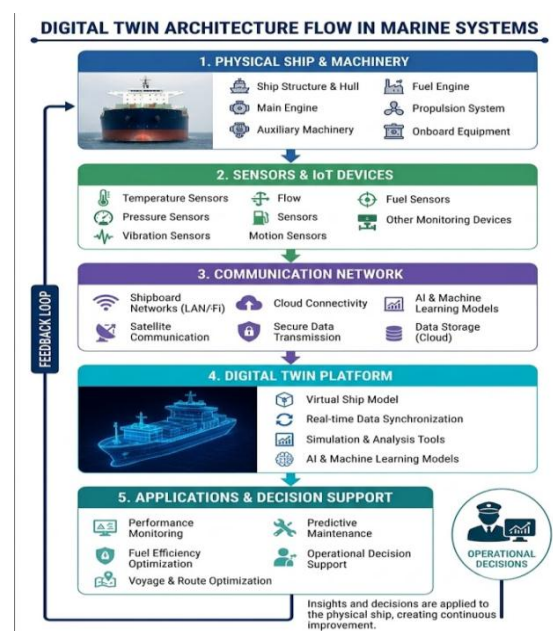


Fig -4: Working flow diagram

Before sending data across the internet it is common practice to filter and process the data using edge computing techniques in order to optimize the communication and also ensure that all data is available when needed. The data will then continue to flow into the digital twin platform at regular intervals and update the virtual model created of the actual machine. The digital twin uses advanced technologies including AI, ML, physics based simulations and data analysis tools to analyze the data coming from the real time operating conditions compared to the historical data and engineering models in order to identify trends and detect abnormalities. These analytical results can provide early warning signals of impending mechanical failure, indicate how well an item of machinery is performing and suggest remedies prior to the problem becoming severe. This analyzed data will be presented to onboard engineers, fleet managers and shore-based technical support staff through interactive dashboards and monitoring interfaces. The Digital Twin supports informed decision-making by providing real-time condition monitoring, predictive maintenance recommendations, fuel

optimization strategies, and operational insights. This continuous feedback loop between the physical asset and its virtual counterpart improves equipment reliability, operational efficiency, safety, and lifecycle management in modern marine engineering.

7. TECHNOLOGIES USED

Technology is comprised of a combination of advanced digital technologies that allow for the creation and continuous update of a highly accurate digital replica of both a ship and its onboard systems. The technology employs multiple types of sensors and data acquisition systems to capture real-time information about how the ship is being operated; edge computing to perform real-time processing onboard the ship; IoT and communication technologies for secure and reliable transfer of data from the ship to the cloud; and uses AI, ML, and physics-based simulation to analyze behavior of the equipment, identify potential failures prior to occurrence, and optimize overall efficiency of operation. Additionally, data visualization dashboards are utilized to make available to operators key information related to the performance of the ship in an easily understandable format. The combined use of all of these technologies allows for real-time monitoring, predictive maintenance, intelligent decision making, and efficient life cycle management of modern maritime assets.

7.1 Sensors and Data Acquisition

Sensors represent the principal sources of data for a Marine Digital Twin system. Sensors are attached to critical shipboard pieces of equipment (such as propulsion engines, auxiliary machines, pumps, compressors, and ship structures) to continuously monitor their operating conditions (e.g., temperature, pressure, vibrations, shaft speeds, fuel consumption rates, oil qualities and structural stresses). In this manner, they provide an accurate model of the physical condition of each piece of equipment.

Data is then transferred via industrial communication protocols (e.g. MODBUS, NMEA 2000 or OPC UA) using data acquisition systems which ensure that the operational data is reliably gathered, synchronized and transmitted to the Digital Twin platform. The collected data serves as the basis for real-time monitoring, diagnostics and predictive analytics.



Fig -5: Performance monitoring

7.2 Edge Computing

Edge computing represents the concept of processing operational sensor data locally onboard a vessel before transferring it to cloud based shoreside platforms. Edge servers provide local filtering, compression validation and organization of operational data, thereby reducing bandwidth required for communications with the cloud and enhancing response times for various applications. By providing for ongoing monitoring even when there are temporary disruptions to communication with the cloud, edge computing supports critical decision making necessary for ship operations independent of reliance upon continued connection with the cloud.

7.3 IoT and Communication Technologies

IoT allows ongoing interaction among onboard sensors, machinery, and digital twin platforms. IoT devices can send data to other onboard IoT devices via industrial communication protocols and onboard automation systems; in addition, IoT devices can send operational data about their respective ship systems via communication technologies (i.e., mqtt, amqp, ethernet, satellite communications (vsat/starlink), etc.) to shore-based monitoring stations that use cloud-gateway technologies to communicate securely and reliably with the ship. IoT and communication technologies enable seamless integration between different shipboard systems and shore-based platforms, allowing marine engineers and fleet operators to monitor vessel performance remotely. Data collected from engines, pumps, generators, fuel systems, navigation equipment, and other machinery can be transmitted at regular intervals or in real time.

Reliable communication networks ensure that this information reaches the digital twin platform with minimum delay, where it can be processed and analysed to identify abnormal operating conditions and performance changes. This continuous flow of information helps improve remote

diagnostics, predictive maintenance, energy management, and operational decision-making while reducing the need for frequent physical inspections.

7.4 Cloud Computing

Cloud computing provides all of the processing power and storage space needed to handle the vast amounts of data being generated by modern ships. In addition to collecting, storing, and processing real-time data sent from multiple ships around the world, cloud platforms like AWS IoT Core & Microsoft Azure IoT Hub allow ship operators, fleet managers, technical superintendents, and manufacturers of equipment on-board ships to have a central source of information for their respective digital twin models. The cloud platform also facilitates scalable computation, historical data analysis, remote diagnostic troubleshooting, and collaborative decision-making across an entire ship's operation during its lifetime.

7.5 Artificial Intelligence & Machine Learning

IT enhances the functionality of a digital twin by analyzing real time and historical operational data. AI algorithms can identify irregularities in how a ship is operating, while ML algorithms continue to learn from past operating conditions to increase the accuracy of predictions made by the algorithms. This capability allows for predictive maintenance, fault diagnosis, remaining useful life (RUL) estimates, optimized fuel consumption, and future performance forecasts.

7.6 Physics-Based Simulation

It utilizes engineering and mathematical representations of marine system behavior under different operating conditions. Tools utilizing physics based modeling include Ansys Fluent, Siemens Simcenter STAR-CCM+, Matlab Simulink, and AVL Cruise to model fluid flow, heat transfer, combustion, propulsions, and machine dynamic responses.

Results obtained from simulating these phenomena are continually validated against real time sensor data collected from the physical asset. Any difference between the simulated response(s) of the physical asset and the actual response(s) of the asset provide evidence of physical asset degradation, non-standard operating conditions, or opportunities for improving performance prior to failure.

7.7 Data Visualization and Dashboards

Digital Twin Platforms visualize raw, often complicated, machine performance data into user-friendly visual displays (dashboards), trends, key performance indicators (KPI's) and alarm systems. The modern digital twin platform uses a variety of visualization tools including Grafana, Microsoft Power BI, Kongsberg Vessel Insight, DNV Veracity, Wärtsilä

Fleet Optimization Solution and many others to show equipment performance/health and current operation.

These dashboard applications show onboard engineers and shore based technical personnel, in real time, the status of all equipment, how much fuel is being consumed, when the next maintenance interval will be due and how well each ship or unit is performing. Improved situational awareness can lead to improved decision making, improved collaboration among units within a fleet.

8. APPLICATIONS OF DIGITAL TWIN IN MARINE ENGINEERING

- **Ship Performance Monitoring:** A digital twin continuously monitors the performance of ship propulsion systems; as well as the level of fuel consumption, performance of engines, resistance generated by the hull and all voyage parameters by utilizing the data from sensors in real time. The digital twin then utilizes this information to compare the performance of an actual ship in its normal operating environment against expected levels of performance.
- **Predictive and Preventive Maintenance:** A digital twin utilizes both real-time and historic data regarding the performance of machinery to identify when equipment may be degrading or has reached a point where it will fail. It uses this same type of analysis to develop optimal schedules for preventative maintenance (PM) which are specifically developed around the current condition of each piece of machinery and thus reduces unnecessary PM and improves reliability in equipment.
- **Fuel Efficiency and Energy Optimization:** A digital twin analyzes the load placed on the engines, as well as the weather conditions surrounding the ship; the amount of fouling present on the hull; trim; and the efficiency at which propulsions are being produced. Based on these elements, a digital twin provides recommendations for optimal operating conditions that result in reduced fuel consumption; improved energy efficiency; and lower greenhouse gas emissions.
- **Fleet Management and Operational Optimization:** A digital twin allows for real-time monitoring of multiple ships from shore-based command centers. The owners/operators of fleets can utilize the digital twin to monitor the performance of each ship; monitor the status of each ship's maintenance; monitor operational efficiencies across entire fleets; support better decisions related to voyage planning, resource allocations; and support decision making that impacts the entire fleet.
- **Enhancement of Safety and Reduction in Risks by a Digital Twin:** A digital twin continually assesses the status of critical shipboard systems and structural

components and identifies operating conditions that do not align with "normal" operations and identifies potential risks associated with those same systems. Additionally, a digital twin supports emergency response planning activities through virtual simulations which improve the overall safety of an organization's operations and reduce their risk of accidents occurring.

- **Crew Training and Simulation:** Digital Twin gives engineers and ship personnel a very realistic place to practice. This is like a world where the crew can learn how to do things normally figure out what is wrong with machines and practice what to do in an emergency. The crew can do all these things without hurting the ship. This makes the crew better at their jobs and more ready to handle things when they're on the actual ship, with Digital Twin.

9. CASE STUDIES

Several major shipping companies have used Digital Twin Technology successfully to help enhance ship performance; increase operational efficiency; and assist in the development of better maintenance plans. For example, Wärtsilä has employed Digital Twin technology to assist with the evaluation of engine performance; optimizing fuel usage; and implementing predictive maintenance. DNV has utilized Digital Twin Solutions for Structural Health Monitoring and Hull Integrity Evaluation. Kongsberg Maritime has also integrated Digital Twin technology into its Propulsion System Optimization and Remote Vessel Monitoring. Lauritzen Kosan has applied Digital Twin technology to Fleet Performance Management and Voyage Optimization. Norway's research vessel Gunnerus has been the testbed for developing various Digital Twin Applications in Autonomous Navigation and Intelligent Ship Operations. The application of Digital Twin Technology by these companies clearly demonstrates the practical advantages of utilizing digital twin technology to enhance the dependability of ships; lower operational costs; and increase safety on ships at sea; as well as provide an additional tool for making decisions based on factual information in today's modern marine engineering.

9.1 Wärtsilä

Wärtsilä is one of the largest suppliers of Digital Twin Solutions in the Marine Industry. Real time data from sensors are combined with advanced analytical methods (such as machine learning) and sophisticated simulation models to create a virtual replica of a marine engine or vessel systems. These virtual replicas, called Digital Twins continually track how a vessel's engines operate and overall vessel performance.

The Digital Twin Solution monitors many operational parameters including Engine Load, Fuel Consumption, Exhaust Gas Temperature, Lubricant Oil Condition, Machinery Performance etc. Using AI and Predictive

Analytics; The Digital Twin solution can identify when there is degradation in performance; detect abnormal operating conditions and recommend maintenance action prior to Equipment Failure occurring. Wärtsilä's Digital Twin Solutions will assist in improving fuel efficiency; decreasing maintenance cost; minimizing unplanned downtime; and supporting voyage optimization. These abilities will allow ship operators to improve the reliability of their operations; decrease emissions; and maximize lifecycle performance while adhering to all regulations.

9.2 DNV

DNV is a global classification society that has developed Digital Twin technologies for ship structural monitoring, risk assessment, and lifecycle management. This technology helps people see how these big structures are doing. If they are in good shape. It does this by looking at information from sensors on the ships and using models to understand the data. The system checks things like how much stress the ships body can take, if it is getting tired and if it is vibrating much. It also checks for damage from water and salt.

All this information helps people know if the ship needs to be fixed and when. This way people can take care of the ship before it breaks down. DNV's Digital Twin technology makes ships safer makes sure they last longer and helps people plan when to do maintenance. It also helps people follow the rules and make decisions.

9.2 Kongsberg Maritime

Kongsberg Maritime is a company that makes Digital Twin technology for ship operations. They use this technology to make ships work better and to make sure the systems on the ships are reliable. They do this by combining real-time information with simulation models. The Digital Twin is like a computer program that always watches the ships systems like the engines and the systems that control the ships movement. It looks at how the equipment's working and uses this information to predict when things might go wrong. This helps people fix problems before they happen and use energy. It also lets people get help from far away.

Kongsberg Maritimes Digital Twin technology makes ships work efficiently use less fuel and makes the machinery on the ships last longer. It also helps create ships that can work on their own. This technology is very important, for making the shipping industry more modern and digital. DNV and Kongsberg Maritime and their Digital Twin technologies are changing the way people take care of ships.

9.3 Lauritzen Kosan

Lauritzen Kosan is an international gas carrier operator that has adopted Digital Twin technology to improve fleet performance and voyage efficiency. They use Digital Twin technology to make their ships work better and use fuel. The

company looks at information from all their ships. Uses computers to figure out how to make them run more efficiently.

The Digital Twin is like a computer program that always looks at how fuel the ships are using how well they are sailing, what the weather is like and how healthy the machines on the ship are. It gets all this information from the ships in time. Then it sends this information to the people on land who're in charge of making sure the ships are working well. These people use the information to find ways to make the ships even better. Since Lauritzen Kosan started using Digital Twin technology they have been able to make their ships use fuel plan their trips better and fix problems before they happen. This technology helps the company make decisions based on the information they have and it makes the ships safer and better for the environment.

9.4 Research Vessel Gunnerus

There is a research ship called Gunnerus that is used by the Norwegian University of Science and Technology. This ship is very special because it is used to test Digital Twin technologies that can make ships smarter. The ship has sensors on it that collect information about how it is sailing how the machines are working and what the environment is like.

All this information is put into a Digital Twin computer program, which lets researchers simulate what the ship will do in situations look at how well the systems are working and develop new technologies that can help the ship sail itself. The Digital Twin on the Gunnerus ship has helped a lot with research on ships that can sail themselves monitoring ships from away and making smart decisions. This project shows that Digital Twin technology is practical and can be used to make ships smarter and more autonomous in the future. It also gives us information that we can use to develop even better technologies, for ships.

10. ADVANTAGES AND LIMITATIONS

10.1 Advantages of Digital Twin Technology

- Real Time Condition and Performance Monitoring; Ships can be continuously monitored by the use of a real time sensor data monitoring system.
- Predictive Maintenance; Helps identify possible equipment failure so that the required maintenance work is done ahead of time so as to avoid unplanned shutdown or loss of production.
- Optimal Preventative Maintenance; Instead of scheduling preventative maintenance at set times (e.g., weekly), optimal preventative maintenance will schedule maintenance based upon the actual working conditions of the equipment.

- Improved Fuel Efficiency; Ship's engines, voyage routes, and propulsive efficiency are optimized for lower fuel usage.
- Lower Cost of Ownership; Reduced total cost of ownership through reduced maintenance expense, repair expense, and fuel expense over the life cycle of the vessel.
- Increased Reliability of Critical Marine Machinery; The overall operational reliability and longevity of marine machinery can be improved with this type of technology.
- Remote Condition Based Monitoring and Diagnostic; Enables shore-based experts to remotely monitor the condition of your vessel, and assist you in making timely and informed decisions regarding your vessel.
- Data Driven Decisions; Provides an ability to make better-informed decision-making for both the operation and maintenance of your vessel through AI and real time analytics.
- Improved Safety; Early detection of abnormal operating conditions reduces the likelihood of machinery failures and potentially catastrophic incidents during operations.
- Fleet-Wide Performance Improvement; Enables shipping companies to assess and improve the performance of multiple ships in their fleets concurrently.

10.2 Limitations

- High Cost to Initiate Technology; Significant costs will need to be incurred for sensors, communication systems, computer software and cloud infrastructure as part of the implementation process.
- Difficulties in Combining Digital Twin Systems; Combining new Digital Twin technology with existing shipboard systems, legacy equipment may be technologically difficult.
- Cyber Security Concerns; The continuous transfer of information from ship to shore (via Internet) creates a larger potential threat to hacking into Digital Twin and other shipboard systems.
- Reliability of Sensor Data; To ensure that accurate predictions are provided by the Digital Twin, sensor data collected must be reliable and all systems properly calibrated.
- High Computing Power Needs; Real-time simulation and the use of artificial intelligence for predictive analysis will require significant computing resources.
- Communication Requirements; Reliable and stable communication via satellite or internet connection will be necessary to provide remote real-time monitoring capabilities and synchronize cloud based data.
- Skilled People Required; Engineers familiar with digital technologies, data analytics and artificial intelligence will be required to implement this successful.

- Maintenance for digital systems: The need for periodic maintenance in digital systems, which include Sensors, communication devices, as well as the software used in a production system, are required. Data
- Privacy and Ownership concerns: properly managing an operation's data will be essential to protect its proprietary or private data and intellectual property.

11. FUTURE SCOPE

Smart shipping is likely to rely on digital twin for its potential to provide "smart", "connected" and "autonomous" vessel operations. As AI, ML, IoT, 5G / 6G communications and Edge Computing are integrated into Digital Twin capabilities, they will increase the ability of Digital Twins to provide real time decision-making assistance for optimizing vessel performance and improving operational efficiency. These advances will allow ships to be operated with higher levels of autonomy while decreasing the need for humans in routine vessel operation. Future Digital Twin Systems will have the capability to enable autonomous ships, intelligent engine rooms, and smart ports through continued remote monitoring, remote diagnostic testing, and automated maintenance planning. Real time collaborative work between onboard crew members, shore based technical staff and equipment manufacturers will decrease vessel down time and improve operational dependability.

12. CONCLUSION

Digital twin has proven itself as one of the most impactful innovations for transforming marine engineering through providing integration of physical shipboard systems with AI, sensor data from real time sources, IoT, Cloud Computing, and Physics based Simulation in one digital environment. Digital twins provide continuous monitoring of physical shipboard systems that support predictive/preventive maintenance of all shipboard equipment. In addition, they help improve the efficiency of fuel consumption and enhance operational safety. They also optimize overall vessel performance.

Data collected through these applications provides opportunities for decision making using data, allowing technical shore side staff and engineers on board ships to work together efficiently to maintain reliable and efficient operations of their vessels. As the maritime industry moves forward toward Smart Shipping, Autonomous Vessels, and Sustainable Maritime Operations, Digital Twin will be a key element of ship management systems going forward. While there continue to be some challenges associated with implementation costs, Cyber Security concerns, and System Integration challenges; ongoing advancements in technology have made Digital Twin Solutions much more applicable/practical to the shipping community.

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