YRKESHÖGSKOLAN NOVIA

Vessel Sensor Performance Analysis

Using Ship Sensors for Comparison Purposes

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Abstract

This thesis presents a case study that utilizes both theoretical and practical research methods to define and tackle the challenges associated with collecting ordinary vessel sensor data for shipowners. The study investigates how shipping companies of any size can implement this development effectively. It emphasizes the importance of leveraging existing sensor systems to reduce fuel consumption and travel time. By creating a dependable strategy and model, the organization aspires to position itself as a proficient entity in the future, ultimately benefiting customers, employees, and other stakeholders. However, relying on existing systems may present challenges, particularly in data collection, highlighting the need for further research into machinery data acquisition. The focus of my thesis is to explore methods for updating and utilizing existing systems and signals to create an effective tool for ship owners, enabling the use of real-time data for a variety of applications. This study primarily examines the products of Furuno and Consilium, as I have hands-on experience with both companies' systems. The current market offers a variety of navigation system suppliers, making it essential to describe the functionalities of navigation sensors and complete systems. The main objective is to provide a comprehensive guide on collecting and integrating data from all ship navigation sensors, including video feeds from radar, ecdis, conning displays and cctv- systems. Additionally, it will cover data from the main engine, rudder, propulsion systems, and bow thrusters. All vital information for navigation officers. A key objective of this research is to consolidate this diverse array of data into a centralized system. By doing so, we can enable real-time monitoring from an autonomous control room or the ship owner´s office, allowing for dynamic responses to changing maritime conditions. The involvement of the international Maritime Organization (IMO) is also integral to this discussion, as their regulations and guidelines will influence the implementation of autonomous technologies in shipping operations. Furthermore, I will present examples of different system interfaces and methodologies for analyzing data streams from various manufacturers’ systems. Understanding how to effectively interface with these systems is crucial for ensuring interoperability and maximizing the benefits of data integration. It is important to note that any modifications made to ship navigation and communication equipment must be approached with caution. Consulting manufacturers manuals is essential to address safety concerns and ensure compliance with industry standards. This thesis will highlight the fact that many manufacturers offer downloadable resources and manuals on their webpages, which can serve as valuable references during the integration process. In summary, this research aims to bridge the gap between existing maritime navigation technologies and the emerging field of autonomous operations. By providing practical insights and detailed methodologies, this thesis seeks to contribute to the safe and efficient advancement of maritime navigation.

Language: English
Key Words: Fuel saving, Sensors and Navigation

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Abbreviations

AIS: Automatic Identification System

ASCII: American Standard Code for Information Interchange

BNWAS: Bridge Navigational Watch Alarm System

CCTV: Closed-circuit television

DCC: Data Collection Computer

ECDIS: Electronic Chart Display Information System

ETA: Estimated Time Arrival

Ethernet/IP: Industrial Protocol within TCP/IP packet

FOG: Fiber Optic Gyrocompass

GALILEO: the EU`S Global Navigation Satellite System

GLONASS: Global Navigation Satellite System

GMDSS: Global Maritime Distress and Safety System

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

HF: Human Factors

HFI: Human Factors Integration

IEC: International Electrotechnical Committee

IHO: International Hydrographic Organization

IMO: International Maritime Organization

INS: Integrated Navigation System

ISO: International Standards Organization

Modbus: is a client / server data communication protocol

NMEA: National Marine Electronic Association

PLC: Programmable Logic Controller

RCU: Rudder Control Unit

ROT: Rate of Turn

TBT: Tributylin

VDR: Voyage Data Recorder

1 Introduction

This thesis will investigate various methods for searching, processing, and integrating data signals in the maritime industry. It will focus on understanding the integration of National Marine Electronic Association (NMEA) data, video signals, and traditional analog communication protocols (such as Modbus) in relation to vessel performance and navigation safety. The aim is to develop effective tools for ship owners that leverage real-time data for improved fleet management, regulatory compliance, and the potential for autonomous operations, ultimately contributing to enhanced safety and sustainability in maritime practices.

Maritime operators effectively identify, process, and utilize real-time data signals from various systems to enhance decision-making, operational efficiency, and safety in maritime operations? This thesis is to explore various methods for searching for and processing data effectively. It will focus on how to identify necessary signals and duplicate them for use in other systems. For example, understanding National Marine Electronic Association (NMEA), data requires reading it on a computer to determine the specific signals being used. Analyzing video data is generally more straightforward on a standard computer monitor. However, sharing this video often necessitates a deeper understanding of resolution settings and the appropriate methods for outputting the signal.

In older ships, commonly used analog signals are dc Voltage, mA. Or Client / Server Data Communication protocol (Modbus), which requires computer interpretation. To handle this diverse array of data correctly and safely, it is essential to be proficient in reading wiring diagrams and device manuals. This knowledge ensures that the integration and processing of data from various systems is conducted accurately, maintaining both functionality and safety in maritime operations. The purpose of utilizing signals is to create an effective tool for ship owners, enabling the use of real-time data for a variety of applications. In the maritime industry, where timely and accurate information is crucial, real-time data can significantly enhance decision-making processes. By consolidating and processing this data, ship owners gain valuable insights into vessel performance, navigation safety, and operational efficiency, which can lead to informed strategic planning. For example, real-time data allows ship owners to monitor key performance indicators such as fuel consumption, engine health, and environmental conditions. This information is critical not only for optimizing operational efficiency but also for ensuring compliance with regulatory requirements. By having access to this data, ship owners can make proactive decisions that reduce costs and improve overall fleet management. Moreover, this approach paves the way for the autonomous use of sensors, enabling systems to operate independently based on real-time information.

By integrating advanced algorithms and data analytics, these sensors can analyze their surroundings and make informed decisions without human intervention. This capability enhances safety by allowing for quicker responses to potential hazards, such as obstacles or adverse weather conditions, ultimately reducing the risk of accidents. Additionally, the integration of real-time data and autonomous systems can lead to improved resource management. For instance, optimized routing based on current weather and traffic conditions can reduce fuel consumption and enhance overall operational efficiency. This not only benefits the ship owner financially but also aligns with the industry's increasing focus on sustainability and reducing environmental impacts. (yliopisto, 2024)

2 Research Questions

How can the integration and analysis of real-time sensor data from vessels enhance fuel consumption efficiency for shipping companies, particularly in fleets comprising similar vessels that exhibit significant differences in operational costs? Expanded breakdown of key components.

- What various sensor technologies are currently employed on vessels, such as fuel flow meters, temperature sensors, pressure sensors, environmental monitoring devices and navigation sensors?
- How is data collected from these sensors transmitted to shore-based offices? What technologies, such as satellite communication frameworks, facilitate this data transfer?
- What specific advantages do real-time sensors provide to shipping companies in terms of operational efficiency and cost reduction? How does real-time monitoring lead to proactive decision making?

3 Connection to office or autonomous control room

In the modern maritime industry, establishing a secure and reliable connection between a vessel Data collection computer (DCC) or Programmable Logic Controller (PLC), and the ship owner office or an autonomous control room is crucial for operational efficiency and safety. This connectivity allows for real-time data transmission, which can significantly enhance decision-making processes, improve navigation safety, and facilitate better fleet management. (SAL Navigation AB, 2024)

All commercial ships that sail under the Imo classification are required to have a Voyage Data Recorder (VDR) installed onboard. The VDR serves as an essential tool for capturing critical data during a voyage, including but not limited to navigational information, command communications, and key operational metrics. This data is invaluable not just for immediate operational needs but also for post-incident analysis, helping to improve safety protocols and prevent future accidents. Interestingly, advancements in technology have led some manufacturers to incorporate internet connectivity directly into their VDR systems. This feature can provide a cost-effective and straightforward solution for shipping companies looking to transmit data back to their shore-based operations. With the ability to receive data over the internet, ship owners can monitor their vessels in real-time, access performance metrics, and make informed decisions based on up-to-date information. However, the decision to implement internet-enabled VDRs must consider several factors. The type of data that needs to be transmitted, the frequency of updates, and the acceptable delay in receiving information are all critical considerations. (SAL Navigation AB, 2024)

For example, while some ship owners may prioritize real-time data for immediate decision-making, others might be more focused on comprehensive data analysis that can occur at scheduled intervals. Moreover, security is a paramount concern when establishing such connections. Ensuring that data transmitted from the vessel to the shore is protected against unauthorized access and cyber threats is critical. Shipping companies must invest in robust cybersecurity measures to safeguard sensitive information and maintain operational integrity. The integration of VDRs with secure communications channels to shore facilities represents a significant advancement in maritime operations. As technology continues to evolve, ship owners will need to carefully evaluate their connectivity options, considering their unique operational needs, the types of data they require, and the associated security implications. The ongoing dialogue about the capabilities if VDRs will help shape the future of maritime safety and efficiency. (SAL Navigation AB, 2024)

4 Collect necessary signals

Depending on what purpose signals are collected from the vessel, some ship owners have a big fleet of vessels. For example, there might be good to have a professional team at the office to optimize fuel composition by following decisions about what different crew is doing. Nowadays fuel is expensive and can be easily save a lot if vessel optimizes all ship parameters and settings. Some ships might have experienced staff who understand well what to do when forecast changes rapidly, how to use ballast tanks and optimize ship power etc. For this kind of purpose is good to have machinery information as well as basic navigation sensor information.

Choose appropriate sensors based on the identified signal types, make sure they can provide the necessary range, precision, and response time. Ensure they are compatible with the PLC or DCC. Check for input specifications such as voltage levels, signal types, and communication protocols. Determine the types of signals what need to collect (analog, digital, nmea, modbus etc.) Analog signals are continuous signals that can vary in range (e.g., voltage, current). Digital signals are binary (on/off). Nmea and Modbus messages need to be read with the computer together with proper software and cabling.

Connect wire properly from the sensors to the inputs. Follow the manufacturer's wiring diagrams for correct connections. Follow industry standards and guidelines to ensure safety and reliability, use shielded cables for all signals to reduce noise interference. Set up the PLC or DCC to read the inputs from the sensors. This may involve configuring input channels for analog, digital, serial or ethernet signals. If required, implement signal conditioning techniques such as amplification, filtering, or isolation to enhance the signal quality before it reaches the PLC or DCC. Calibrate the sensors to ensure accurate reading. This may involve using known reference points or devices.

Keep detailed records of calibration results, including the date, method, and any adjustments made. This documentation is crucial for maintaining accuracy over time. Set a schedule for regular recalibrations to ensure ongoing accuracy, especially in dynamic environments. Write a program in the PLC to collect, process, and store the data from sensors. This may involve defining sampling rates and data logging intervals. Implement any necessary filtering or data validation steps. After the setup, conduct initial tests to verify that the sensors are providing accurate readings. Compare readings with known values to validate performance.

Implement error-checking routines to identify and handle potential issues during data collection. This can include checks for out-of-range values or signal interruptions. If errors are detected, troubleshoot the system by checking wiring, sensor functionality and program logic. Configure communication protocols such as Modbus, Industrial protocol with TCP/IP (Ethernet/IP), or Nmea for transmitting data from the Plc to destination, Office or remote operation room. Ensure proper network configuration, including IP addresses, port settings, and any necessary firewalls or security settings.

If applicable, set up remote monitoring capabilities to allow for real-time data access and analysis from anywhere. Document the entire setup, including signal types, sensor specifications, wiring diagrams, calibration results, and program logic. This documentation will aid in maintenance and troubleshooting. Schedule regular maintenance checks for sensors and the data collection system to ensure reliability and accuracy over time. By following these steps, you can effectively collect necessary signals for your DCC or PLC. Maintain logs for regular maintenance activities, calibration dates, and any changes made to the system.

5 Navigation sensors

Navigation sensors are systems used to measure ship movement, position and meteorological parameters. Gyro compass, Satellite compass, Magnetic compass, a Fiber-optic gyroscope (FOG), Gps, Speed log, Echo sounder, wind sensor and Ais. Navigation workstations are systems which are used to plan and execute navigation duties. Navigation duties. Navigation sensors will supply information to navigation workstations. Navigation workstation systems are Arpa radar system, Ecdis, Conning Display and Autopilot. Integrated Navigation System is a concept to integrate Navigation sensors and workstations. Ins included all sensors and workstations. (Annex 3 Recommendation on performance standards for an integrated Navigation system (INS), 1998; Anschuetz, 2024;

Emri, 2022; Furuno, 2024 b; Furuno, 2024 c; Furuno, 2024 d; Furuno, 2024 e; Furuno, 2024 h)

An additional system which belongs to Ins is the conning display. The purpose of the conning display is to collect important navigation related information, as well as propulsion and steering information on the one screen. The purpose of Ins is to provide added value to the functions and information needed by the officer in charge of navigational watch to plan, monitor or control the progress of the ship. (Annex 3 Recommendation on performance standards for an integrated Navigation system (INS), 1998)

Dynamic Positioning system (DP) is classification society class dependent system. Dp is installed normally in Off-shore vessels, Oil and Gas vessels, Research vessels and other special vessels. Dp is the art and science of keeping a vessel in a particular position or moving in a particular direction at a particular speed and a particular rate of turn with the help of the thrust generated by its own thrusters. (Emri, 2022)

Marine radars are X- and S-band radars, to provide bearing and distance of ships and land targets in vicinity from own ship radar scanner for collision avoidance and navigation at sea. Radar is a vital component for safety at the sea and near the shoreline and the radar is therefore Imo requires radars almost on all size of the vessels. Radar's main functions are detecting other ships and objects around their own ship, calculation of collision risk with other ships and recognizing the ship position when navigating in narrow waters. Electronic charts Display and Information System (ECDIS) is a geographic information system used for nautical navigation that complies with Imo regulations as an alternative to paper nautical charts. Ships have been required to carry nautical charts and nautical publications to plan and display the ship´s route for the intended voyage and to plot and monitor positions throughout the voyage. The amendments entered into force on 1 January 2011, making Ecdis mandatory for new ships built after set dates and phasing-in the requirement for existing ships. The undeniable safety benefits of navigating with Ecdis have been recognized through formal safety assessments submitted to the organization and experience gained by the voluntary use of Ecdis for many years. (Furuno, 2024 h; Furuno, 2024 e)

Ecdis is a complex, safety-relevant, software-based system with multiple options for display and integration. The ongoing safe and effective use of Ecdis involves many stakeholders including seafarers, equipment manufacturers, chart producers, hardware and software maintenance providers, shipowners, and operators, and training providers. It is important that all these stakeholders have a clear and common understanding of their roles and responsibilities in relation to Ecdis. (Furuno, 2024 e)

Global Maritime Distress and Safety System (GMDSS) is a communication system. The Gmdss is a maritime communications system used for emergency and distress messages. Vessel-to-vessel routine communications and vessel-to-shore routine communications. Safety systems are Bridge Navigation Watch Alarm System (BNWAS), Search Lights, Tyfon, Bell & Gong, Navigation Lights and Vdr. (Furuno, 2024 f; Furuno, 2025 a)

Short interview of mandatory sensors from the vessel. A gyro compass system is important for navigation. Gyro provides relative to true north heading information to navigation system. Depending on the gyro, some of them are included with Rate of turn (ROT), It indicates the rate of ship is turning in degrees per minute. Rot- value is useful especially when a ship is navigating in the narrow water or making collision avoidance maneuvers. Gyro uses serial data communication between master gyro compass to repeaters and other devices, this connection is better in case data is not lose the synchronization. (Anschuetz, 2024)

Speed log is an important source of data when calculating performance. Sensor accuracy depends on calibration and manufacturer. An offset between the speed log reading and the actual speed indicates a need for calibration. In terms of accuracy, different manufacturers of speed logs provide different information. There are several environmental factors that affect speed log measurements. Velocity measurement in the water depends on acoustic reflection from solid particles in the water, such as micro-organisms or suspended dirt. In very clean water, the number of diffusers may not be sufficient for adequate signal return. Aerated water below the transducer can reflect sound energy that could be misinterpreted as the return of the seabed. Sailing in bad weather or non-laminar flow around the sensor can be a source of this effect. Following the sea results in a variable change in the speed of the vessel. This causes fluctuations in the measured speed. The ship has two sensors, one in the bow and the other in the aft. The frequency ranges for the transducers from 28 to 210 kHz, and the measurement accuracy is about 2.5% of the measured depth. Environmental factors that can affect measurement accuracy are the state of the sea, heavy rolling in the bad weather. Sea water temperature increase in water temperature in several sea areas. Hot water discharges from power plants, noise from bow thrusters, vibration of the main engine and reverse rotation of the propeller. The echo sounder is used in confined waters for navigation purposes for which the echo sounder frequency is set to 50 kHz. At this frequency, the level of detection of the seabed is about 90-150 meters, depending on the salinity and temperature of the seawater. Consequently, depths above this level are not detected. (Furuno, 2024 b; Furuno, 2024 d)

Propeller torque is usually measured using strain gauges. Load cells are mounted on a propeller shaft and measure the elongation of the shaft under the action of forces and moments. Deformations transform into stresses that determine the deformation of the shaft. Typical propeller shaft torque with strings, strain gouges and speed with a laser. Shaft rings are installed and placed as close to the main engine as possible. The measurement accuracy is about 0.5%, and the update period for measurement results can be varied. The speed / torque meter is calibrated on installation and, depending on the manufacturer and type, different calibration intervals and methods are offered. The torque meter and speed measurement are used to determine the shaft power. A gross motor is an electric motor that transfers power to a shaft. The shaft engine powered by electricity generated by the ship´s waste heat recovery system, which provides optimum performance when the ship is operating under high engine loads. The thrust meter measures rpm, torque and the shaft force. The measurement accuracy is in the range of 0.1%, and the update period of the measurement results can be varied. The rudder indicator continuously measured the rudder angle. (Jinbo marine, 2024 b; Jinbo marine, 2024 e)

The stabilizer ribs counteract the roll of the boat while sailing. They are installed on both sides of the vessel with a hold turn of approximately 3.5 meters above the keel and in the aft part of the hold. They are installed at an angle of 25 degrees to the horizontal and, when they are not in use, retracted into the ship´s hull. When it is in use, the angle of attack of the fins changes and this is continuously measured. (Jinbo marine, 2024 a)

The wind anemometer is a helical type with a blade to measure the direction or sensor type, where is tree optical sensor, what can calculate the direction. It is installed in the bow of the mast, which is in accordance with the general rule that anemometers should be placed as high and further on the ship as possible, so there is no distortion of the air flow entering the anemometer. The anemometer measures the relative wind speed and direction. This is converted into true wind speed and direction in the onboard recording system. Ultrasonic Wind sensor has 3 arms which contain ultrasonic transmitters and receivers. Simple operations principle is that one arm, which contains ultrasonic transmitter transmits a pulse, which is received by other arm´s to ultrasonic receiver. Receiving arms measures the time delay between the transmission and reception of ultrasonic pulse. After all arms have sent their pulses, there are several measurements in different directions. Between all arms combinations by analyzing all propagation times in built-in microcomputer units, computers can calculate the apparent wind direction. The mechanical wind speed and direction measurement system is based purely on the speed the cups are rotating, and the direction vane is pointing. Wind speed and direction are either transmitted on serial line or analog voltages represent the speed and direction with a range of 4 to 20mA. (Vaisala, 2024)

Gps unit onboard is a part of Gnss system, which provides users with positioning, navigation, and timing services. The most common Gnss in the world are Gps from USA, The EU`s Global Navigation Satellite System (Galileo) from Eu, and Global Navigation Satellite System (Glonass) from Russia. They are using geostationary satellites to provide position accuracy up to 3 meters or more. Automatic Identification system (AIS), Electronic chart display and information system (ECDIS) benefits Ais- information, as well as radar systems. All ships 300 cross tonnage and upwards must carry Ais onboard, therefore most of the targets are visible on Ecdis and Radar screens. (Furuno, 2024 f; Furuno, 2024 g; Furuno, 2024 c; Furuno, 2024 e)

6 NMEA data

The Nmea 0183 interface standard is used worldwide across many industry segments. The standard defines electrical signal requirements, data transmission protocol and time, and specific sentence formats for a 4800-daud serial data bus. Each bus may have only one talker but many listeners. This standard is intended to support one-way serial data transmission from a single talker to one or more listeners. This data is in printable American Standard Code for Information Interchange (ASCII) form and may include information such as time, position, speed, water depth, etc. The Nmea 0183 interface standard is a copyrighted document and available only from Nmea. Latest Nmea 0183 version is 4.30.

Nmea data serves as a prevalent format for collecting information from navigation equipment. (IEC, 2024; IEC webstore, 2024; NMEA, 2024; Nmea data, 2024)

This standardized format streamlines the process of gathering data from various sources, including Gps receivers, depth sounders, compasses, and other navigation devices. By utilizing the Nmea format, users can easily access and interpret essential data for navigation and positioning. The serial data interface standard, known as IEC61162, plays a crucial role in facilitating communication between different sensors and systems. This standard, established by the International Electrotechnical Commission (IEC), sets guidelines and protocols for data exchange to ensure seamless interoperability among various maritime and offshore devices. (IEC, 2024; IEC webstore, 2024; NMEA, 2024; Nmea data, 2024)

When multiple navigation equipment outputs are in use simultaneously, it may be necessary to employ NMEA buffers to manage and segregate the incoming data effectively. Alternatively, additional outputs can be installed to accommodate the expanded data flow and maintain system integrity. By adhering to the IEC61162 standard and leveraging the versatility of NMEA data, navigation equipment manufacturers and users can enjoy the benefits of standardized communication protocols and simplified data collection processes in maritime and offshore operations. The full publication, which explains all the messages and electrical interfaces, IEC61162-1 is specified for 4800bps transmission speed and IEC61162-2 specifies transmission rates higher than 4800bps. For example, 38400bps transmission speed is used when a higher amount of data is required to be transmitted, AIS or Arpa targets are good examples of high amount of data. (IEC, 2024; IEC webstore, 2024; IMO, 2024; Moxa INC., 2024; NMEA, 2024; Nmea data, 2024; Furuno, 2024 c; Furuno, 2024 h)

The IEC-61162 Serial Data Format is a standardized method for transmitting navigation and related data using ASCII text messages. 1. Sentence Delimiter: Each message begins with a $ character, an indication of the start of a new sentence. For AIS messages, and exclamation mark (!) is used instead. 2. Talker Identification is the next two characters identify the source of the data. For example, HE indicates a heading device, while GP represents GPS. 3. Field Delimiters: commas (,) separate different fields within the message. 5. Data Value: The actual data value follows the delimiter. For example, 010.3 represents a heading of

10.3 degrees. 6. Flags: Additional characters may indicate the status or reference of the data. For example, T signifies that the heading value is true (referenced to North). 7. Checksum: A * precedes the checksum, which is a two-character hexadecimal value used to verify the integrity of the message. 8. End of Message: Each message ends with a carriage return and line feed (CR><LF). Heading message: $HEHDT,030.3,T*2D indicates a true heading of 30.3 degrees. Speed Log message: The format allows for multiple messages to be sent in sequence, such as: $VDVBW,0.65,,A,0.74,-0.50,A,,V,-0.56,A*40 $VDDPT,27.8,,400*59 $VDVLW, 11271.99,N,832.68,N11630.44,N,1055.12,N*6B The IEC61162 document provides comprehensive details about all standard messages, including their structure, purpose, and usage within marine navigation systems. (IEC, 2024; IEC webstore, 2024; Anschuetz, 2024; Furuno, 2024 b; Furuno, 2024 d)

The integration of proprietary messages in maritime systems particularly in relation to VDR and Conning Display systems. These systems can be configured to understand proprietary messages, which are typically integrated by system integrators. While some equipment, like watertight door system and navigation lights, may not be required to adhere strictly to IEC standards, they often still provide NMEA output. This output allows for communication and interoperability between various maritime devices, even if they do not follow standardized protocols. (SAL Navigation AB, 2024)

7 Modbus

Modbus protocol is a messaging structure, widely used to establish master-slave communication between intelligent devices. A Modbus message sent from a master to a slave contains the address of the slave, the command, e.g. Read register or write register. The data, and a check sum LRC or CRC. Since Modbus protocol is just a messaging structure, it is independent of the underlying physical layer. It is traditionally implemented using RS232, RS422, or RS485. The function code in the request tells the addressed slave device what kind of action to perform. The data bytes contain any additional information that the slave will need to perform the function. For example, function code 03 will request the slave to read holding registers and respond with their contents. The data field must contain the information telling the slave which register to start at and how many registers to read. The error check field provides a method for the slave to validate the integrity of the message contents. If the slave makes a normal response, the function code in the response is an echo of the function code in the request. The data bytes contain the data collected by the slave, such as register values or status. If an error occurs, the function code is modified to indicate that the response is an error response, and the data bytes contain a code that describes the error. The error check field allows the master to confirm that the message contents are valid. (modbustools, 2024; modbus, 2024)

Controllers can be set up to communicate on standard Modbus networks using either of two transmissions modes, American Standard Code for Information Interchange (ASCII) or Remote Terminal Unit (RTU). When controllers are set up to communicate on a Modbus network using Ascii mode, each eight-bit byte in a message is sent as two Ascii characters. The main advantage of this mode is that it allows time intervals of up to one second to occur between characters without causing an error. When controllers are set up to communicate on a Modbus network using Rtu- mode, each eight-bit byte in a message contains two four-bit hexadecimal characters. The main advantage of this mode is that its greater character density allows better data throughput than Ascii for the same baud rate. Each message must be transmitted in a continuous stream. (modbus, 2024; modbustools, 2024)

8 Serial line splitter

The serial line splitter is designed to connect a single input to multiple outputs, ensuring that each output drives only one receiver. It operates as a single listener/single talker device, meaning that it does not decode NMEA sentences but transmits all unchanged data, maintaining the original message and checksums. One of the key features of this splitter is its true galvanic isolation between the power supply, input, and outputs. This isolation allows for flexibility in installations where the components do not need to share common ground, which can be particularly beneficial in larger systems. However, if a common ground is desired, it is acceptable to connect the ground together, with the recommendation to use a ground bar near the splitter to manage these connections effectively. (O.overland as, 2024)

IEC 61162-1/IEC 61162-2 Signal name	*UPC 3002/3005/5000P/6000 Connector marking*	*Description*
A	+	Positive signal, will be negative with respect to - when idle.
B	—	Negative signal, will be positive with respect to + when idle.
C	Not used	Ground. Not used on UPC device. Do not connect to - The installer may opt to tie all external grounds together with a simple ground bar, see description above.

Table 1 Description of Serial Line Splitter

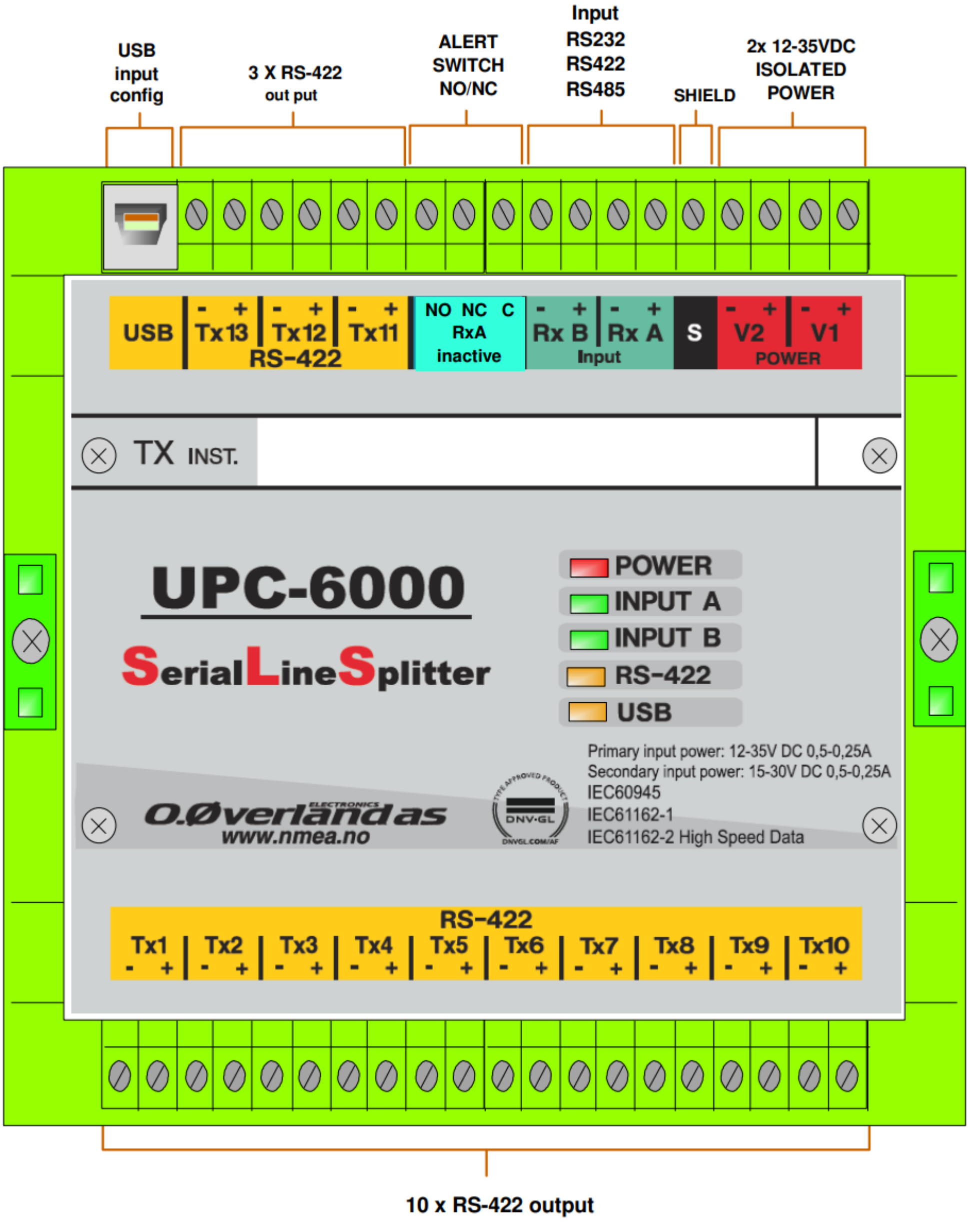

Figure 1 Serial Line Splitter

Signal polarities, Line A and B shown as described on Table 2 connection. Some of the equipment may have some different interpretations of A and B lines and the listener does not decode the message, practical experience is to swap the A and B lines. (O.overland as, 2024)

8.1 How to analyze data with a computer

One effective solution is to utilize a USB-to-serial converter. This device allows users to bridge the gap between the USB port of the laptop and the serial communication lines. To implement this solution, one would typically use a USB-to-serial converter along with a standard COM cable. The essential connections involve connecting the appropriate pins on the COM cable specifically pin 2, which corresponds to the Receive (RX) line, and pin 5, which is the Ground (GND) line. These connections can then be linked directly to the IEC61162 communication line. However, while direct connections can work, it is often advisable to incorporate additional safety measures to ensure reliable communication and prevent potential signal integrity issues. One recommended approach is to use an RS-422 to RS-232 converter. This converter acts as an intermediary between the COM port and the IEC61162 serial line, providing several benefits. RS-422 is known for its ability to transmit data over longer distances and in electrically noisy environments, which can be particularly advantageous in industrial settings or on vessels where electromagnetic interference might be a concern. By employing this converter, users can achieve a more robust and reliable connection that enhances the overall performance of the serial line monitoring. (Moxa INC., 2024)

8.2 Serial line monitoring software

The Internet has a bunch of freeware programs you can use. My personal favorite is HyperTerminal, a program that is easy to use and provides a lot of different functionality for my use. Teraterm and Realterm programs are good as well.

8.3 Converter

Moxa´s range of converters, particularly the RS-232/422/485 model, serves as a versatile solution for various communication needs. Its robust support for different operating systems, user-friendly indicators, and high-speed transmission capabilities renders it an invaluable tool for professionals seeking reliable data communication solutions. Further exploration of Moxa's product offerings can provide deeper insights into optimizing communication infrastructure in diverse applications. The RS-232/422/485 converter emerges as a particularly effective multifunctional device. This model is adept at facilitating serial communication among devices, making it suitable for applications that require robust data transmission. (Moxa INC., 2024)

Figure 2 Converter

9 Video image

The VGA/DVI/Video Converter serves as a crucial technological device for the conversion and output of video signals from various sources into the Digital Visual Interface (DVI) format. This functionality is particularly beneficial in scenarios where multiple video inputs are available simultaneously, as the converter can function as a switch, facilitating seamless transitions between different sources. Additionally, the converter is equipped with scaling capabilities, allowing it to adjust video signals to specific output formats and resolutions. This adaptability is essential for ensuring compatibility with diverse display devices, particularly in environments where older video graphics cards or analog outputs are prevalent. The converter's design prioritizes user-friendly configuration, enabling users to easily set the appropriate video parameters. In situations where the input video resolution is unknown, the converter features an automatic configuration option that simplifies the setup process. By executing auto-configurations, the device can quickly ascertain and adjust to the optimal settings, enhancing usability and efficiency. Overall, this converter represents an effective solution for bridging the gap between legacy video technologies and modern digital displays, ensuring that users can achieve optimal visual performance across various platforms. (Black Box, 2024 a; Blackbox, 2024 b)

10 Cloud Applications and Services in Maritime Operations

The advent of cloud computing has revolutionized numerous industries, including maritime operations. Sal Navigation exemplifies this transformation by offering a comprehensive suite of intuitive, web-based applications tailored for the maritime sector. These applications empower users by providing them with enhanced operational oversight and deep insights into the functioning of their vessels. By leveraging the robust capabilities of cloud technology, Sal Navigation ensures that users can access critical information in a reliable and secure manner, fostering an environment of informed decision-making. A primary advantage of utilizing cloud applications in maritime contexts is the facilitation of seamless data management. Traditional methods of data handling often involve cumbersome processes that can lead to inefficiencies and delays. In contrast, cloud-based solutions enable users to access and manage data from various geographic locations without the constraints typically associated with on-premises systems. This level of accessibility is particularly beneficial for fleet managers and operators who require instantaneous access to operational data to optimize vessel performance and ensure compliance with regulatory standards. (SAL Navigation AB, 2024)

Moreover, the applications developed by Sal Navigation are equipped with features that support real-time data streaming. This functionality is crucial in today's fast-paced maritime environment, where timely insights can significantly impact operational efficiency and safety. By continuously monitoring key performance indicators and other vital metrics, stakeholders can respond swiftly to emerging issues, thereby mitigating potential risks and enhancing overall operational resilience. Another significant aspect of Sal Navigation's offerings is the option for data export. This feature allows users to download and analyze operational data independently, facilitating in-depth evaluations and long-term strategic planning. By empowering users to manipulate and assess their data, Sal Navigation promotes a culture of data-driven decision-making, which is essential for navigating the complexities of modern maritime operations. Furthermore, the security of data is paramount in any cloud-based application, particularly in industries such as maritime, where sensitive information is often at stake. (SAL Navigation AB, 2024)

Sal Navigation prioritizes data security by implementing robust encryption protocols and access controls, ensuring that users can trust the integrity and confidentiality of their operational data. This commitment to security not only protects user interests but also enhances the overall credibility of cloud solutions in the maritime sector. In conclusion, the deployment of cloud applications and services in maritime operations represents a substantial advancement in the efficiency and effectiveness of vessel management. By providing reliable, secure, and accessible data, Sal Navigation empowers stakeholders to make informed decisions that enhance operational performance. As the maritime industry continues to evolve, the integration of cloud technology will likely play an increasingly critical role in shaping the future of maritime operations, fostering a more connected and data-centric approach to vessel management. (SAL Navigation AB, 2024)

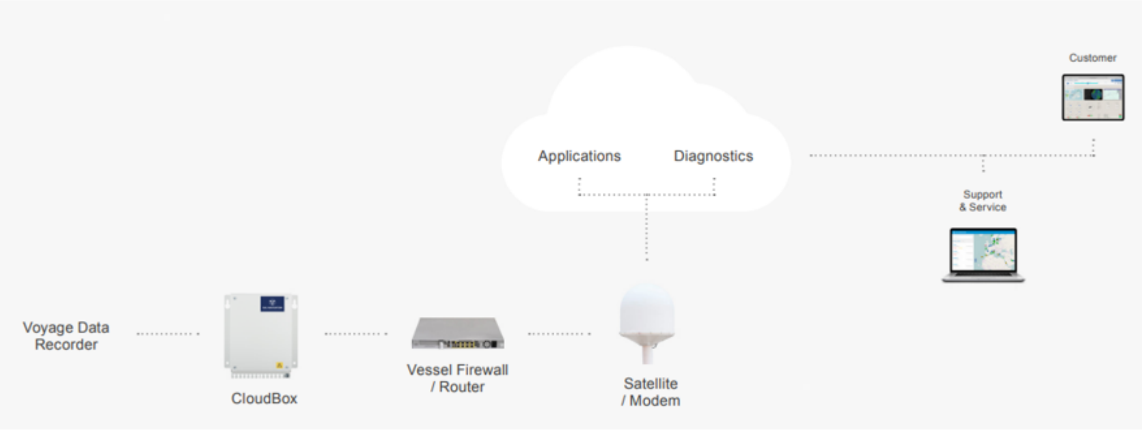

Figure 3 System Overview

SAL Cloud is a ship-to-shore solution for Voyage Data Recorders (VDR) offering remote diagnostics as well as a range of voyage data-based applications for shore-based fleet safety management, such as Remote Playback, Notifications and Event reports. SAL Cloud can be accessed securely from the web browser on any computer, tablet or smartphone. The on-board hardware (Cloudbox) connects to the onshore server infrastructure through a standardized and secure HTTPS- connection outgoing from the vessel, keeping the firewall intact. To keep data access secure, users log in to the cloud server via two-factor authentication. Also, data category access level can be set per user account. Through Remote diagnostics, strictly authorized personnel can analyze VDR system behavior from the office, and if necessary, suggest pro-active maintenance in a well-planned manner. Range of end-user applications lets ship management transfer and playback voyage data easily and securely by a few clicks, without having to handle any files or spend time on software setup. Automated reporting of critical events is another key to providing valuable insights, leading to more informed decisions. (SAL Navigation AB, 2024)

11 A Comparative analysis of fuel consumption in tratitional maritime vessels

To collect data for the study focused on optimizing fuel efficiency in maritime operations, the following comprehensive data collection framework can be implemented: Data Collection Methods, Fuel Flow Meters to measure real-time fuel consumption. Implementation: Install fuel flow meters on each vessel to provide continuous data on fuel usage. This allows for precise calculations of fuel consumption rates under varying operating conditions. GPS Tracking Systems purpose is to monitor vessel routes and speeds. Implementation: Equip vessels with GPS devices to record their tracks and speeds. This data will be crucial for analyzing how different navigational choices impact fuel efficiency. Environmental Sensors: Purpose: To collect data on atmospheric conditions. Implementation: Use sensors to measure wind speed, sea state, temperature, and other relevant environmental factors. This information will help contextualize fuel consumption patterns against external conditions. (yliopisto, 2024; University, 2018)

Load Sensors, Purpose: To determine cargo weight. Implementation: Install load sensors to accurately measure the weight of cargo being transported. Understanding cargo weight is vital for analyzing how it influences fuel efficiency. Crew Operational Logs, Purpose: To capture human operational factors. Implementation: Maintain logs of crew practices, including speed management, route selection, and maintenance schedules. This qualitative data complements quantitative sensor data and provides insights into operational practices. Voyage Data Recorders (VDRs), purpose: To capture comprehensive voyage data. Implementation: Utilize VDRs to record a wide array of operational parameters, such as engine performance, navigation decisions, and environmental conditions throughout the voyage. Data Analysis and Application. Once data is collected, the following analytical approaches can be employed: Statistical Analysis: Identify patterns and correlations within the data to understand the factors influencing fuel consumption. Techniques such as regression analysis can reveal relationships between operational variables and fuel usage. Machine Learning Algorithms: Develop predictive models that forecast fuel usage based on the collected operational parameters. These models can help in making informed decisions to minimize fuel consumption. (yliopisto, 2024; University, 2018)

Visualizations: Create charts and graphs to represent findings clearly. Visual tools will aid stakeholders in grasping complex relationships between different variables affecting fuel efficiency. Comparative Analysis: Compare data across vessels within the same fleet to identify best practices. Understanding variations in fuel consumption will provide actionable insights that can be implemented fleet wide. How This Saves Fuel? Identifying Inefficiencies: By analyzing real-time data, the study can pinpoint inefficiencies in fuel consumption caused by human operational factors, weather conditions, and cargo types. Optimizing Crew Practices: Insights gained from crew operational logs can lead to better training and adherence to best practices in navigation and speed management, which are crucial for reducing fuel usage. Data-Driven Decision Making: With predictive models in place, vessel operators can make real-time adjustments to operational parameters, such as speed and route, to optimize fuel consumption based on current conditions. Targeted Strategies: The analysis will reveal effective strategies for specific vessels, allowing operators to implement tailored solutions that enhance fuel efficiency and reduce operational costs. Environmental Impact: By optimizing fuel consumption, the study contributes to sustainability efforts, reducing greenhouse gas emissions and aligning with industry regulations. (yliopisto, 2024; University, 2018)

Meaning, a robust data collection framework combined with advanced analytical techniques will enable a thorough understanding of the factors influencing fuel consumption in maritime operations, leading to significant fuel savings and enhanced operational efficiency. The study saves fuel in the maritime industry by conducting a detailed comparative analysis of real-time data from traditional vessels within the same fleet. Here’s how this approach contributes to fuel savings: Identifying Variability, the study highlights that even vessels operating under similar conditions can show significant differences in fuel consumption and travel times. By analyzing this variability, operators can pinpoint specific factors that cause inefficiencies, such as weather conditions, cargo types, and crew practices. Data-Driven Insights: A comprehensive data collection framework utilizing a range of sensors (e.g., fuel flow meters, GPS, environmental sensors) allows for real-time monitoring of fuel usage and operational parameters. This data enables precise calculations of fuel consumption, helping identify patterns and correlations that influence fuel efficiency. Operational Practices: The study emphasizes the role of human factors, such as adherence to best practices in navigation, speed management, and cargo handling. By understanding how crew decisions affect fuel usage, operators can train crews to adopt more efficient practices, leading to reduced fuel consumption. (yliopisto, 2024; University, 2018)

Cargo Considerations: Different cargo types and weights can significantly impact a vessel's performance and fuel efficiency. By analyzing how cargo variations affect fuel consumption, operators can optimize loading practices and make informed decisions about routes and speeds based on the type of cargo being transported. Predictive Modeling: Advanced analytical techniques, including regression analysis and machine learning, can forecast fuel usage based on various operational parameters. By developing predictive models, the study enables operators to anticipate fuel needs and adjust operations proactively, minimizing unnecessary fuel consumption. Best Practices Identification: The comparative analysis seeks to identify the best practices among vessels that achieve optimal fuel efficiency. By disseminating these insights into the fleet, other vessels can implement similar strategies, enhancing overall fuel savings across the fleet. (yliopisto, 2024; University, 2018)

Sustainability Focus: By optimizing fuel usage, the study not only reduces operational costs but also contributes to environmental sustainability by decreasing greenhouse gas emissions, addressing both economic and environmental challenges in the maritime sector. Overall, by leveraging real-time data, understanding operational variabilities, and implementing data-driven strategies, the study aims to optimize fuel consumption, leading to significant savings in operational costs and improvements in environmental impact. The maritime industry is increasingly focused on enhancing fuel efficiency, a critical concern given the economic and environmental implications of fuel consumption. This study aims to conduct a detailed comparative analysis of real-time data from various vessels within a single fleet, specifically traditional vessels lacking autonomous capabilities. Despite operating under the same ownership and navigating similar routes, these vessels often demonstrate significant variability in fuel consumption and travel times. This variability can be attributed to a range of factors, including but not limited to fluctuating weather conditions, the nature of the cargo carried, and the operational practices employed by onboard crews. (yliopisto, 2024; University, 2018)

To accurately evaluate and comprehend the determinants of fuel consumption, a comprehensive data collection framework utilizing an extensive array of sensors is essential. Fuel efficiency in maritime operations is a multifaceted challenge that necessitates a thorough investigation of operational parameters across similar vessels. The focus here is on traditional vessels that do not possess autonomous functionalities, emphasizing the importance of human operational factors in influencing fuel consumption metrics. Given the rising costs of fuel and the increasing scrutiny on environmental impacts, optimizing fuel consumption is not only a matter of operational efficiency but also a pressing requirement for sustainability within the maritime sector. The maritime industry is characterized by its unique operational challenges, including the need for compliance with international regulations, the management of complex supply chains, and the influence of unpredictable environmental factors. As vessels traverse vast distances across global trade routes, the opportunity for optimizing fuel consumption becomes pivotal to enhancing overall operational efficiency and reducing greenhouse gas emissions. Existing literature highlights several studies that have examined fuel consumption in maritime operations, focusing on various factors that contribute to fuel inefficiency. (yliopisto, 2024; University, 2018)

Research indicates that vessels operating under similar conditions can exhibit a wide range of fuel consumption rates due to differences in technology, design, and operational strategies. For instance, studies have shown that the implementation of advanced technologies, such as hull modifications and energy-efficient engines, can lead to substantial reductions in fuel usage. However, these advancements are often not uniformly adopted across fleets, particularly among traditional vessels. Moreover, the role of human behavior and decision-making in maritime operations has been increasingly recognized. Crew members' adherence to best practices in navigation, speed management, and cargo handling can significantly influence fuel efficiency. This underscores the need for a holistic approach to understanding fuel consumption that integrates both technological and human factors. A comparative analysis will be employed, leveraging real-time data collected from multiple vessels within the same fleet. This analysis will account for various operational contexts including the following. (yliopisto, 2024; University, 2018)

The type and weight of cargo can alter a vessel´s performance and fuel consumption, making it imperative to consider these variables in the analysis. Different cargo types, such as bulk goods versus containerized freight, may necessitate distinct operational approaches that impact fuel efficiency. The practices adopted by crew members, such as speed management and route selection, also play a crucial role in determining fuel efficiency. This study will explore how variations in operational routines, including maintenance schedules and emergency procedures, can affect overall fuel consumption. To facilitate an accurate assessment of fuel consumption, a robust data collection strategy will be implemented. This strategy will employ a range of sensors to gather pertinent information, including fuel flow meter. This device will provide real-time data on fuel usage, allowing for precise calculations of consumption rates under varying operating conditions. Gps for tracking vessel routes and speeds, continuous monitoring of vessel speed and trajectory will enable a detailed analysis of how navigational choices impact fuel efficiency. Environmental sensors collecting data on atmospheric conditions will help contextualize fuel consumption patterns against external factors. (yliopisto, 2024; University, 2018)

Load sensors to determine cargo weight, accurate measurements of cargo weight will ensure that analyses account for variations in load, which can significantly influence fuel efficiency. The collected data will be subjected to statistical analysis to identify patterns and correlations that elucidate the factors influencing fuel consumption. Advanced analytical techniques, such as regression analysis and machine learning algorithms, may be employed to develop predictive models that forecast fuel usage based on operational parameters. Additionally, visualizations such as charts and graphs will be utilized to present findings in an accessible manner, enabling stakeholders to grasp complex relationships between variables easily. The analysis will seek to identify the best practices among vessels achieving optimal fuel efficiency, providing actionable insights for other vessels within the fleet. The findings from this comparative analysis will provide valuable insights into the factors affecting fuel consumption in maritime operations. By understanding the interplay between diverse operational parameters and their impact on fuel efficiency, stakeholders can implement targeted strategies to optimize fuel usage, thereby enhancing the sustainability and economic viability of maritime activities. (yliopisto, 2024; University, 2018)

11.1 Data collection of navigation sensors

In the pursuit of optimizing fuel consumption within maritime operations, the collection and analysis of navigation sensor data are paramount. The maritime industry faces increasing pressure to reduce operational costs and environmental impact, making the efficient use of fuel a critical concern. By leveraging an extensive network of navigation sensors, fleet operators can gather essential metrics that inform operational strategies aimed at minimizing fuel usage without compromising service quality. This comprehensive approach enables a detailed examination of how various navigational factors influence fuel efficiency, ultimately leading to more sustainable maritime practices. To facilitate a thorough and nuanced analysis of fuel consumption patterns, several key metrics should be collected from navigation sensors. Ship speed is fundamental in understanding the relationship between a vessel´s velocity and its fuel consumption. Research indicates that fuel efficiency often follows a non-linear relationship with speed; thus, variations in speed can significantly impact fuel efficiency. By monitoring and analyzing these fluctuations, operators can make informed decisions about optimal cruising speeds that balance fuel economy with travel time. (yliopisto, 2024; University, 2018)

Collecting data on a vessel´s heading (the direction in which the ship is pointed) and course (the actual path over the ground) is crucial for optimizing routes. Analyzing this data can help identify the most efficient navigational paths, considering currents, wind resistance, and geographical obstacles. For example, a vessel may consume less fuel by slightly altering its course to avoid headwinds or strong currents. Accurate geospatial data obtained through Gps technology allows for precise tracking of a vessel´s location and trajectory. This information is vital for effective route planning and for avoiding areas of adverse weather or high traffic that could increase fuel consumption. By integrating geospatial data with other navigational metrics, operators can create dynamic routing strategies that adapt to real-time conditions, thereby optimizing fuel usage. Incorporating data on weather conditions, such as wind speed and direction, wave height, and sea state, can significantly enhance the understanding of fuel consumption patterns. Weather conditions can impose additional resistance on vessels, leading to increased fuel use. By correlating weather data with navigation metrics, operators can identify optimal sailing conditions that minimize fuel consumption. The integration of these metrics into a centralized data system enhances the ability to monitor real-time performance across the fleet. Such a system not only consolidates various data streams but also facilitates the analysis of complex interrelationships between different navigational parameters. (yliopisto, 2024; University, 2018)

By analyzing the collected data, fleet operators can identify patterns in navigation that correlate with fuel efficiency. For instance, understanding how variations in speed affect fuel consumption can lead to the development of optimized sailing schedules. These schedules can be designed to minimize fuel use while ensuring that vessels adhere to operational timelines and customer commitments. Utilizing advanced analytics within the centralized data system enables fleet operators to generate actionable insights that inform operational decisions. By employing sophisticated data analysis techniques including machine learning algorithms and predictive modeling operators can discern relationships between navigational practices and fuel efficiency metrics. For example, predictive analytics can forecast fuel consumption based on historical data and current operating conditions, allowing operators to proactively adjust routes and speeds to achieve optimal fuel efficiency. Furthermore, advanced analytics can facilitate the identification of best practices across the fleet. (yliopisto, 2024; University, 2018)

By benchmarking fuel consumption against similar vessels and operational contexts, operators can determine effective strategies that can be shared and implemented fleet wide. This collaborative approach fosters a culture of continuous improvement, driving operational excellence within the organization. In addition to real-time monitoring, comparing historical data allows operators to identify long-term trends and evaluate the effectiveness of implemented strategies. By examining how navigational practices have evolved over time and their corresponding impact on fuel consumption, operators can make informed decisions about future operational adjustments. Historical data can also reveal seasonal variations in fuel consumption, enabling operators to anticipate and prepare for periods of increased demand or operational challenges. Moreover, leveraging historical data can enhance fleet resilience. By analyzing past incidents of fuel inefficiency or operational disruptions, operators can develop contingency plans and adaptive strategies that mitigate the impact of similar challenges in the future. This proactive approach not only improves fuel efficiency but also enhances the overall reliability and reputation of the fleet. The combination of real-time and historical data analysis provides a comprehensive view of vessel performance and fuel efficiency. By systematically collecting and analyzing navigation sensor data, fleet operators can optimize their operations, leading to reduced fuel consumption and improved sustainability within the maritime sector. This data-driven approach not only enhances operational efficiency but also contributes to broader environmental goals by minimizing the carbon footprint of maritime activities. (yliopisto, 2024; University, 2018)

In the realm of maritime operations, the significance of a comprehensive assessment of the operational status of vessels cannot be overstated. When combined with precise navigation data, such an assessment becomes essential for enhancing the hydrodynamic performance of vessels and, by extension, their fuel efficiency. Various critical operational parameters warrant meticulous attention, including draft, trim, ballast conditions, cargo load, and the degree of hull fouling. Each of these factors plays a pivotal role in determining how effectively a vessel navigates through water, influencing its resistance and overall energy consumption. To elaborate, the draft of a vessel refers to the vertical distance between the waterline and the bottom of the hull. An improper draft can lead to suboptimal performance, as vessels that are either too deep or too shallow in the water may experience increased drag. Similarly, trim—the balance of the vessel along its longitudinal axis—affects how the hull interacts with water. An uneven trim can cause a vessel to ride at an angle, resulting in higher hydrodynamic resistance and, consequently, increased fuel consumption. (yliopisto, 2024; University, 2018)

Ballast conditions also merit careful consideration. Ballast serves to stabilize the vessel and maintain its structural integrity, especially when not fully loaded. However, improper management of ballast can lead to inefficiencies; for instance, excessive ballast may weigh the vessel down unnecessarily, while insufficient ballast can compromise stability and performance. This nuanced relationship between ballast management and fuel efficiency underscores the complexity of maritime operations. Cargo load is another critical factor that influences a vessel’s operational efficacy. The weight and distribution of cargo affect the vessel's draft and trim, directly impacting how it moves through water. Understanding the optimal loading conditions is vital for minimizing resistance and maximizing fuel efficiency. Furthermore, hull fouling, which refers to the accumulation of marine organisms and other debris on the vessel's hull, poses a significant challenge to operational efficiency. A fouled hull can dramatically increase frictional resistance, forcing the vessel to expend more energy to maintain its speed. This not only escalates fuel consumption but also necessitates more frequent maintenance interventions, adding to operational costs. (yliopisto, 2024; University, 2018)

The systematic collection and analysis of these operational data points are critical for identifying inefficiencies and enabling the adoption of best practices in vessel management. Fleet operators can leverage advanced monitoring technologies to establish benchmarks for optimal operational parameters. By continuously tracking these benchmarks in real time, operators can quickly identify and address deviations that may arise during voyages. This proactive approach enables timely interventions, such as adjusting ballast levels or scheduling maintenance for hull cleaning. Such measures are essential for mitigating the negative impacts of hydrodynamic inefficiencies and ensuring that vessels operate at peak performance. In this context, fostering a culture of continuous improvement and accountability becomes imperative. By instilling a commitment to operational excellence among crew members and management, organizations can drive significant enhancements in fuel efficiency. Moreover, the implications of optimizing fuel usage extend beyond the immediate operational benefits. Improved fuel efficiency contributes to reduced greenhouse gas emissions, aligning with global sustainability goals. As the maritime industry faces increasing scrutiny regarding its environmental impact, adopting best practices in vessel management not only enhances operational performance but also positions organizations as responsible stewards of the marine environment. (yliopisto, 2024; University, 2018)

The meticulous examination of operational parameters—coupled with real-time data analysis—serves as a cornerstone for effective maritime management. By comprehensively understanding and optimizing factors such as draft, trim, ballast conditions, cargo load, and hull fouling, fleet operators can enhance hydrodynamic performance, reduce fuel consumption, and promote a culture of continuous improvement. This multifaceted approach not only leads to immediate operational gains but also supports broader objectives of sustainability and environmental responsibility within the maritime sector. A critical component of analyzing fuel consumption patterns within maritime operations is the comprehensive examination of the engineering systems present aboard each vessel. The collection of specific metrics, including fuel oil volumetric flow, fuel oil density, fuel oil temperature, propeller revolutions per minute (RPM), and engine power output, provides essential insights into the operational efficiency and performance of marine engines. This data is invaluable for fleet operators seeking to identify and target specific areas for potential fuel consumption reductions, thereby enhancing both economic and environmental sustainability. To elaborate, fuel oil volumetric flow indicates the quantity of fuel being consumed over a specific period, which, when analyzed in conjunction with fuel oil density, allows operators to understand the energy content of the fuel being used. (yliopisto, 2024; University, 2018)

Fuel oil temperature also plays a significant role; optimal temperature conditions are necessary for efficient combustion. If fuel is too cold, it may not vaporize effectively, leading to incomplete combustion and increased emissions. Conversely, excessively high temperatures can lead to fuel degradation, negatively impacting engine performance. By closely monitoring these parameters, operators can make informed decisions to adjust fuel management practices, thereby optimizing engine efficiency. Propeller RPM is another vital metric, as it directly correlates with the thrust produced by the vessel. Analyzing the relationship between propeller RPM and engine power output helps operators determine the most efficient operating speeds, thereby minimizing fuel consumption while maintaining operational effectiveness. For example, operating at higher RPMs may increase thrust but can also lead to significant fuel waste if not aligned with the vessel's operational profile. Fleet operators can thus employ strategies to optimize propeller performance in conjunction with engine power output, achieving a balance that maximizes efficiency. Recent advancements in engine monitoring technologies have transformed the landscape of maritime operations by significantly enhancing the ability to obtain real-time data regarding engine performance and associated fuel consumption metrics. (yliopisto, 2024; University, 2018)

The integration of sophisticated monitoring systems, such as those utilizing IoT (Internet of Things) capabilities, allows for continuous oversight of engine parameters. This advancement enables fleet operators to observe performance trends and identify inefficiencies as they arise, facilitating timely interventions. Moreover, employing predictive maintenance strategies that leverage data analytics represents a significant benefit of these technological advancements. Predictive maintenance involves analyzing historical and real-time data to forecast potential issues before they escalate into serious problems. For instance, if data analytics reveal abnormal vibrations or temperature fluctuations in engine components, operators can initiate maintenance procedures before mechanical failure occurs. This proactive approach not only prevents costly repairs and unplanned downtimes but also extends the lifespan of critical engine components, thereby enhancing overall operational reliability. The implications of these strategies extend beyond mere fuel efficiency. By implementing data-driven maintenance practices, fleet operators can ensure that vessels remain operationally reliable and adhere to established schedules. This reliability is crucial in the maritime industry, where delays can lead to significant financial penalties and reputational damage. (yliopisto, 2024; University, 2018)

Furthermore, consistent operational performance contributes to customer satisfaction, as timely deliveries are a key expectation in shipping and logistics. In summary, the systematic gathering and analysis of engineering system metrics aboard vessels are integral to understanding and improving fuel consumption patterns. By optimizing engine performance and utilizing advanced monitoring technologies, fleet operators can enhance operational efficiency, reduce costs, and promote a culture of maintenance and reliability. This multifaceted approach underscores the importance of adopting best practices in maritime operations, ultimately contributing to broader objectives of sustainability and environmental responsibility within the industry. As the maritime sector continues to evolve, the integration of sophisticated data analytics and monitoring systems will play an increasingly critical role in driving efficiency, reliability, and sustainability in maritime operations. (yliopisto, 2024; University, 2018)

The incorporation of metocean data-comprising meteorological and oceanographic information plays a crucial role in understanding the external factors that significantly influence vessel performance and fuel consumption in maritime operations. This category of data encompasses several critical variables, including air pressure, air temperature, sea surface temperature, wave height, and current speed. A thorough analysis of these environmental conditions provides valuable insights into their effects on fuel efficiency, operational safety, and overall vessel performance. To begin with, atmospheric variables such as air pressure and temperature are fundamental in shaping the environmental conditions vessels encounter. Changes in air pressure can affect wind patterns, which in turn influence the aerodynamic resistance experienced by a vessel. For instance, a vessel navigating in high winds may face increased drag, necessitating adjustments in speed or operational strategies to maintain optimal fuel efficiency. (yliopisto, 2024; University, 2018)

Additionally, air temperature impacts the density of the air, affecting the engine's combustion efficiency. Colder air can enhance engine performance by increasing the oxygen available for combustion, while excessively hot air may lead to reduced efficiency and increased fuel consumption. Sea surface temperature is another critical factor that influences fuel consumption and engine performance. Variations in temperature can affect the viscosity of the fuel, potentially altering its combustion characteristics. Warmer sea temperatures may lead to lower fuel density, which can impact the efficiency of fuel injection systems. Consequently, understanding the relationship between sea surface temperature and fuel properties is essential for optimizing fuel management practices. Moreover, wave height and current speed are particularly significant in the context of maritime operations. These factors directly affect the hydrodynamic forces acting on a vessel, influencing its stability and maneuverability. For example, in conditions of high wave height, a vessel might experience increased rolling and pitching, which can lead to greater fuel consumption as the engines work harder to maintain speed and course. (yliopisto, 2024; University, 2018)

Similarly, strong ocean currents can create additional resistance, compelling vessels to adjust their speed or routing to counteract the effects of these conditions. This necessity for operational adjustments underscores the importance of real-time metocean data in planning and executing maritime voyages. By systematically integrating metocean data into operational analyses, fleet operators can proactively adapt their strategies in response to dynamic environmental changes. Advanced modeling techniques, such as predictive analytics, machine learning, and simulation models, can forecast how varying meteorological and oceanographic conditions will impact fuel consumption and vessel performance. This capability enables operators to make informed, data-driven decisions regarding routing, speed adjustments, and operational parameters. Furthermore, this adaptive approach enhances safety by facilitating informed navigation choices that mitigate risks associated with challenging environmental conditions. For instance, by analyzing wave height and current speed, operators can determine safer operational speeds and routes that minimize the likelihood of accidents or equipment failures. (yliopisto, 2024; University, 2018)

This proactive risk management is particularly important in scenarios involving severe weather patterns, where the ability to anticipate and respond to changing conditions can safeguard both crew and cargo. The implications of incorporating metocean data extend beyond fuel efficiency and safety; they also contribute to broader objectives of sustainability within the maritime industry. By optimizing routing and speed based on real-time environmental data, vessels can reduce their fuel consumption and, consequently, their greenhouse gas emissions. This alignment with sustainability goals is increasingly vital as the maritime sector faces growing pressure to minimize its environmental impact and adhere to international regulations aimed at reducing emissions. In summary, the integration of metocean data into maritime operational frameworks is essential for a comprehensive understanding of the multifaceted factors influencing vessel performance and fuel consumption. By leveraging this data, fleet operators can enhance fuel efficiency, adapt to dynamic environmental conditions, and improve overall safety outcomes. This multifaceted approach not only contributes to operational effectiveness but also underscores the importance of environmental awareness in the increasingly complex landscape of maritime transportation. (yliopisto, 2024; University, 2018)

As the industry continues to evolve, the ability to analyze and respond to metocean conditions will be critical for achieving sustainability and efficiency goals in maritime operations, ultimately leading to a more resilient and responsible maritime sector. The comparative analysis of real-time data derived from a diverse fleet of vessels constitutes a pivotal advancement in the optimization of fuel consumption within conventional maritime operations. This analytical approach hinges on the systematic collection and examination of multifaceted data sets that encompass various critical dimensions, including navigation sensors, the operational status of the vessels, engineering systems, and prevailing metocean conditions comprising meteorological and oceanographic factors. The integration of these diverse data streams enables fleet operators to gain comprehensive insights into the operational dynamics of each vessel within the fleet. By meticulously analyzing this data, operators can identify patterns and correlations that may not be immediately apparent through traditional observational methods. Such insights are instrumental in pinpointing inefficiencies and formulating targeted strategies for improvement. For instance, adjustments to vessel speed, course alterations, or modifications to engineering systems based on real-time feedback can lead to significant reductions in fuel consumption. (yliopisto, 2024; University, 2018)

Through the application of these data-driven strategies, fleet operators are positioned to realize substantial economic benefits, including reduced operational costs and improved turnaround times. These efficiencies not only enhance the financial viability of maritime operations but also contribute to a more sustainable approach to shipping, as diminished fuel consumption correlates directly with lower greenhouse gas emissions. Moreover, the implications of this analysis extend beyond immediate cost savings. The ability to make informed, data-driven decisions fosters a culture of continuous improvement within maritime operations. By embracing an evidence-based approach, fleet operators can enhance their adaptability to changing conditions and optimize resource allocation, thereby improving overall fleet performance. Furthermore, as the maritime industry increasingly faces regulatory pressures and societal expectations regarding environmental stewardship, the implementation of data analytics for fuel optimization becomes not only a practical necessity but also a strategic imperative. By prioritizing data integration and real-time monitoring, maritime operators can align their operational practices with broader sustainability goals, thereby contributing positively to the global maritime ecosystem. In summary, the comparative analysis of real-time data from multiple vessels within a fleet emerges as a transformative tool that not only facilitates immediate operational efficiencies but also aligns with long-term sustainability objectives. By harnessing the power of data analytics, fleet operators can navigate the complexities of modern maritime logistics, ensuring both economic viability and environmental responsibility in an increasingly competitive industry. (yliopisto, 2024; University, 2018)

11.2 Ship crew decision-making comparison between vessels

The composition of a vessel´s crew serves as a pivotal element that significantly influences decision-making processes within maritime operations. This analysis aims to elucidate the interplay of various factors, including crew experience, training backgrounds, and individual competencies, which collectively contribute to the variability in decision-making outcomes across different vessels. A comprehensive understanding of these dynamics is essential for enhancing operational effectiveness, safety, and overall maritime governance. Crew composition and decision-making efficacy is one of the foremost factors affecting decision-making on board a vessel is the experience level of its captain and crew. The captain, often the primary decision-maker, carries the responsibility of navigating complex situations, particularly in emergencies. A vessel manned by a seasoned captain, coupled with a well-trained crew, is more likely to execute swift and effective decisions. This capability stems from their collective experiential knowledge, which allows them to draw upon past encounters and lessons learned. For instance, an experienced crew may recognize early warning signs of adverse weather conditions or mechanical failures, enabling preemptive action to mitigate risks. Moreover, the significance of formal training cannot be overstated. (The Nautical Institute, 2021; Human Factors Methods, 2013; yliopisto, 2024)

Training programs that emphasize scenario-based learning, crisis management, and teamwork can equip crew members with the necessary skills to handle unexpected challenges. Such training not only enhances individual competencies but also fosters a culture of preparedness and resilience within the team. Consequently, vessels that prioritize continuous training and skill development are better positioned to respond effectively to emergencies and operational challenges. In addition to individual experience and training, the dynamics within the crew are crucial in shaping the quality of decision-making. Team dynamics encompass the interpersonal relationships among crew members, which can significantly influence their collective performance. Research indicates that cohesive teams characterized by trust, respect, and open communication tend to outperform those with poor interpersonal relationships. Effective teamwork creates an environment where crew members feel empowered to share insights, voice concerns, and contribute to collective problem-solving. (The Nautical Institute, 2021; Human Factors Methods, 2013; yliopisto, 2024; University, 2018)

Communication serves as the lifeblood of effective decision-making. In high-pressure situations, clear and concise communication can be the difference between successful navigation and potential disaster. Teams that employ structured communication protocols, such as standardized reporting and briefing procedures, can enhance situational awareness and ensure that critical information is disseminated efficiently. Additionally, regular debriefings and feedback sessions can further strengthen communication patterns and foster continuous improvement. Beyond internal team dynamics, the capacity of crew members to engage in effective communication with external entities such as port authorities, other maritime vessels, and emergency services plays a vital role in operational outcomes. The efficacy of these interactions can determine the success of logistical operations, safety protocols, and emergency responses. For instance, timely communication with port authorities regarding docking procedures or weather conditions can facilitate smoother operations and enhance overall safety. Furthermore, in an increasingly interconnected maritime environment, the ability to collaborate with other vessels is becoming increasingly important. This collaboration can involve sharing navigational information, coordinating responses to maritime incidents, or engaging in joint training exercises. (Human Factors Methods, 2013; The Nautical Institute, 2021; yliopisto, 2024; University, 2018)

By fostering relationships with external stakeholders, vessels can improve their situational awareness and enhance their decision-making capabilities. In recent years, advancements in technology have introduced new dimensions to decision-making processes in maritime operations. The integration of digital tools, such as navigation systems, real-time data analytics, and communication platforms, has the potential to enhance situational awareness and facilitate informed decision-making. For example, automated systems can provide real-time updates on weather conditions, navigational hazards, and vessel performance metrics, enabling crews to make data-driven decisions swiftly. However, the reliance on technology also necessitates a critical assessment of crew competencies. While technological tools can augment decision-making, they cannot replace the essential human elements of judgment, intuition, and experience. Therefore, it is imperative that crew members receive adequate training in the use of these technologies to ensure that they can leverage them effectively while maintaining their core decision-making skills. The decision-making capabilities of a vessel's crew are multifaceted and influenced by a combination of experience, training, team dynamics, communication practices, and technological advancements. A comprehensive understanding of these factors is essential for enhancing operational effectiveness and ensuring safety within maritime environments. Future research should focus on developing frameworks that facilitate improved training and communication strategies among vessel crews to mitigate risks and enhance decision-making outcomes. By investing in the development of skilled, cohesive teams and leveraging technological advancements, the maritime industry can continue to evolve and improve its safety and efficacy in an increasingly complex operational landscape. (Human Factors Methods, 2013; The Nautical Institute, 2021)

12 Ship Operational performance

Optimization of ship operational performance in maritime operations, focusing on enhancing efficiency and reducing fuel costs. It identifies five key factors that impact operational performance: speed optimization, trim optimization, weather routing, autopilot adjustment, and monitoring of propeller and hull maintenance. The text discusses the importance of minimizing operational costs, particularly fuel consumption, and how this aligns with environmental sustainability efforts. It emphasizes the use of predictive modeling and machine learning to analyze historical data and generate insights on crucial operational metrics, while also addressing the complexities of optimizing ship performance due to interdependent variables and external factors like weather and sea conditions. The text highlights the role of decision variables, which are controlled by ship operators, in the optimization process. Additionally, it discusses the significance of integrating optimization results into decision support systems, enabling data-driven decision-making for real-time operational adjustments. (University, 2018; The Nautical Institute, 2021)

Ultimately, the text presents optimization as a multifaceted challenge with profound implications for cost reduction, operational efficiency, and sustainability in the maritime industry. The optimization of ship operational performance is a critical area of focus for enhancing efficiency and reducing costs in maritime operations. Five pivotal issues have been identified that significantly impact operational performance: speed optimization, trim optimization, weather routing, autopilot adjustment, and the monitoring of propeller and hull maintenance. Each of these factors plays a vital role in determining the overall efficiency and fuel consumption of a vessel during its voyage. At the core of optimization is the concept of achieving the best possible value—whether minimum or maximum—of a particular function through the careful selection of variable values from a predefined set. In the context of marine operations, this optimization is predominantly concerned with minimizing operational costs, particularly fuel costs, which represent a substantial portion of a ship's overall expenditure. Reducing fuel consumption not only contributes to cost savings but also aligns with global efforts to promote environmental sustainability by decreasing greenhouse gas emissions from maritime transport. Once an effective algorithm is identified and trained through historical data, it can be applied to new datasets to generate predictions regarding crucial operational metrics, such as fuel oil consumption or propulsion power. (University, 2018; The Nautical Institute, 2021)

The objective of this predictive modeling is to minimize fuel consumption, which serves as the primary optimization goal. However, the application of machine learning in modeling ship performance should not terminate at the predictive modeling phase. Instead, it should extend towards the overarching objective of optimization. This is particularly important given that ship performance is governed by complex nonlinear functions with numerous interdependent variables. Traditional analytical methods often fall short in effectively optimizing these types of functions due to their inherent complexity and the multitude of variables involved. To achieve the optimization objective of minimizing the operational fuel consumption function, it is essential to identify the optimal values for the input variables. The datasets employed for operational ship performance modeling typically comprise both ship-specific data and navigational data. The navigational data encompasses external factors that influence the ship’s performance, such as weather conditions, sea state, and ocean currents. These factors are largely uncontrollable and, therefore, present a challenge for optimization efforts. (University, 2018; The Nautical Institute, 2021)

In contrast, ship-specific input variables such as speed, course, and operational settings are manageable and can be adjusted by ship operators based on operational schedules and performance targets. These variables are categorized as decision variables, as they are within the control of the ship's crew and management. Thus, the optimization process is fundamentally concerned with determining the most effective values for these decision variables to minimize the fuel consumption function derived from the set of operational variables. The implications of successful optimization are profound, as they can lead to significant reductions in operating costs and improvements in overall vessel efficiency. Moreover, the results obtained from optimization processes are frequently incorporated into decision support systems, which provide critical insights and recommendations to ship operators. These systems facilitate data-driven decision-making, allowing operators to make informed adjustments to their operational strategies in real time. In conclusion, the optimization of ship operational performance is a multifaceted challenge that involves the interplay of various variables and external conditions. By leveraging advanced predictive modeling techniques and focusing on the optimization of decision variables, maritime operators can enhance fuel efficiency, reduce operational costs, and contribute positively to environmental sustainability. (The Nautical Institute, 2021; University, 2018)

As the maritime industry continues to evolve, the integration of sophisticated optimization methodologies will likely play an increasingly vital role in shaping the future of maritime operations. Unconstrained optimization, as its name indicates, is finding the best variables to minimize or maximize a function without any constraint on the variable’s values. Ship operators make decisions to reduce fuel consumption by reducing the speed with the specified constraint to arrive on time, to avoid extra fuel usage if the ship stays at the waiting area. This is a minimization problem subject to a constraint. The decision variables are not chosen among an infinite number of values. They are rather limited by one or more constraints. The system will then choose the values that meet the defined objective while respecting the specified constraints. This expanded version delves deeper into the implications of the study, emphasizes the importance of optimization in maritime operations, and discusses the role of decision support systems in facilitating effective management strategies. (The Nautical Institute, 2021; University, 2018)

12.1 Speed Optimization

Speed plays a critical role in maritime transportation, particularly in the context of growing global trade volumes. The demand for high-speed vessels has increased as they offer economic advantages such as timely cargo delivery, reduced inventory costs, and enhanced trade throughput over time. However, escalating fuel prices and environmental concerns necessitate a reevaluation of ship speed practices. Consequently, optimizing ship speed has emerged as a significant area of research. The optimal speed for a vessel is not simply the lowest possible speed, but rather a carefully determined pace that integrates various parameters influencing the voyage plan. While reducing speed can yield fuel consumption benefits, it must be harmonized with other commercial and operational priorities. Determining the optimal speed involves balancing low-speed navigation, fuel efficiency, and market requirements. (Furuno, 2024 b; University, 2018; yliopisto, 2024)

Market demands are dynamic, meaning that the optimal speed is not static throughout a voyage. It should be continuously updated based on real-time information from stakeholders such as maritime companies, ship agents, and charterers. Reducing ship speed is particularly effective for enhancing fuel economy, given the nonlinear relationship between speed and fuel consumption. Specifically, ship speed significantly impacts fuel usage due to its cubic relationship with the power output needed for propulsion. (Furuno, 2024 b; University, 2018; yliopisto, 2024)

12.2 Trim Optimization

Trim optimization is critical for enhancing fuel efficiency and minimizing emissions in maritime operations. The optimal trim is unique to each vessel and is influenced by the ship's speed and draft. Trim affects hull resistance; therefore, hull designs usually take specific drafts into account. By aligning the ship's trim with these drafts, resistance can be reduced. In cases where the trim is not optimal, even with a low draft, resistance can increase, particularly if the trim is not suited to the actual draft conditions of the vessel. The resistance faced by a ship is influenced by fluid pressure and wave generation, both of which change with trim adjustments. Optimizing trim for a specific draft and speed can significantly enhance fuel efficiency. Trim adjustments are made through load distribution, fuel management, and ballast adjustments. However, ballasting can also increase fuel consumption due to the added displacement. (yliopisto, 2024; The Nautical Institute, 2021)

Operational risks, such as overlooking bending moments and shear forces, pose challenges during trim optimization. Additionally, practical difficulties arise from changes in trim due to fuel and water consumption, ballast exchange requirements, the ship's design features (like drain and scupper placement) and maintaining control in adverse weather conditions. The engine power required for a ship can vary by over 10% between optimal and suboptimal trim settings. Achieving the best draft and trim necessitates the careful distribution of cargo, ballast, and consumables, tasks typically managed by ship captains and cargo planners. Monitoring tools are often needed to maintain optimal conditions throughout a voyage. Despite the availability of trim-power tables based on model tests, seafarers are sometimes hesitant to use them. Therefore, implementing information systems that provide ship-specific hydrodynamic data through numerical experiments is crucial. These monitoring systems help identify the most efficient trim for a given draft, allowing for adjustments in ballast and consumables to optimize performance. (yliopisto, 2024; The Nautical Institute, 2021)

12.3 Weather Routing

Variability in weather can significantly affect fuel efficiency, necessitating the collection of meteorological data alongside operational metrics. The impact of factors such as wind speed, wave height, and sea currents will be examined to determine their correlation with fuel consumption rates. In contemporary maritime navigation, there is a growing emphasis on routes that prioritize safety and energy efficiency over sheer speed. The primary objective of weather routing is to optimize speed to enhance the energy efficiency of the voyage plan, thereby reducing fuel consumption while ensuring the safety of the ship, crew, and cargo. Ensuring timely arrival at port and effective port planning are integral aspects of weather routing. Potential benefits of weather routing include a reduction in fuel consumption by up to 3%, in addition to time savings. (Ocean Route, 2024)

Weather routing is defined as the process of determining the optimal route while considering prevailing weather conditions. The optimization aims to achieve the expected time of arrival with minimal fuel consumption and sailing time, maintaining safety margins. Analyzing ship behavior in various weather conditions offers both economic and environmental advantages. For ship owners and crew, understanding ship responses to weather conditions is crucial for achieving fast, safe, and cost-effective voyages. There are generally two parameters affecting weather routing optimization: voluntary and involuntary speed loss. Voluntary speed loss is influenced by the preferences of the ship's captain and navigator. In contrast, involuntary speed loss results from the ship's resistance to sea and weather conditions, which varies with the weather. In adverse weather, strong environmental forces increase ship resistance, necessitating greater engine power and, consequently, higher fuel consumption. (Ocean Route, 2024)

Numerous companies offer weather routing services that gather meteorological data, analyze wind and sea conditions, evaluate ship responses, and provide route recommendations based on these conditions. Ships can access weather routing information through email or computer applications, which also facilitate comprehensive visual information sharing for ship and fleet management. Notably, the shortest distance between two points is not always the fastest due to factors like currents, wave height, and winds. When modern systems are integrated with bridge computers, they enable fuel-efficient routing based on real-time weather data, enhancing overall navigational efficiency. (Ocean Route, 2024)

12.4 Autopilot Adjustment

The Emri autopilot system, grounded in extensive experience with cost-efficient and safe design, features a control panel equipped with a tiller for direct adjustment of set points, including both heading and radius control. The panel's push buttons, enhanced with LED backlighting and a light bar above each button, clearly indicate the active mode, ensuring safe operations and clear communication of commands. The design requires a specific actuation force for the tiller and buttons, eliminating any ambiguity for the navigator. Operators can select from three modes: Precise, Medium, and Economy. Economy mode optimizes fuel efficiency by minimizing rudder or propulsion system movements. Precise autopilot adjustment is crucial for maximizing steering system accuracy, enabling vessels to achieve their intended heading more efficiently. (Emri, 2022; University, 2018)

The adjustment process begins with fine-tuning the entire steering system. Initial steps include verifying the zero point of the rudder or propulsion system and ensuring linearity and equal voltage/current across the maximum port to starboard range, using both pumps. For Azipod or Azimuth propulsion systems, a full 360-degree check is required to confirm accuracy with both pumps. Autopilot adjustments should be conducted in open seas with minimal traffic, allowing the crew sufficient time for precision work. The process begins with basic factory settings tailored to the ship's specifications, such as length. Adjustments are ideally made at approximately 70% of maximum speed in optimal weather conditions, free from currents or winds that could affect the results. The Heading control mode on the autopilot panel is activated to maintain the set course, requiring manual drift compensation by the navigator. The autopilot's load conditions should be set to a middle setting, and Precise mode is selected. Initial tests involve 15-degree turns to port and starboard to assess responsiveness, with adjustments made to rudder and counter-rudder settings as needed. Once satisfactory performance is achieved, further testing with 30-degree turns ensures comprehensive functionality. Lastly, the Autopilot radius and programming modes are tested, typically straightforward if the Heading control mode is functioning effectively.

12.4.1 Introduction of Autopilot

The introduction of autopilot systems in maritime navigation has become increasingly prevalent, despite specific regulatory requirements. According to the Imo, vessels of 10,000 gross tonnage and above are mandated to have autopilot systems installed. However, in practice, autopilot systems are commonly found on nearly all ships, regardless of this stipulation. Traditionally, manual steering with a helmsman is reserved for navigation in constrained waterways, during port approaches, or when a pilot is on board. Autopilots are essential devices that maintain a vessel's heading stability during navigation. The basic operation of an autopilot requires inputs from a gyro compass, a speed log, and the capability to adjust the steering gear angle. Modern advancements have integrated autopilot systems with Ecdis and position reference systems. This integration enables track steering functions, allowing the autopilot to maintain a predetermined course in conjunction with Ecdis, enhancing navigational accuracy and efficiency. The conventional steering gear control system in maritime vessels primarily relies on hydraulic pistons to maneuver the rudder stock. This hydraulic system is designed with redundancy to ensure continuous steering capability under all circumstances, thereby preventing potential catastrophic failures. (Emri, 2022)

Typically, one hydraulic motor is powered through the main switchboard, while the other is connected to an emergency switchboard. This configuration ensures operational reliability in case of power supply issues. The movement of the hydraulic pistons, which direct the rudder to port or starboard, is controlled via solenoid valves operating on a 24 VDC system. The rudder stock is equipped with a feedback potentiometer that communicates the rudder's position to the autopilot system. The autopilot's algorithm receives critical inputs such as the ship's actual heading from a gyro compass, the desired heading set by the ship's officer, and the vessel's speed. The autopilot system uses these parameters to adjust the rudder angle, ensuring the ship maintains the intended course. The relationship between the ship's speed and its steering response is critical; higher speeds require smaller rudder angles for effective maneuvering. This adaptive capability to adjust based on speed variations gives rise to the term "speed adaptive autopilots," reflecting their efficiency in optimizing steering responses relative to the vessel's velocity. The autopilot system offers users various parameters tailored to the ship's loading conditions, which include loaded, medium, and light states. These settings are selectable based on the vessel's current load, allowing the autopilot to optimize steering performance accordingly. (Emri, 2022)

The autopilot panel also presents three behavioral settings: Precise, Medium, and Economy. These settings dictate the strictness with which the vessel adheres to the predetermined heading. The Economy mode prioritizes fuel efficiency by reducing rudder movements to a minimum, thus providing a more relaxed control over the vessel's direction. This system enhances navigational efficiency by adapting to both the vessel's load and desired steering precision, ultimately contributing to operational effectiveness and fuel conservation. (Emri, 2022)

12.4.2 Optimizing Autopilot Usage in Maritime Navigation

The operation of a ship's rudder inherently contributes to increased hull drag and resistance, which in turn affects fuel efficiency. Minimizing the frequency and extent of rudder movements can thus lead to significant fuel savings. Autopilots serve as crucial auxiliary systems for bridge teams, optimizing navigational paths by reducing unnecessary rudder activity, thereby lowering resistance and the power needed to maintain a steady course. Traditional autopilot systems rely on basic correlations between rudder angle and the rate of turn to achieve desired heading changes. These are generally effective for ships with directionally stable hull designs and when only small rudder angles are necessary. However, when external forces such as wind, waves, and currents impose large dynamic loads on the vessel, larger rudder angles may be required. Additionally, variations in draft, speed, and water depth can impact the relationship between rudder angle and turning rate. Advanced adaptive autopilot systems incorporate features that enhance navigational precision. These systems optimize rudder actions by utilizing minimal angles over short durations, thereby maintaining course accuracy even under adverse conditions like strong winds and waves. While adaptive systems possess the capability to self-adjust to varying weather and load conditions, optimizing autopilot settings to account for factors such as wind, currents, speed, trim, draft, and water depth can further enhance fuel efficiency. In summary, the strategic utilization of autopilot systems, particularly those with adaptive capabilities, plays a vital role in reducing fuel consumption by optimizing rudder usage and improving navigational accuracy under diverse maritime conditions. (Emri, 2022; University, 2018)

12.4.3 Emri systems interview

The rudder control unit (RCU) serves as a critical interface between the autopilot system and the vessel's steering mechanisms. It comprises servo units that are directly linked to the rudder or azimuth steering gear, facilitating precise maneuverability. Notably, multiple RCU models cater to various steering gear manufacturers, including prominent brands such as Mitsubishi and Kawasaki, which utilize either proportional control systems or Bang-bang control mechanisms. Conversely, brands like ABB and Hatlapa designate their RCU as an Analog Control Unit (ACU), underscoring the diversity in control methodologies across different systems. Additionally, the text introduces the concept of Rudder Feedback Units (RFU), which are essential for providing real-time feedback on the rudder's position. The RFUs vary in design according to the specific requirements of different rudder or azimuth systems. (Emri, 2022)

The original RFU was designed with a uni-ball link mechanism suitable for metal rudder rods, while subsequent iterations have evolved to incorporate belt drive mechanisms. This advancement enables the RFUs to support azimuth operations of up to 30 degrees, thereby enhancing the maneuverability and responsiveness of the vessel in various maritime conditions. In summary, the Emri SEM300 autopilot system exemplifies a sophisticated integration of steering control components that are tailored to the operational characteristics of diverse steering gear systems, ensuring efficient navigation and positioning of maritime vessels. (Emri, 2022)

Figure 4 Autopilot Overview

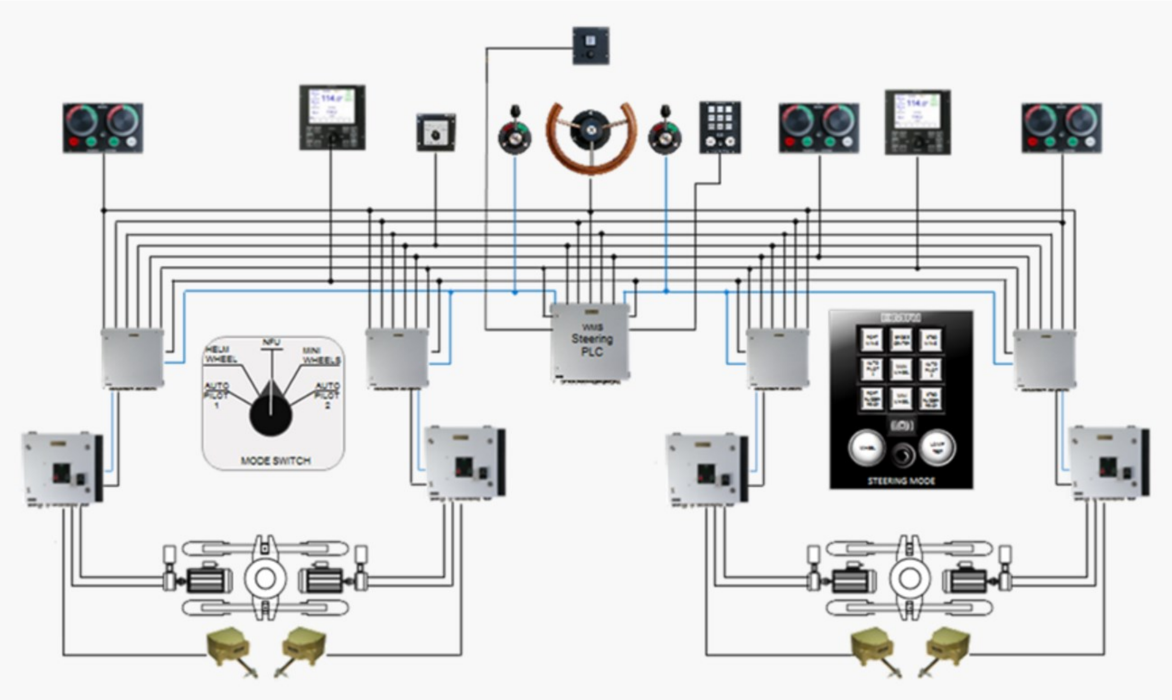

Figure 5 Steering System Overview

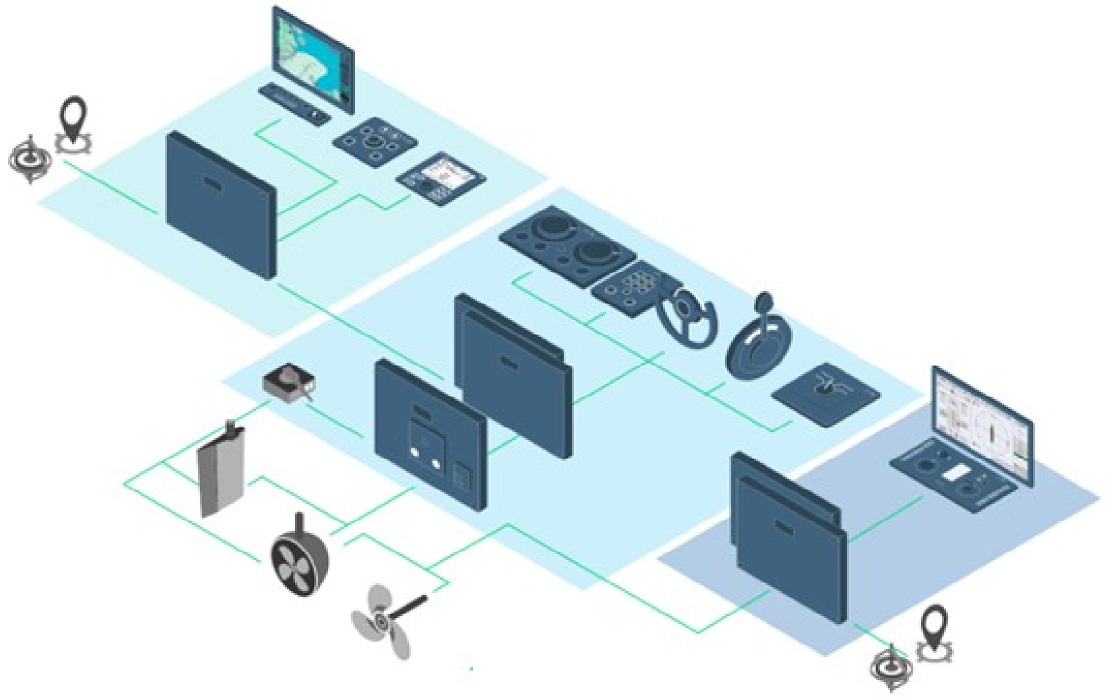

Figure 6 Dp System Overview

12.5 Propeller and Hull maintenance monitoring

The phenomenon of surface roughness on maritime vessels, particularly in regions that interact with water, such as the hull and propeller, presents significant implications for operational efficiency. Over time, the accumulation of roughness, especially at the leading edges of propellers, can result in increased fuel consumption, thereby elevating operational costs and adversely affecting the vessel's speed, power output, and overall performance metrics. Surface roughness can be attributed to a combination of abiotic and biotic factors. From a physical standpoint, roughness may arise from mechanical damage or from the degradation of protective coatings applied to the vessel's surface. Common forms of deterioration include peeling, blistering, and cracking, which can result from inadequate application techniques or environmental stressors. (University, 2018; The Nautical Institute, 2021)

Biologically, hull roughness is exacerbated by fouling, which refers to the adhesion and proliferation of marine organisms on submerged surfaces. The composition of seawater plays a critical role in the types of bacteria and marine life that contribute to this fouling process, with variations observed depending on geographic and ecological conditions.

Research underscores the importance of selecting appropriate coating materials as a strategic measure to mitigate the development of surface roughness. Effective coatings can not only enhance the hydrodynamic efficiency of the vessel but also prolong the intervals between maintenance activities, thereby reducing long-term operational costs and improving sustainability in maritime operations. In summary, the maintenance monitoring of propellers and hulls is essential for optimizing vessel performance and minimizing fuel consumption. Understanding the multifaceted causes of surface roughness, both physical and biological, is crucial for the implementation of effective maintenance strategies and the selection of appropriate protective coatings. (University, 2018; The Nautical Institute, 2021)

12.6 The Role of Paint in Enhancing Vessel Performance

Throughout maritime history, the protection of vessels from the deleterious effects of prolonged exposure to aquatic environments has been paramount. The evolution of vessel coatings has significantly influenced various facets of vessel performance, including fuel efficiency, environmental safety, and structural integrity. Historical practices reveal a continuous innovation in protective measures: ancient Greeks employed hot wax, Vikings utilized tar, and by the mid-18th century, shipbuilders adopted copper plating to mitigate biofouling from barnacles and marine flora. In contemporary maritime operations, paint has emerged as the predominant protective medium. Its applications extend beyond mere aesthetic enhancement; it serves critical functions in safeguarding vessels against environmental challenges. Modern marine paints are engineered to fulfill specialized requirements, such as anti-slip surfaces and flame-retardant barriers. Notably, the selection of an appropriate coating can lead to substantial reductions in fuel consumption and emissions, while also minimizing the quantity of steel required during the construction phase. The formulation of modern marine paints is a complex interplay of chemical components, reflecting decades of technological advancement. (lr.org, 2021)

These coatings typically consist of resins that act as binders, alongside pigments that provide color and visual appeal. Additionally, fillers and extenders contribute to the bulk of the paint, while solvents and diluents are incorporated to optimize application characteristics, such as viscosity and reactivity. Marine-specific paints often contain a variety of specialized additives designed to combat issues such as corrosion and ultraviolet

(UV) light degradation. This tailored approach to paint formulation aligns with the increasing awareness of environmental stewardship and vessel safety, particularly considering numerous maritime incidents over the past two decades. (lr.org, 2021)

In response to these challenges, the International Maritime Organization (IMO) has assumed a critical role in establishing minimum standards for vessel coatings, thereby underscoring the importance of regulatory frameworks in promoting maritime safety and environmental protection. In summary, paint coatings are integral to enhancing vessel performance, serving multifaceted roles that encompass protection, efficiency, and compliance with international standards. The ongoing evolution of these coatings reflects broader trends in maritime technology and environmental awareness, highlighting their significance in contemporary maritime practice. (lr.org, 2021)

12.7 Key Areas for Coatings

In contemporary maritime operations, owner/operators are mandated to comply with regulations established by Classification Societies and the International Maritime Organization (IMO) concerning the application of coatings in critical areas of marine vessels. These areas include seawater ballast tanks, cargo oil tanks, and underwater hulls, all of which are subject to stringent governance to ensure safety and environmental protection. The coatings applied to these marine components must adhere to specific guidelines that prioritize both structural integrity and ecological considerations. For instance, underwater hull coatings are particularly scrutinized due to their role in preventing biological fouling—organisms such as barnacles and algae that can attach to a vessel's hull, thereby increasing drag and reducing fuel efficiency. A significant environmental concern has arisen from the use of tributylin (TBT) in anti-fouling paints, which has been shown to cause detrimental effects on marine life, including deformities in oysters and gender alterations in whelks. (lr.org, 2021)

In response to these findings, legislative measures have been implemented to ban TBT and similar harmful substances. This has led to a heightened focus on monitoring the impact of biocidal additives in marine ecosystems, resulting in a burgeoning market for non-biocidal alternatives in anti-fouling coatings. The application of coatings in underwater environments requires specific technical attributes. For instance, high-resistance paints are essential for underwater hulls, particularly in polar regions where abrasion-resistant ice coatings are necessary. The use of effective coatings can significantly decrease the thickness of additional steel plating required, from 7mm to 3.5mm, thus yielding substantial savings in both fuel consumption and fabrication costs. Additionally, the application of weldable pre-fabrication primers is critical. The selection of inappropriate primers can lead to porosity during the welding process, compromising the structural integrity of the vessel. Therefore, rigorous testing protocols must be established to ensure that any primer utilized in pre-fabrication does not adversely affect the welding process and the overall strength of the structure. (lr.org, 2021)

The management of coatings within the marine sector is governed by a complex interplay of regulatory frameworks, environmental considerations, and technical requirements. As industry evolves, the emphasis on sustainable and efficient coating solutions continues to grow, reflecting commitment to both operational efficacy and environmental stewardship. In the realm of vessel management, the maintenance of paintwork is often relegated to a lower priority among the myriad concerns faced by owner/operators. However, adopting a proactive strategy regarding the condition and upkeep of marine coatings can yield substantial benefits with minimal additional effort. From a risk management perspective, a thorough understanding of the paintwork's condition is crucial in mitigating the potential for catastrophic failures, particularly concerning the structural integrity of critical components such as cargo oil tanks. Furthermore, the strategic application of anti-fouling paint is instrumental in enhancing a vessel's operational efficiency by facilitating unhindered navigation, which subsequently optimizes fuel consumption and reduces associated costs. (lr.org, 2021)

Moreover, a proactive maintenance strategy can defer the necessity for premature dry docking, which is typically scheduled at five-year intervals. When dry docking does become necessary, vessels that have been maintained effectively are likely to transition back into active service more swiftly than those requiring extensive recoating due to insufficient upkeep. In summary, a forward-thinking approach to marine coatings not only conserves financial resources for owner/operators through minimized maintenance and repair needs but also mitigates productivity losses associated with vessels being out of service for prolonged periods. This comprehensive strategy underscores the importance of proactive maintenance in the maritime industry, highlighting its role in enhancing operational efficiency and safeguarding asset integrity. (lr.org, 2021)

13 Human Factors

Definition and problem identification, Human Factors (HF) methods are an essential component of system design that focuses on the interactions between humans and various systems. Hf problems typically arise when human behavior deviates from expected patterns due to inadequacies in system design, leading to adverse outcomes such as accidents, inefficiencies, and user frustration. These problems are particularly significant in complex systems where human actions are critical to success, such as in aviation, healthcare, and maritime operations. Hf problems possess several characteristics that distinguish them from other technical issues. Primarily, they have a negative impact on overall system performance, often leading to suboptimal outcomes. For instance, in a high-stakes environment like a ship´s navigation system, if crew members cannot effectively interpret navigational data due to a poorly designed interface, the risk of accidents increases significantly. (Human Factors Methods, 2013; Production quality and human factors engineering: A systematic review and theoretical framework, 2018)

Additionally, Hf problems tend to be resistant to purely technical solutions, addressing these challenges often requires a deeper understanding of human behavior and the context in which these systems operate. This complexity underscores the need for interdisciplinary approaches that draw from psychology, ergonomics, engineering, and design principles. Hf problems do not reside solely within the purview of engineering or human sciences. Rather, they emerge at the intersection of these fields, necessitating collaborative efforts to devise effective solutions. The integration of Hf methods into the design process is crucial for enhancing usability and overall system performance. Research indicates that incorporating Hf principles early in the design life cycle can lead to significant time and cost savings, as well as improved user satisfaction. (Human Factors Methods, 2013; Production quality and human factors engineering: A systematic review and theoretical framework, 2018)

The earlier Hf considerations are integrated, the more flexibility designers need to make necessary adjustments, ultimately avoiding costly redesign efforts after system implementation. Various Hf methods, such as user-centered design, participatory design, and usability testing, play a pivotal role in this process. For example, user-centered involves engaging end-users throughout the design process to gather their insights and feedback. This iterative approach ensures that the final product aligns closely with the user's needs and expectations. In maritime context, involving crew members in the design of navigational interfaces allows designers to understand their workflows, preferences, and potential pain points. Leading to more effective solutions. Moreover, Hf analyses can transition through different stages of the design lifecycle. (Human Factors Methods, 2013; Production quality and human factors engineering: A systematic review and theoretical framework, 2018)

In the initial phases, methods may focus on understanding user requirements and behavior patterns through techniques like contextual inquiry or task analysis. As the design process progresses, methods may shift toward usability testing, human error analysis, and interface evaluation, allowing for continuous refinement based on empirical data and user feedback. Human Factors Integration (HFI) represents a strategic framework that emphasizes the importance of human considerations throughout the development of the system lifecycle. This integration is critical in ensuring that systems are designed not only with technological advancements in mind but also with a focus on user experience and safety. Hfi encompasses multiple domains, including manpower, personnel, training, Hf engineering, system safely, and health hazards. By ensuring that these domains are systematically addressed, Hfi fosters the development of systems that are user-friendly and aligned with human capabilities. For instance, in the aviation industry, Hfi practices ensure that cockpit designs accommodate pilots' needs, enhancing situational awareness and reducing the likelihood of human error during critical flight operations. Implementing Hfi requires collaboration among various stakeholders, including designers, engineers, end-users, and decision-makers. (Human Factors Methods, 2013; Production quality and human factors engineering: A systematic review and theoretical framework, 2018)

Effective communication and collaboration among these groups are essential for developing systems that meet both functional and human-centered design criteria. This collaborative effort can involve workshops, focus groups, and iterative testing, where feedback loops are established to ensure that user insights are continuously integrated into the design process. The application of Hf methods is often guided by the scientistpractitioner model, which emphasizes the dual roles of Hf professionals as both researchers and practitioners. In their capacity as scientists, Hf practitioners engage in empirical research to understand human behavior in relation to system use. They extend existing theories related to human-system interactions, develop hypotheses, and conduct rigorous experiments to derive insights that inform better design improvements. Conversely, as practitioners, Hf professionals focus on addressing real-world challenges that users face. This involves applying scientific knowledge to develop practical solutions that enhance system usability and performance. Practitioners strive to find a balance between ideal scientific principles and the practical constraints of real-world environments, such as time limitations, budget cons, and varying user skill levels. This dynamic interplay between scientific inquiry and practical applications allows Hf professionals to operate efficiently. (Human Factors Methods, 2013; University, 2018; Human Factors Methods, 2013)

14 Results

Question 1. Shipping companies utilize a variety of sensor technologies to monitor different operational parameters critical to enhancing fuel efficiency. Key sensors include Fuel Flow Meters: These devices measure the rate of fuel consumption in real time, providing essential data for assessing fuel efficiency. By analyzing fuel usage patterns, operators can identify inefficiencies and implement corrective actions. Temperature Sensors: Monitoring engine temperatures and fuel system temperatures is vital for optimal performance. Keeping these temperatures within a specified range can prevent fuel waste and improve overall engine efficiency. Pressure Sensors: These sensors track pressure levels in fuel lines and other critical systems. Abnormal pressure readings can signal potential mechanical issues, allowing for timely maintenance and preventing increased fuel consumption due to system inefficiencies.

Environmental Monitoring Devices: These sensors measure atmospheric conditions such as wind speed, humidity, and sea state. Understanding these external factors enables operators to adjust vessel speed and route, optimizing fuel usage based on current conditions. Navigation Sensors (GPS): GPS devices provide real-time location, speed, and course data. This information is crucial for route optimization, helping operators make informed decisions that minimize fuel consumption based on navigational choices. Load Sensors: These sensors measure the weight of cargo onboard. Accurate cargo weight data is essential for assessing how different loads impact vessel performance and fuel efficiency, allowing for better load management.

Question 2. Data Transfer Mechanisms: VDR. All commercial ships under the IMO classification are equipped with a VDR, which captures critical data during a voyage, including navigational information and operational metrics. The VDR serves as a central hub for data collection, ensuring that essential information is recorded for both immediate operational needs and post-incident analysis. Internet Connectivity, some manufacturers have integrated internet connectivity directly into VDR systems. This allows for efficient data transmission back to shore-based operations. With internet-enabled VDRs, ship owners can monitor vessels in real-time, accessing performance metrics and making informed decisions based on up-to-date information. Data Transmission Channels, Satellite Communication: For vessels operating in remote areas, satellite communication systems (like VSAT) provide reliable connectivity for data transmission. Cellular Networks: In coastal regions or when docked, vessels can utilize cellular networks to send data back to shore. Wi-Fi Networks: When in port, ships can connect to local Wi-Fi networks to transfer larger datasets quickly.

Considerations for Data Transfer, the nature of the data being transmitted (e.g., navigational data, command communications) influences the choice of transmission method. Critical data may require more frequent updates compared to less urgent information. Frequency of Updates, ship owners must determine how often they need data updates. Real-time data is crucial for immediate decision-making, while other data might be transmitted at scheduled intervals for comprehensive analysis. Acceptable delays, the acceptable delay in receiving information can vary by operational needs. Some operations may require instantaneous updates, while others can function with periodic data assimilation. Security Considerations, ensuring the security of data transmitted between vessels and shore is vital. Robust cybersecurity measures must be implemented to protect against unauthorized access and cyber threats. This includes encryption protocols, secure communication channels, and regular vulnerability assessments to maintain operational integrity. The integration of VDRs with secure communication channels represents a significant advancement in maritime operations. As technology evolves, shipping companies will need to evaluate their connectivity options based on their operational needs, the types of data they require, and the associated security implications. This ongoing dialogue about VDR capabilities will shape the future of maritime safety and efficiency, enhancing decision-making processes and improving overall fleet management.

Question 3. The integration of real-time sensors provides several significant advantages for shipping companies, particularly in terms of enhancing operational efficiency and reducing costs. Enhanced Fuel Efficiency, continuous monitoring, allows for the immediate identification of fuel inefficiencies. By analyzing real-time data, operators can adjust optimize fuel consumption, such as modifying speed or altering routes based on environmental conditions. Proactive Decision Making, real-time data facilitates quick responses to changing circumstances. For example, if environmental sensors indicate adverse weather conditions, operators can alter navigation strategies to minimize fuel consumption and avoid delays. Predictive Maintenance, Data from temperature and pressure sensors can help identify mechanical issues before they escalate. By addressing these issues proactively, shipping companies can schedule maintenance during port calls, avoiding costly repairs and minimizing downtime.

Operational Insights, analyzing historical and real-time data together, provides insights into trends and best practices across vessels in a fleet. This understanding enables shipping companies to standardize operational efficiencies and share successful strategies among crew members. Route Optimization, the data gathered from navigation sensors, allows for in-depth analysis of routes taken by vessels. By evaluating which routes yield the best fuel efficiency under specific conditions, operators can make informed decisions that reduce travel time and fuel costs. Cost Reduction, Ultimately, optimizing fuel consumption leads to substantial reductions in operational costs. Given that fuel represents a significant portion of shipping expenses, enhancing fuel efficiency directly impacts profitability. The integration and analysis of real-time sensor data from vessels are transformative for shipping companies, particularly those managing fleets of similar vessels that exhibit significant differences in operational costs and fuel consumption. By employing a diverse range of sensor technologies, effectively transmitting data to shore-based offices, and leveraging the advantages of real-time monitoring, companies can enhance fuel consumption efficiency. This not only results in considerable operational cost reductions but also aligns with broader sustainability goals within the maritime industry, making it a critical area of focus for shipping companies in today's economic and environmental landscape.

15 Critical review

The thesis aimed to explore the optimization of fuel consumption efficiency in maritime operations through the integration of real-time sensor data from the vessels. Focusing specifically on traditional vessels lacking autonomous capabilities, the study investigated the significant variability in fuel consumption and identified key operational factors that influence efficiency.

What Went Well, the thesis successfully implemented a robust data collection strategy utilizing an extensive array of sensors, including fuel flow meters, GPS, temperature sensors, pressure sensors, steering systems, autopilot and environmental monitoring devices. This multifaceted approach enabled the gathering of relevant operational data, which is essential for accurate analysis. By employing diverse sensor technologies, the research ensured that a holistic view of the operational environment was captured, allowing for more nuanced insights into fuel consumption patterns. Focus on Real-Time Analysis. Emphasizing real-time data transmission and analysis represented a critical aspect of modern maritime operations. The study's focus on this area allows timely decision-making, which is crucial in operational contexts where conditions can change rapidly.

The ability to access real-time data meant that vessel operators could make immediate adjustments to optimize fuel consumption, thereby enhancing operational efficiency and potentially reducing fuel costs significantly. Incorporation of Human Factors. One of the standouts features of the thesis was its recognition of the importance of human operational practices in influencing fuel consumption. By including crew behavior, decision-making processes, and adherence to best practices, the study provided a holistic view of the factors affecting fuel efficiency. This focus on human factors is vital, as it underscores the interplay between technology and human input, emphasizing that technology alone cannot drive efficiently; effective crew training and operational protocols are equally essential. My experience of navigation systems and how to collect data was a strong point of the thesis. Wide range of sensor provided valuable insights into fuel consumption patterns, enabling the development of predictive models that can be employed to optimize operations. The use of advanced analytical techniques not only enhanced the rigor of the research but also positioned the findings as relevant to ongoing discussions in the maritime industry about data-driven decision-making. Identification of Best Practices, the comparative analysis among similar vessels yielded actionable insights, allowing for the identification of best practices.

This information is crucial for fleet management, as it provides a roadmap for other vessels to adopt more efficient operational strategies. By disseminating these best practices, the thesis contributes to the larger body of knowledge in the maritime industry, facilitating improvements in fuel efficiency across fleets. Contribution to Environmental Sustainability, the thesis also highlighted the broader implications of optimizing fuel consumption, particularly in relation to environmental sustainability. By reducing fuel usage, vessels can decrease greenhouse gas emissions, aligning with global efforts to promote sustainability in the maritime sector. This aspect of the research not only enhances its relevance but also positions it within the context of increasingly stringent environmental regulations. Complexity of Data Integration can be hard for many ship owners to understand the systems possibilities. The data collection and integration process proved to be more complex than initially anticipated.

Coordinating multiple sensor types and ensuring compatibility with existing systems took significantly longer than expected. This complexity not only delayed the data gathering phase but also required additional iterations to refine the data integration process. Technical Challenges, Unforeseen technical difficulties arose in setting up the sensor systems and ensuring consistent data transmission. Issues related to sensor calibration, connectivity problems, and the need for frequent adjustments to the data collection framework impeded progress. The time required to troubleshoot these technical challenges was substantial, contributing to delays in the overall project timeline. Resource Limitations, limited access to necessary resources, including personnel, funding, and equipment, also slowed the research process. Delays in securing essential technology, such as advanced sensors and data analysis software, impacted the timeline. Additionally, the availability of skilled personnel to assist with both data collection and analysis was less than anticipated, further compounding the delays.

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