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The Impact Of Big Data On Port Performance: A Review

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Abstract - Most of the world trade are being transported by sea and Seaports are interface between land and sea. Seaports, hub of sea, rail & road transport to transfer cargo from one transport mode to other, are growth engine of the country. Many large cities in the world are developed around seaports because of the ease of international trade and transportation facilitated by maritime access. Multiple agencies are working together for smooth operation of the seaports. They use different types of hardware, software, database and communication technologies to ensure smooth, efficient, and secure port activities. Since these agencies operate with diverse technologies, a unified system/database is required to enable data sharing, interoperability, and data analytics. Big Data can play a crucial role in integrating and analyzing the vast amounts of information generated by these different agencies. Analysis of the data from different sources can be used to enhance efficiency of whole supply chain, safety and security of cargo and predictive decision-making.

Index Terms - Big Data, Port Performance, Cargo, Loading and Unloading

INTRODUCTION

Application of information and communications technology (ICT) is integral part of smart ports [1][2]. Developing a smart port architecture is essential elements in the era of Industry 4.0 [3][4]. These smart port initiatives create massive volume of data, that can be termed as Big data.The significant volume of Big Data generated from various sources such as cargo, vessels, cranes, and other IoT devices within the port must be organized into meaningful information that can provide insights pertinent to the relevant business areas [5][6].

The application of Big Data in port operations has become a transformative influence, improving performance, efficiency, and sustainability. As global trade continues to expand, ports are under growing pressure to enhance their operations while reducing environmental effects. This paper investigates how Big Data analytics can enhance port performance, highlighting its uses, advantages and challenges.

Big Data refers to extensive datasets that are too intricate for conventional data-processing tools to manage effectively. These datasets are defined by the 3 Vs:

- Volume: The vast amount of data produced from various sources such as shipping schedules, cargo movements, and equipment sensor data.
- Velocity: The rapidity at which new data is created and analyzed for immediate decision-making.
- Variety: The diverse types of data, which include structured data (e.g., databases) and unstructured data (e.g., social media, emails).

Big data includes datasets that are not only extensive in volume but also varied and rapidly changing, comprising both structured and unstructured information from multiple sources, which presents difficulties for traditional tools and methods [7]. Given the swift increase of such data, it is essential to explore and implement solutions that can effectively manage and derive insights and knowledge from these datasets. Additionally, decision-makers must be equipped to extract meaningful insights from this diverse and swiftly evolving data, which can include everything from daily transactions, cargo movements, vessel operations, port employee and customer interactions and social media data. This value can be achieved through big data analytics, which involves utilizing advanced analytical techniques on big data [8].

I. CHALLENGES IN BIG DATA

Big data presents significant challenges for data acquisition, data management, data processing, data storage, and data analysis, despite its potential benefits. Big data differs from typical data due to its huge volume, velocity, variety of sources, and the need to integrate them for analysis. Traditional data management and analytics systems rely on relational and structured databases. These

technologies are not built to handle the large volume and diversity of big data [9].

Analytics and Scientists face limitations when working with data due to its diverse sources, and as the amount of data increases from globally connected information-sensing mobile devices, aerial sensing technologies (remote sensing), software logs, cameras, radio-frequency identification (RFID) readers, IoT devices, and wireless sensor networks. Analyzing, capturing, storing, transferring, and visualizing data can pose challenges when considering the information [10].

Wide range of Industries have been impacted by large amounts of data i.e. Big Data. It is important that this data be managed and analyzed, in order to make the maximum benefit from the data. But such large data also contains numerous uncertainties and difficulties surrounding big data. Some of these difficulties are prevalent throughout industries, while others are exclusive to certain sectors [9].

Quality of Data: The Quality of Data is critically crucial. Having a large amount of data does not always mean greater results. Most data scientists spend a lot of their time cleaning up data. Analyzing poor quality data yields deceptive results [9]. The quality of data is more crucial when businesses depend more and more on it, for decision making.

Data Consistency - Consistency pertains to how values will be displayed as well as data formatting. It also refers to the format in which a specific sample of data is obtained from the source [9]. Inconsistent or incomplete data can lead to mistakes, lost opportunities, or legal problems.

Data Reliability and Availability: Reliability is the dependability of results is influenced by both the methods of data collection and the way measurements are defined. The trustworthiness of the data is contingent upon the process used to gather the raw data. The robustness of the analysis is linked to the quality and dependability of the data. Whereas Availability refers to the timely access to data. Data must be accessible at all times for analysis purposes. When sensors deliver data at a certain sample rate, the raw data will be retrievable for a designated time frame. Archived or historical data ought to be accessible for gathering and examination [9].

Data Link: Data is gathered for a particular task or objective and may need various types from different datasets. When a single user interacts with multiple datasets, a primary key is necessary to join the data [9].

Pattern and Trends: Data needs to viewed and manipulated to get meaningful insights and see pattern in it. Poor visualization or presentation could make it difficult to find a pattern or insight.

Data Redundancy: Data from different sources can lead to high levels of redundancy, hence data needs to be filtered as per the required criteria in order to compress it, to more meaningful data.

Data Life Cycle Management: It concerns the frequency and criteria for storing or eliminating data. Typically, the worth of big data is linked to how current the data is. Sensor network systems can produce data at exceptional speeds and volumes, making the handling and storage of these extensive datasets critical [9].

Data Privacy: It pertains to the safeguarding and security of information. The analysis or sharing of data with external parties can heighten the associated safety risks. It is essential to safeguard the data from any potential threats [9].

Port Performance has a connection with the shipping sector. As any factors or variables that affect the shipping sector has an effect on the port performance. The shipping sector produces a significant amount of data from various sources and formats, including traffic, cargo, weather, and machinery data. The volume and diversity of this data continue to rise daily, largely due to the implementation of sensor technology within the industry. Data collection and processing are predominantly done remotely at high transmission speeds. Consequently, the industry is becoming more aware of the numerous challenges posed by big data. Big data analytics are relatively new to the shipping sector and tackle various problems, such as adaptability and integration. Numerous difficulties are linked to the adoption of big data in the shipping industry [9].

A. Storage and Transfer of Data

The primary challenge connected with Big data is managing its storage and transfer. Massive data generated from various stakeholders, its various formats like text, images, video, sensor readings, log data, etc. and rapid rate of data generation makes Big data very challenging technology. Vessels generally carry numerous sensors onboard. A significant source of uncertainty arises from the data transmission from these sensors. Each sensor necessitates a particular communication bandwidth, making it essential to provide suitable data communication for each sensor to relay its information to the database. The speed of data transfer can be enhanced through advanced communication systems [9].

B. Cybersecurity and Data Protection Issues

Addressing the safety and security of data networks and information management is a critical concern for any IT system. Protecting these systems from external threats like piracy, malware, and terrorist activities will be essential for the future of shipping. Cybersecurity will be crucial for any marine operation to ensure maritime security remains intact. A cyber-attack on the sensor network could disrupt the entire system and potentially lead to substantial financial losses for the business [9].

Information will flow among various parties due to differing interests. It is likely that sensitive information will need to be shared externally, making security and privacy essential for safeguarding data and ensuring its quality [9]. Ports operate under different international regulations, requiring careful data handling and compliance.

C. Integration of Data

The existing data collection methods in the marine sector are frequently inconsistent and can lack reliability. To perform analysis, data from various sources must be combined. For instance, fuel use, GPS information, and engine statistics must be merged to assess the vessel's performance [9]. Port handles data from multiple sources like ships, port equipment, port community system, logistics companies, customs, rail carriers, trucking companies, freight stations, consignees, weather agencies, security agencies, making integration complex. By creating an interconnected integrated system of good transport infrastructure for all types of transport and cargo owners and also a unified information environment of technological interaction of various modes of transport and participants transport process for a modern distribution network will be better solution [11].

D. Ownership of Data

The Possessing ownership enables the ability to access data for reading, creating, updating, and deleting records in databases, in addition to facilitating traceability throughout the data's lifecycle. The shipping sector relies on a complicated supply chain that involves various stakeholders such as ship owners, operators, customers, port authorities, and Classification Societies. Ship operators will possess access to the comprehensive set of machine data, while Classification Societies will require access to information for safety or classification reasons. Port state authorities will need access to details about cargo and personnel. The ownership of data is vital to the shipping sector, and it is expected that ship operators will face increasing difficulties in distributing data ownership and determining the level of authority in the future [9].

E. Standardization

The sector must progress by embracing big data analytics to uncover the latent characteristics and advantages of the data at its disposal. The shipping sector will have to foster a culture and consciousness among stakeholders to embrace innovative technologies, tools, and processes, as well as to establish regulatory standards [9]. Data exchange standardisation like EDIFACT – Electronic Data Interchange for Administration, Commerce, Transport is a bigger step in this path.

F. Social Factor

Enhancing the connectivity between onboard crew and shore staff in shipping firms will become increasingly crucial. In the future, the volume of data exchanged between vessels and shore facilities, as well as from shore to vessels, will rise to promote maximum operational efficiency and safety. Both ship and shore teams will need to receive further training to ensure effective support for this system [9]. One of the initiative in this direction is Cold Ironing or Shore Power wherein electricity is supplied to ship while it is docked at a port. This can avoid the running of onboard generators while in port reduction in emissions, fossil fuel consumptions and noise pollution.

II. Port Performance Indicators

Port Performance logistics encompasses a diverse array of tasks, including the positioning of containers within the yard, the loading and unloading of cargo between vessels and the yard, storage and transportation operations, and customs clearance [12]. In order to reduce transportation costs and enhance economies of scale, the size of vessels is increasing. This trend presents challenges for terminals in terms of accommodating larger vessels and heightens the risks associated with the supply chain [13].

Ports offer a range of services for vessels, cargo, and inland transportation. The level of satisfaction experienced by shippers reflects the performance level of the port. Consequently, ports must deliver highly satisfactory services to vessel operators while also providing optimal infrastructure suited to the specific types of vessels and specific cargos like refrigerated, Hazardous, Over Dimensional they have to manage. Therefore, evaluating port performance requires a set of metrics that pertain to the duration of vessels' stay at the port, the efficiency of loading and unloading cargo, and the quality of storage and inland transportation [14]. There is a significant interconnection between these metrics and various indicators of port performance. Analysis indicates that the quantity of vessels processed and the output per crane during each shift are highly significant [15]. Both the supply and demand side needs to be considered, which creating strategies for a positive port performance influence [16][17]. The increasing digitization, along with improvements in information gathering, diagnostic skills, and predictive capabilities, indicate a larger role for data analytics in shaping container port strategy and enhancing performance [18]

A. Traffic at Port

Traffic at Port means the goods or cargo transported typically for commercial purposes by ships or other transportation methods. The amount of cargo processed within certain time frame at the port serves as a crucial metric, indicating the productivity level of the port. As the port must offer various facilities based on the type of cargo being managed, this also shows how effectively the port's resources are being utilized. The cargo handled within a specific time frame consists of the total amount loaded, unloaded, and transshipped cargo during that defined duration [15].

B. Loading and Unloading Products

Stevedoring operations at the port necessitate monitoring of safety, safety motivation, and safety performance, all of which are enhanced by vigilant safety management oversight. Key concerns include the effects of stevedoring on both employees and service users, work organization, and evaluating the consequences of its performance. Research findings indicate that enhancements in infrastructure at Mombasa Port, Kenya, have boosted the productivity of port operations, suggesting that improving the efficiency of the loading and unloading processes can help reduce a ship's budgetary expenses [19]. Additionally, the results demonstrate that containers weight has a notable adverse effect on the loading and unloading of products, while simultaneously having a significant positive influence on loading and unloading productivity. A study performed in Australia verified that the commencement of stevedoring activities was driven by organizational factors such as workplace distrust, high levels of individualism, and insufficient resources [20] [21].

C. Service Performance at Port

The performance of port services, can be assessed through the lenses of technical efficiency, cost efficiency, and effectiveness by measuring the actual port throughput against the theoretically optimal throughput that is both technically and economically viable. The performance of port services is not uniform and may fluctuate over time, as the evaluation of each port manager's performance can vary significantly. According to the theoretical framework of service performance, port service performance is defined as a thorough evaluation by customers of the perceived outcomes they experience when utilizing services from providers, enabling more precise service delivery. The five dimensions utilized to gauge service performance are: 1) Time, 2) Accessibility, 3) Completeness, 4) Courtesy, and 5) Responsiveness [20] [22] [23].

D. Safety

Occupational Safety and Health (OSH) aims to ensure safety and security against the potential risks of accidents and hazards that can affect workers, companies, communities, and the environment. Regular monitoring, inspection, and assessment of health and safety protocols are crucial for improving and controlling risks to ensure the occupational health of port workers. According to the theoretical framework, OSH is understood as an initiative to establish protection and security against any accident risks affecting workers, companies, communities, and the environment, including physical, mental, and emotional aspects. The OSH variable is comprised of five key dimensions: (1) the state of the work environment; (2) the usage of work equipment; (3) air conditioning; (4) the physical health of employees; and (5) lighting and its arrangement [20] [24].

III. Use of Big Data in Port Performance

It is recognized that Big Data, combined with appropriate business strategies, can significantly influence port performance. Research indicates that Big Data has a beneficial impact on port efficiency. There exists a direct correlation between port indicators and Big Data with regard to port performance. Ports aiming to enhance their performance should leverage Big Data analytics [25].

A. Handling Cargo

Through the use of big data analysis, new opportunities are arising to enhance cargo handling efficiency within the maritime industry. The sector positions itself as a leader in applying technology for operational excellence, with ships navigating the seas informed by data. In this era of intelligent logistics, cargo handling transcends its traditional role; it becomes a fundamental element of the maritime sector as data-driven insights pave the way for future scenarios where efficiency, sustainability, and competitiveness are prominently showcased across our ocean's landscape. Enhanced big data analysis provides ports with intelligence that reveals cargo arrival schedules and vessel utilization, allowing ports to function at maximum capacity, thus preventing congestion and expediting cargo handling processes with precision [26]. A port can lower these time-related expenses by minimizing the duration that the cargo of shippers and the ships and vehicles of carriers spend in port, which means enhancing the quality of its service [27]. Thus minimising the turnaround time of the ship, connecting rails, vehicles and thereby cargo is the primary objective of the todays port. A shorter berth occupancy or shorter overall turnaround time of ship allows ports to handle more ships within a given period, which reflects in increased cargo throughput and better overall port efficiency. It also directly reduces the waiting time of the incoming ships by freeing up the berth, and reduces the operational cost of the ships. A study shows that Terminal Operating system-TOS are designed to control the terminal operations, the system cannot provide multiple parameters to evaluate and analysis of many performance indicators [28].

The role of information technology is crucial for the swift and precise movement and handling of vast amounts of data within global transport companies and port authorities. Effectively managing the systems that handle this information and relay it to those overseeing port operations is essential for smooth transportation. This highlights the importance placed on container-tracking systems among the key operational software utilized in ports [29].

B. Dynamic traffic update

It is real time information about the movement and location of the ships. This information particularly in the vicinity of the port is very crucial for Port authorities. They will be able to utilize ship data for managing ship traffic and safe movement near port area. Data-driven applications known as intelligent traffic management systems will be implemented in the shipping sector. Information regarding the ship's current location, cargo, and crew will be communicated to the port, allowing authorities to track congestion and enhance cargo handling efficiency [26]. Mobile app can be designed for travelers, improving their travel experience. Enhanced visibility of tugboats (in person) at ports. Delivery of information regarding traffic conditions and obstacles on routes to ports [30]. The data gathered from the automatic identification system not only allows vessel traffic service control staff to analyze in real-time whether an incoming vessel's behavior is abnormal at any given moment but can also be utilized to develop a traffic flow operating model for the port [31].

Port state control (PSC) inspection data, which is evaluated for compliance of ship with safety and security regulations in European countries and cruise related activities mostly in south American countries, also creates huge amount of data [32][33]. IMF also emphasis on the requirement to generate a real-time worldwide indicator of trade statistics with comparability across countries [34]. Big Data techniques can be used to monitor vessels in real time and analyze ship performance with cost reduction and environmental benefits [35].

C. Efficiency of Operations

Examining big data enhances operational efficiency by enabling real-time monitoring of performance. Ships fitted with intelligent sensors and IoT devices send continuous data to stakeholders, providing immediate insights into engine performance, fuel usage, and overall operational condition. This approach minimizes downtime and facilitates prompt decision-making to implement necessary changes in course [26]. To optimize data gathering and management, it is essential to incorporate all relevant participants and stakeholders related to the port, including various public and private entities [36]. IoT technology provides smart solutions to storage and monitoring of port data [37]. IoT sensors like RFID attached to containers allow for precise tracking of their location within the port which helps in real time tracking of containers resulting in faster loading, unloading and import delivery operations also. Nowadays, cranes with IoT can be controlled automatically, results in optimization of efficiency in container stacking and handling. Port equipment like cranes, reach stackers and trucks can monitor be monitored using sensors fitted on them to predict potential failures which helps in preventative maintenance. Sensors can be used to monitor parameters like temperature, pressure, vibration, and environmental conditions. Wireless communications like walkie-talkies are used for effective communication between personnel deployed at various port locations like berth, yard, rail, control tower, etc. for smooth operations. Collecting and analyzing large amounts of data from IoT devices can be used to identify operational bottlenecks and to optimize workflows.

D. Customer Satisfaction

Customer satisfaction is closely associated with prompt deliveries. By utilizing big data analytics, companies can provide predictive arrival notifications through the examination of past data, weather patterns, and vessel efficiency. This forward-thinking strategy guarantees that customers obtain precise and timely updates regarding the arrival of their cargo, allowing for improved planning and reducing disruptions in their supply chain [26]. End users as customer expects movement of cargo with safety, less time and cost through the port area. Time events of containers, trucks, rails and ships can be recorded at every stages inside as well as outside the port area, through ship channels. Monitoring of these time events helps to predict the possible congestion of vehicles outside port area or pre-berthing waiting time of ships.

E. Supply Chain

The analysis of big data is advancing the port industry into a phase of real-time cargo monitoring. Ships outfitted with intelligent sensors and IoT Technology transmit live information, allowing stakeholders to effortlessly follow the movement of goods, reducing interruptions, and improving the efficiency of the entire supply chain [26] [38] [39]. Sensors like RFID are helpful in live visibility of location of the container or cargo throughout the journey from port area to end points and supply chain thus can be managed by identifying potential issues, avoiding traffic congestions, thus improving delivery time.

IV. Discussion

Many seaports are adopting various digital technologies to improve port operations and efficiency, which in turn benefits to entire logistic network involving other connecting modes like rail, trucks and ships. However, use of digital technologies like IoT sensors, automation and robotics generates huge amount of data in various formats. Storage, processing and analysis of such huge amount of data requires Big data and analytics. Though Big data contains many challenges, its benefits is the base of current informed decision making scenario.

Many seaports like Rotterdam, Singapore, Antwerp, Felixstowe, Hongkong have already implemented Big data analytics and the positive results indicate that Big Data significantly influences port performance in various ways like predictive analysis, real time data sharing, Risk management, efficiency, cost saving, Traffic management, Energy management, Predictive maintenance and most important decision making etc.

The study underlines that the critical interconnected components in seaports i.e. Man (Human resources), Machine (equipment, technology) and Material (cargo, goods) can be optimized using data driven insights. Thus Big data turn into valuable asset for ports. These results resemble with earlier research that has highlighted the advantages of big data within the port sector. However, this study offers perception in terms of safety and sustainability. A study by analyzing stakeholders' preferences and ranking of innovations by importance in the Adriatic region significantly focuses on Big data [40].

Involvement of multiple national agencies related to security and economy in port operations, there are certain limitations in data sharing. Several private seaport terminal operators often hesitate to share the data to maintain business confidentiality, competitive advantages and some regulatory compliances.

Big data analytics have been accepted in many seaports with particular objectives in certain operational areas. Future research could examine the effects of particular Big data technology implementation in all related agencies to the seaport and evaluate overall port performance with sustainability.

V. Conclusions

Digital transformation of different areas of port sector increases efficiency, productivity, turnaround time, safety and security. It also decreases paper documents and overall cost. Various types of IT solutions are implemented in seaports and related agencies. These IT solutions are essential to be integrated for improvement of performance of whole supply chain. It will also help in evaluation analysis and to compare port performances. Various initiatives of the government like landlord port model or One Nation One port process documentations, in Major ports will generate huge amount of structured and unstructured data. Landlord port model motivates the Port Authority to act as landlord i.e. to develop required infrastructure like berths, dedicated ports & rail tracks, etc and leasing out labor intensive cargo handling operations to private parties. Major ports have started implementation on government policy of One Nation One port process documentations which provides standardized list of documents involved in port processes like ship profile registration, vessel call number generation, pre-arrival notification of security, payment of vessel and cargo related charges to port authority, berth applications, sharing of bay plans for containerized cargo, Truck gate in-out reports, Rail in-out reports, stuffing and destuffing of cargo, etc. Exchange of such documents in digital formats will also generate unstructured data. Ports being connecting node in the supply chain are very complex and dynamic environment which handles millions tons of cargo every year. They also face many challenges like storms, high winds, road congestions, delays, security, accidents, safety, involvement of different agencies and competition. To defeat these barriers, port sector needs the power of Big data and analytics. Integration of real time data analytics with other IT solutions will assist to port sector to real time cargo/container tracking, streamlining logistics, monitoring key performance indicators, identify & address bottlenecks. It will also support, to government planning authorities to analysis cargo flow at micro level and to take informed decisions, which affects in case of agriculture products like onion, edible oil, petroleum products and other essential commodities. Finally, customer who sends or receives the cargo gets benefitted by lower transport time and cost.

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