JOURNAL OF EMERGING TECHNOLOGY AND DIGITAL TRANSFORMATION

ONLINE ISSN 3006-9726

PRINT ISSN 3006-9718

VOLUME. 5 ISSUE 01 (2026)

Smart Shipbuilding: Integrating Lean Tools with Industry 4.0 for Agile High-Performance Production

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Abstract:

Shipbuilders around the world continue to face significant challenges stemming from prolonged lead times, delayed work orders, and high defect rates in processes such as block fabrication, outfitting, painting, and electrical works. These issues are largely attributed to outdated practices in design, planning, quality control, and resource utilization, many of which have remained unchanged for decades. While lean manufacturing has been successfully adopted in various industries, its implementation in shipbuilding remains limited due to the perception that lean tools are exclusive to automotive production systems, such as the Toyota Production System (TPS). Proposed study offers an advanced integrated methodology that combines lean tools, quality management systems (QMS), and Industry 4.0 technologies to improve operational efficiency in the shipbuilding industry. The proposed model demonstrates enhanced responsiveness, flexibility, and performance, where comparative analysis proves its effectiveness before and after implementation, confirming measurable improvements in productivity and defect reduction, supporting its applicability for modernization across the shipbuilding sector.

Key Words: *Shipbuilding, Integration of Lean and Industry 4.0, Reliability and Quality, Continuous Improvement.*

ONLINE ISSN
3006-9726
PRINT ISSN
3006-9718
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1. Introduction

Since the inception of shipyards around the world are continuously striving for benchmark solutions and standardization to stay competitive. In the shipbuilding industry, continuous improvement has been achieved through the adoption of new technologies and organizational restructuring. However, current challenges in the industry include production efficiency, quality, ship safety, cost efficiency, zero wastages, and environmental sustainability. To address these challenges and create new value, the concept of Shipbuilding 4.0 has emerged by adopting the new industrial revolution in the shipbuilding sector and analyzing the transformations in various aspects of the shipbuilding industry. The challenge for researchers is to deliberate the main problem with the shipbuilding industry, which has excess waste, undue delays, major and minor defects, improper planning, improper handling of man, machine, and material. Factors such as resource scarcity, rising labor and material costs, environmental concerns, and a slowdown in foreign direct investment and export growth necessitate a re-evaluation of manufacturing strategies. In light of the global trend of reindustrialization and Germany's "Industry 4.0" initiative, the Chinese government introduced the "Made-in-China 2025" Plan in May 2015 as a strategic response to drive technological advancements and innovation in the manufacturing sector[1]. Through this drive, China succeeded to achieve the target "Made-in-China 2025" by digitalization with industry 4.0 from the food chain to heavy discrete manufacturing. Thus, it is very important to illustrate the possible ways of combining the performance paradigms that lead to their implementation[2], which resulted in minimized work order delays, reduced defects, elimination of breakdowns, improved quality & overall performance.

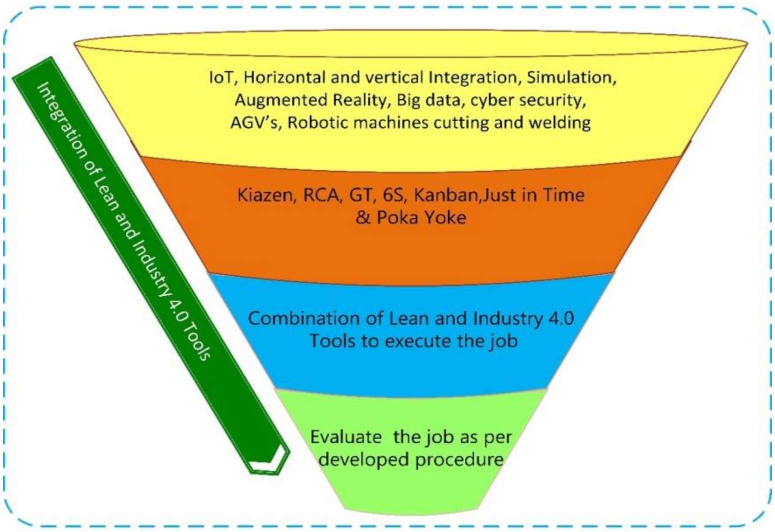

Fig.1. 1. Proposed Integrated tools of lean and Industry 4.0 for Shipbuilding

This study has focused on the proposed integrated model and its implementation, where the results are compared with previous traditional management systems. Traditional models

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3006-9726
PRINT ISSN
3006-9718
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increase the extra paperwork for unnecessary documentation and continual improvement. This results in helping to gather the data base. Realizing the fact of digital technology transformation of the shipbuilding industry, it is very difficult to identify how & when the activities and tools are combined [3] to be competitive and to overcome traditional problems such as production lead time delays and late work order completion, higher defect rates in block fabrication, machinery outfit, paints, and electrical works. As the maturity of the integrating models is not yet standardized, only a few studies mixed up the lean tools[4] with Industry 4.0. Lean Enterprise Self-assessment Tool (LESAT) indicates the lean manufacturing operational level maturity[5]. An exploration was conducted to examine the advantages, challenges, and critical factors for the integration, with particular emphasis on environmental, social, and operational aspects. The integration yielded diverse operational advantages pertaining to lead time, throughput, and quality[6]. Further, implementation of Shipbuilding 4.0 offers the potential for creating new value, reducing production and operational costs, and improving production efficiency in the shipbuilding process[7]. There is an acute need to introduce a novel revolutionary model which will change the situation with its integration. Lean manufacturing and Industry 4.0 need to be integrated with a quality management system and with traditional.

2. Background

2.1.Shipbuilding Industry Revolution

The history of Lean Manufacturing mainly focuses on the elimination of waste within the process and streamlining the processes. The same technique was used by researchers in the literature review over the last three decades [8]. The term 'lean' was first introduced on the basis of the philosophy 'The Machine that Changed the World', which reported the production practices adopted by Toyota Motor Corporation, where the Toyota Production System (TPS) improved performance by eliminating waste as originated through the three Japanese concepts Muda, Mura, and Muri[9].

Lean production is characterized as a "waste-free production system" [10]where everything is waste except the essentials, such as simply man, machine, and material[11]. Lean production signifies a hypothetical structure that employs established principles and methodologies, namely the development of cross-functional teams, the elimination of non-value added activities, and the integration of suppliers to optimize production [12] and also to enhance technology and innovation[13]. In addition to that, it optimizes efficiency and minimizes inventory, which means a fast-paced, technology-driven leading system, which combines with supply chain management, and it requires industry 4.0 integration with lean to improve the process and reduce the lead time [14]. Whereas Industry 4.0 represents a progressive advancement beyond Computer Integrated Manufacturing (CIM), and presents itself as a network-oriented approach that synergistically complements CIM with Information and Communication Technology (ICT)[15]. After the abrupt conclusion of the Computer Integrated Manufacturing (CIM) era, which was characterized by its unmanageable complexity in automation technology, the Lean approach emerged triumphant by offering remarkable efficiency gains through complexity reduction and elimination of non-value-

ONLINE ISSN
3006-9726
PRINT ISSN
3006-9718
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adding processes. At present, the concept of Industry 4.0 embodies a visionary perspective of future manufacturing[16]. Since the last decade, Shipyards have been Quality Management System (QMS) shipbuilding industry ISO 9001:2015 certified, but it has lost international competitiveness due to delay, excess utilization of manhours and rework in comparison to its regional competitors, namely India, South Korea, and Bangladesh[17]. Shipbuilders prefer the lean principles, but there are certain constraints to implementation of lean, such as layout and supply chain design, process design technology, and inventory management [18]. But some Shipyards after the implementation of lean manufacturing philosophy, like the USA, Norway, Japan, and China, have minimized labor expenses and shortened production timelines [19] in order to thrive and enhance their competitive edge from steel cutting to ship launching [20]. Competitive shipbuilders simply minimize wastes such as rework, overprocessing, underutilization of resources, planning, transportation, lead, and setup time [21]. Shipbuilding has many packages and dossiers, which are subdivided based on the shipbuilding operations. The task package's scheduling strategy is developed with the constraints of resources and personnel at the production site in mind [22]. A novel integration methodology based on Industry 4.0 and earlier Lean system tools is proposed as a fit-in solution to address man, machine, and production problems in this study [23]. It has the potential to transform the shipbuilding industry by enabling shipyards to optimize their operations and gain a competitive advantage.

2.2.Limitations of Adopting Technology

The complexity of discrete manufacturing in the construction of large, medium, and small-sized vessels, tugboats, and ferries is extremely difficult to manage. Every product has its own set of Jigs and Fixtures, as well as different workmanship and handling processes, so lean maturity is critical [24]. Shipyards have an outdated layout to create a modular workshop or cellular manufacturing in which there is a constant flow of basic and intermediate products, which are assembled in most cases on moving lines. Currently, old machines are not found suitable for atomization based IoT. Furthermore, because the movement of gantry cranes and overhead cranes is static and is based on predefined routes, positional jobs are difficult to manage, and thus fully automation may not be incorporated into the system based on lean and Industry 4.0 [25]. Furthermore, many problems cannot be simulated using database simulation software[26]. The modular nature, adaptability, and nimbleness of intelligent manufacturing facilities are coupled with the customization aspect of digitalization in the Industry 4.0 era to accelerate product lifecycles and to hasten the rapid obsolescence of goods and services. This undesirable environmental situation can result in heightened energy and resource requirements, and ultimately can lead to an increase in waste generation. With the advancement of digital technologies and the global population's rapid growth, there is a continuous rise in the demand for raw materials and energy, which may counterbalance the efficiency benefits of digitization[27].

2.3.Significance of Integration

The lean system includes activities such as supply, design, and manufacturing focus on value stream mapping, flow, and workforce capabilities. Lean implementation reduces delays,

ONLINE ISSN 3006-9726
PRINT ISSN 3006-9718
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defects, rework, machine downtime, process failures, and result in higher output per man-hour, quality, and improved performance and customer satisfaction [28]. The goal of lean manufacturing and Industry 4.0 integration is to improve product cycle time, cost competitiveness, and quality. The interdependence and interconnectedness of Industry 4.0 do not pose a constraint, as these conditions foster the interoperability aspect of Industry 4.0 and facilitate the transformation of the customer-manufacturer-supplier relationship. With the development of the Internet of Things (IoT), customers can actively participate in decisions regarding product quality and customization[29]. Finally to meet the ever-growing demand for shipbuilding products, intensified competition, and a greater focus on prompt and adaptable service, organizations are being compelled to embark on a journey of digitalization and embrace service-oriented frameworks[30]. It explores the relationship between Industry 4.0 and lean manufacturing to examine the feasibility of implementing lean principles within Industry 4.0. Implementing Industry 4.0 entails high costs but reduced waste and other perceived benefits[31].

2.4.Motivation of Research

The goal of current research is to reduce unnecessary waste by utilizing lean and Industry 4.0 tools and to investigate the results on basis of a novel proposed model that contributes to knowledge-based and potential integration achievement. Because this methodology is not yet mature, most shipbuilders have a pessimistic approach to improvement; however, positive results from the case study will lead to optimistic thinking and will undoubtedly change the opinion of traditional shipbuilders seeking to improve competitiveness across the board, from manpower to production. The adoption of Lean principles is expected to result in a 40% cost reduction within 5 to 10 years of implementation[7]. The proposed model has excellent results before and after the implementations.

3. Methodology

The methodology for implementing lean principles and practices in shipbuilding have certain limitations in shipbuilding that can be gradually upgraded to turn them into opportunities. The job shop floor layout needs to be improved, and parallel line productions with the help of automation and semi-automation based on robotic welding. Jigs and Fixtures are critical and differ for one another project and are based on the size of ships, but flexible jigs and fixtures can be identified to reduce the lead time with alternative solutions, such as quick replacement of flexibility and movements. The shipbuilding industry can move closer to an integrated model by taking the commanding steps as shown in Fig 3.1. The integrated model is based on procedures, work instructions, form generation, and data analysis.

3.1.Integration of the Lean System with Industry 4.0

The proposed model has an initial state where all the shipbuilding operation are taken place as per the assigned schedule, which is based on quality system procedures and methods. It evaluates the quality records to identify the gaps in order to narrow down the gap between both practices. All the waste activities are identified and eliminated by implementing the

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"Transition State Level-I". In this state, lean manufacturing tools reduce defects, delays, reworks and enhance production performance with quality.

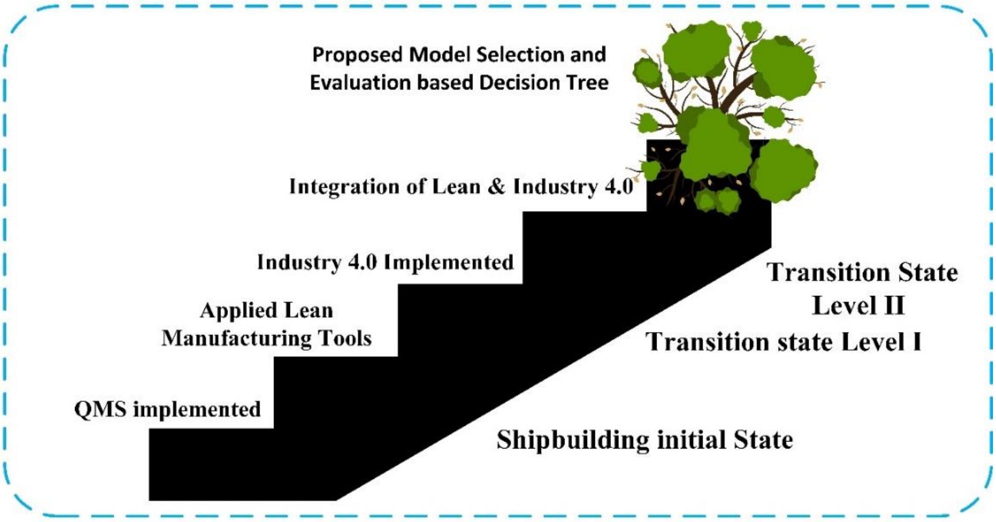

Fig. 3.1. Proposed steps towards the Decision Tree for Integrated model

3.1.1. Implementation of Lean Tools

Lean manufacturing comprises the following stages for the visualization control tools of lean philosophy:

I. **6-S:** The 6-S method combines the 5S (sorting, straightening, shining, standardizing, and sustaining) with safety to organize, clean, develop, and sustain a productive environment. It represents workplace practices, which are amenable to visual controls and the Sixth 'S', which stands for 'Safety'.

II. **Poka-Yoke:** It is an error-proofing method where defects in the production process are detected at developing fail-safe systems via self-check to reduce human error and machine defects to develop a foolproof system. Quality Management System (QMS) tools are very important for taking the Corrective and Preventive Actions (CAPA), which are based on the PDCA cycle, and these help to improve the organization's manufacturing process by eliminating causes of nonconformities and other undesirable situations for every process during product realization.

III. **Just in Time and Kanban:** This method of lean controls materials in and out for product realization. A supermarket store was developed on a Kanban and Just-in-Time basis with suppliers, which is further linked with Industry 4.0. Implementation of Just in Time philosophy is important because it eliminates redundant capacity (or inventory), eliminates non-value-added processes in operations, and improves flow and responsiveness. A mechanism that organizes resources, information flows, and

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3006-9726
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decision rules is utilized to enable an organization to realize the benefits of JIT principles using inventory supplier cloud data based on Industry 4.0.

IV. **Kaizen:** This tool develops a strong bond between the managers, engineers, supervisor, technician, and workers. Three-tier Kaizen teams are developed, such as Kaizen-M, Kaizen-E, & Kaizen-S and it comprises of top level management, a medium-level technical Optimization team of engineers, and a bottom-level team of supervisor implementers, respectively, for identifying problematic areas for improvement and elimination of waste by involving all the employees in problem-solving and decision-making for continuous improvement with quality and productivity.

V. **RCA:** Root Cause Analysis technique is used to identify the main cause from the process, machine, man, environment, or any other relation with the product realization. Three RCA models were used, such as fault tree diagnosis, 5-why method, and fishbone diagram, to address the problems and other nonconformances in order to identify the source of the problem.

VI. **Group Technology:** Group Technology (GT) works robustly because it implies the classification of parts and components into groups based on their similarities in design, shape, size, and function in the line and modular pattern. It helps to optimize production processes by reducing setup time, minimizing inventory, and increasing production flexibility. After the production flow analysis, the part codes are assigned to each manufacturing job, and work orders are developed by using coding and classification techniques. The coding technique assigns a unique code to each part or component based on its design and manufacturing specifications. The classification technique groups parts and components with similar codes into families. This classification can be done by using hierarchical clustering and fuzzy clustering. As parts and components are classified into families, the production process can be optimized using various techniques such as modular manufacturing and group scheduling. Parts and components in the same family are produced in a dedicated workshop, which reduces the need for transportation and handling, which results in reduced setup time and increased productivity.

3.1.2. Implementation of Industry 4.0 Tools

It is important to choose all the areas of shipbuilding for implementation of the Industry 4.0 tools such as IoT, Horizontal and vertical Integration, Simulation, Augmented Reality, Big data, Cyber Security, AGVs, Robotic machines, cutting, and robotic welding. There are three phases of implementation of Industry 4.0, which are shown in Fig. 3.2. In this phase-I problem is illustrated, and the implementation goals are identified. This phase involves the introduction of the shipyard facilities, processes, material, and information flow for the detailed definition of the goals and deadlines. Lean principles have extended towards robotic process automation, virtual and augmented reality, virtual modelling and simulation, 3D modelling, digital twin, additive manufacturing, big data and analytics, ubiquitous connectivity and the Internet of Things (IoT), secure cloud, cyber security, health, safety, and environment, new materials, artificial intelligence, autonomous vehicles.

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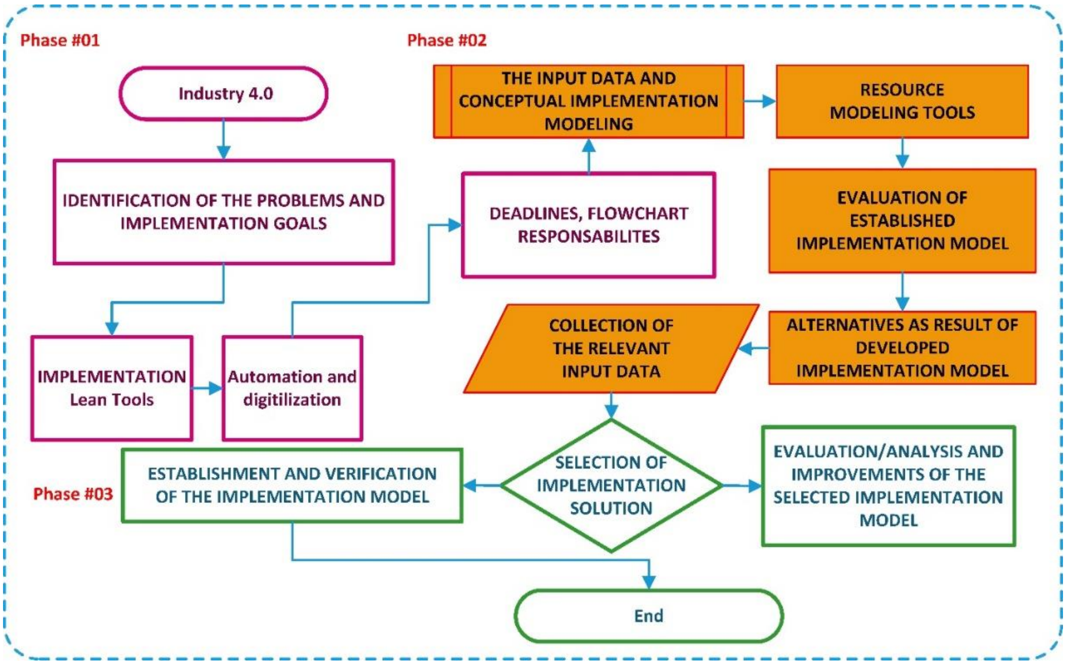

Fig. 3.2. Three Phase proposed Implementation model for shipbuilding Industry 4.0.

Hence, the first step clearly define the previous problems and their causes in the current shipyard production process that needs improvement. To achieve this, the shipyard should prepare and establish necessary shipbuilding standards for the safe flow of information and data, followed by the creation of a Value Stream Mapping of the production process to reduce nonvalue-added activities by implementing Lean tools. This will help to develop flow charts that outline responsibilities and deadlines for each process.

The second phase involves processing the input data gained in modelling tools for implementation to manage resources with higher productivity in less time and increased satisfaction. The finalized model for implementation is based on future data that considers different types of production. The third phase is crucial, and it involves raising the knowledge and skills of employees to work in the digitized shipbuilding industry. Here it is important to take a decision if the established model works as per the desired goals, then the process ends, and if the model evaluation fails to satisfy the goals during evaluation, then it requires restarting the process for its implementation. The Industry 4.0 model requires excellent IT skills and overall networking and digital connectivity throughout the shipbuilding process, from design, purchasing, planning, financing, and production, using wireless technologies. In the interconnected integrated shipyard, the timely and secure exchange of information is central.

3.2.Hypothesis

A closer examination of the data, it was found that although six out of seven areas; had improved, the value-added time in days had not shown any improvement. This led the author

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to investigate further and question whether the implementation of single-piece flow had resulted in significant improvement. To test this hypothesis, it is decided to use the t-distribution test method, based on a small number of samples (less than 30). The following formula is used for the t-test are applied.

$$t = \frac{\bar{x}\sqrt{n}}{s}$$

Where $\bar{x}$ is the mean difference, $, s =$ the standard deviation and $n =$ the number of parameters measured.

The equation of standard deviation in this case is as:

$$s = \sqrt{\frac{\sum x^2 - n(\bar{x})^2}{n-1}}$$

After Integration into three phased methodology lean flow process is validated.

4. Results:

4.1.Data Collection and Data Analysis

The data were collected from the department of Planning, shipbuilding workshops and Quality Assurance, which includes job cards, work orders, inspection, and defect reports of the shipbuilding industry. The sample data was collected before implementation by means of an old dossier of the same blocks of Tugboat, and after the implementation of the integrated revolutionary tools of lean with Industry 4.0, it was compiled for analysis before and after to validate the results of implementation. The features of data were extracted from Quality management system formats and reports, i.e., Work Order Sheets (WOS), Request for Inspections form, Material Inspection Report, work order schedules, Daily Manpower strength report, Safety, quality & maintenance report & Machine Performance Utilization Report.

4.2.Lean Flow Implementation Results

A single section of the shipbuilding block cycle time domain data was extracted as shown in the Table. 4. 1. where traditional shipbuilding data and lean implementation data are compared for analysis.

Table. 4. 2. A single block feature extraction

Parameters	Traditional Shipbuilding (SHB)	Integrated Revolutionizing SHB

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Parameters	Traditional Shipbuilding (SHB)	Integrated Revolutionizing SHB
Value added Time(hrs)	360 hrs	360 hrs
Mandatory Non-value added time (hrs)	480 hrs	192 hrs
Untainted non-value added wait time (hrs)	1488 hrs	72 hrs
Lead Time (hrs)	1608 hrs	624 hrs
Job cards paper work (ft)	31 units (30744)	11 units (1100)
Handoffs	58	10
Number of process routes	70	23

After the extraction of data, it is analyzed that value added time is the same for both cases. However, mandatory non-value-added time, untainted non-value-added wait time, and lead time are reduced before and after the implementation. Similarly, job card paper, handoffs, and the number of process routes are decreased, which are shown in the table. 4.1.

4.3.Statistical Hypothesis Analysis

The statistical data further organized to verify the claim hypothetically by using the statistical tools as reflected in the Table. 4. 3.

Table. 4. 4. Statistical tools apply on the data Setting

Parameters	Statistical data used for the hypothesis traditional vs Integrated Revolutionizing SHB	
Limits	Difference both $\bar{x}$	$\bar{x}^2$
Value added Time (hrs)	0	0
Mandatory Non-value added time (hrs)	288	82,944
Untainted non-value added wait time (hrs)	1416	2005056
Lead Time (hrs)	984	968256
Job cards paper work (ft)	20	400
Handoffs	48	2304
Number of process routes	47	2209
Total	$\sum 2803$	$\sum 3061169$

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3006-9726
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The data was converted from hrs to days, the difference $\sum \bar{x} = 227$ & $\sum \bar{x}^2 = 10219$

$$\bar{x} = \frac{\sum \bar{x}}{n} \approx \frac{227}{7} = 32.4$$

$$s = \sqrt{\frac{\sum x^2 - n(\bar{x})^2}{n-1}} \;, = \sqrt{\frac{10219 - 7(32.4)^2}{7-1}} = 21.8$$

$t = \frac{\bar{x}\sqrt{n}}{s}, = \frac{32.4\sqrt{7}}{21.8}$ =3.9

The reliability of the model is further validated by incorporating the proposed integrated model data, which satisfies the requirement of optimization, as shown in the Fig.4.1.

The results of the statistical analysis indicate that the implementation of the integrated revolutionizing shipbuilding one-piece flow process in shipbuilding has a significant effect. The calculated t-value of 3.931 is greater than the standard reference table value of 2.447 at a 5% level, which leads to the rejection of the null hypothesis. This indicates that there is a significant difference in resulting scores before and after the implementation of the Integrated Revolutionizing Shipbuilding one-piece flow process. Additionally, the calculated t-value of 3.931 was higher than the value of 3.3707 at a 1% level, which means that the results are highly significant.

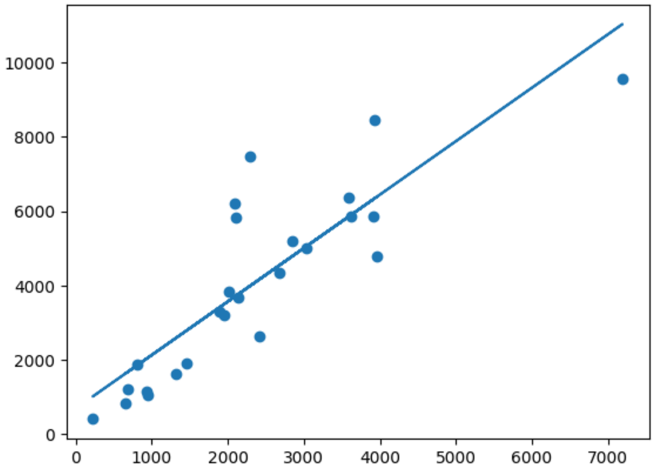

Fig.4.1. Reliability of proposed integrated model based on standard and observed data.

4.4.Work order delays before and after integration of the proposed model

The selection of Lean System tools with integrated implementation of Industry 4.0 has resulted in reduced man-hours, minimized delays, minimized reworks, minimized unnecessary motion and less idle manpower.

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Fig.4.2. Project Compression before and after integration of the proposed integrated model

The above data is reflected in Fig.4.2, where different WOS sheets were analyzed, where the blue line block indicates completion in the traditional shipyard, and the orange line indicates that the reduction is about 26% percentage in tugboat completion. A linear regression model, based on planned vs. actual man hours, was applied. This support model claim further results standard man-hours plotted with a straight line and scattered dotted solid circles reflect the actual linearity of the model. The pattern is shown in Fig.4.1. As a result, the model indicated that with the greater use of lean and Industry 4.0 tools, there is a greater increase in production.

4.5.Product Manufacturing Defects before and after integration of the proposed model

The data from Quality inspection reports analysis identified major and minor defects in production, consumed man-hours, and material before and after the implementation of revolutionary shipbuilding 4.0 tools. These categories include fabrication, painting, machinery outfit, and electrical defects and problems. Inspection reports perceived a high number of defective items primarily in the fabrication, welding, painting, and installation of various components in the traditional shipyard, as reflected in the Fig.4.2. The quality of blocks is greatly improved in fabrication up to 90.8%, in the painting 91.6%, machinery problems reduced up to 89.4%, and electrical problems minimized up to 80% percentage, respectively. Further, other value-added SHB production problematic areas are investigated, where it is visualized that there was underutilization of manpower, as indicated in the Daily Manpower

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3006-9726
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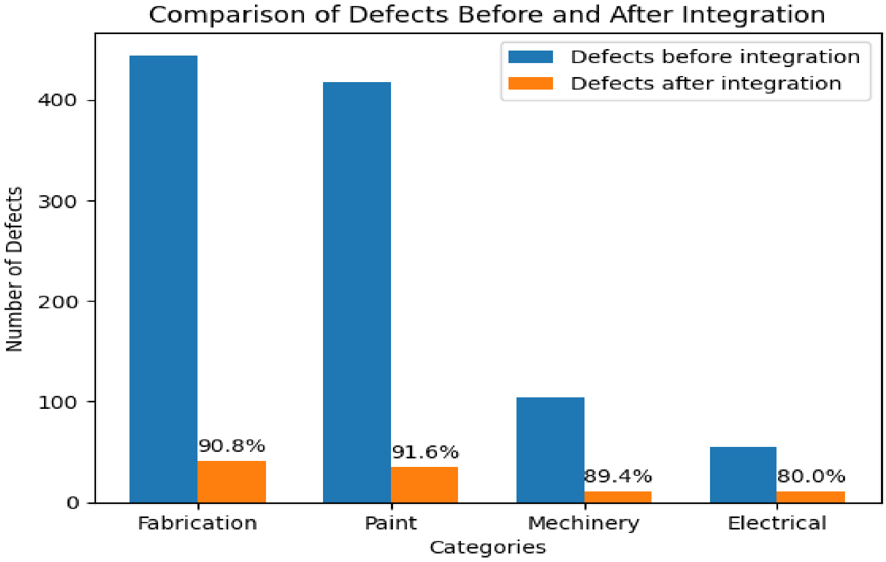

Fig.4.3. Optimization of defects elimination towards Zero defects before and after proposed integrated model.

strength report, with many workers not being effectively assigned or utilized on the shop floor. The SHB computing resources were also underutilized, and facilities were not utilized to their maximum advantage. These challenges can negatively impact SHB productivity and efficiency, and lead to increased costs and reduced profitability. Therefore, it is essential for the company to address these issues and find ways to improve its production process and better utilize its resources to stay competitive in the market.

4.6.Comparison of Problems Reduction Before and After Integration

Fig.4.4. presented in this study highlight the significant impact of production practices on reducing the number of problems in various sections. The findings indicate that the integration of a Lean System can lead to a substantial decrease in design problems by up to 66.7%, measurement problems by up to 66.7%, resource planning issues by up to 50%, materials problems by up to 77.8%, man power problems by up to 24%, work plan problems by up to 65.4%, duties and responsibilities problems by up to 65.5%, safety problems by up to 32.3%, maintenance problems by up to 45%, and method problems by up to 48%.

These results suggest that the implementation of a Lean system in shipyards can be considered as an effective solution to problems in various sections of the production process. The reduction in design problems by up to 66.7% can be attributed to the systematic approach of the Lean System, which emphasizes the importance of involving designers in the production process from the very beginning. This enables them to identify and resolve any potential design problems before they occur. Similarly, the reduction in measurement problems by up to 66.7% can be attributed to the implementation of standardized measurement techniques. The decrease in resource planning issues by up to 50% can be

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attributed to the implementation of a more efficient resource allocation system, which enables the use of the resources more effectively.

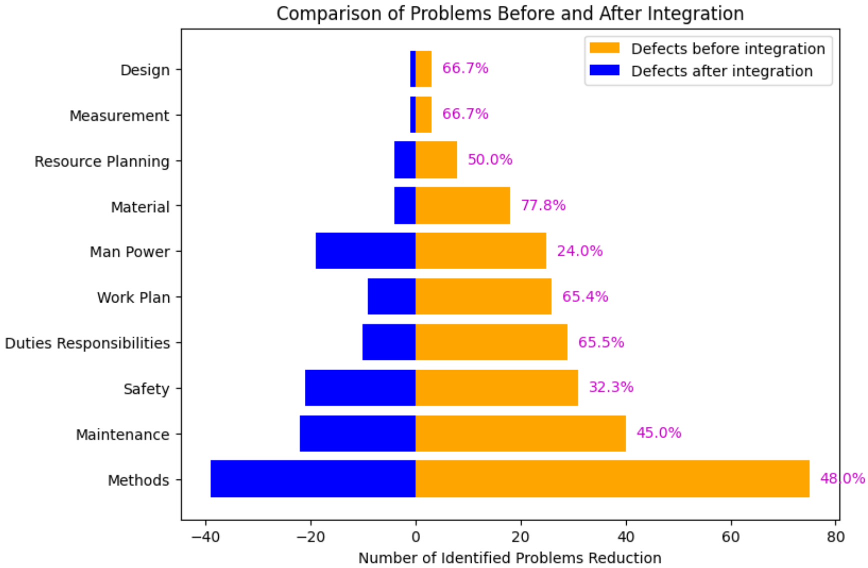

Fig.4.4. Problems reduction toward elimination before and after proposed integrated model.

The reduction in materials problems by up to 77.8% can be attributed to the implementation of a material control system, which ensures that the right materials are available at the right time and in the right quantity. The decrease in manpower problems by up to 24% can be attributed to the implementation of standardized work procedures, which minimize errors and ensure that the required manpower is available when needed. The reduction in work plan problems by up to 65.4% can be attributed to the implementation of a more efficient scheduling system, which enables shipyards to complete their work on time and within budget. The reduction in duties and responsibilities problems by up to 65.5% can be attributed to the implementation of a more structured system for assigning tasks and responsibilities, which ensures that everyone knows what they are supposed to do and when. The decrease in safety problems by up to 32.3% can be attributed to the implementation of a safety management system, which ensures that safety procedures are followed and that potential hazards are identified and addressed. The reduction in maintenance problems by up to 45% can be attributed to the implementation of a preventive maintenance programme, which helps to identify potential problems before they occur and to address them proactively. Finally, the reduction in method problems by up to 48% can be attributed to the implementation of standardized work procedures and the use of best practices, which ensure that the production process is optimized for maximum efficiency and effectiveness.

5. Theoretical, managerial, and practical contributions

The integrated model has linked the tools of lean manufacturing and Industry 4.0 with the processes from the start of customer enquiry to delivery of the product according to a quality management system on need basis to get maximum benefits. The table. 5.1. illustrates the

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combination of tools with QMS, with their ultimate result as achieved based on the case study. The research offers useful insights and practical implications.

Table. 5. 1. Shipbuilding Practices Linkages of Lean and Industry 4.0 tools with QMS

QMS	Lean	Industry 4.0	Outcome Results
Inventory	Kanban and Just in Time	Based on Real-Time Data, Use of Robotics and AVGs	It automatically generates the demand and replenishes the bins as empty
Inspection request (Surveyor and Customer)	Customer value activities and Checks	IoT	Automatically send a request and the time to avoid delays
PDCA for continual improvement	Kaizen	Big data digital twin	Analyze and Suggest solution
Schedule Maintenance	Preventive maintenance	PHM (Prognosis-based predictive maintenance)	Reliability and remaining useful based on prognosis suggest maintenance
Job Schedule and its realization	Elimination of waiting time through value stream mapping and SPT	Augmented Reality	Resource minimization to avoid idle man and machines.
Workshop based Job order	Group Technology	IoT and big data	Used to classify the parts and families to generate order.
Defect if observed, Corrective and Preventive actions (CAPA)	RCA	Big data and fault identification and solution generation through prognosis, simulation, & Augmented Reality.	The technique will minimize the defects, improve prevention controls, and decrease motion and inventory.
Process plan and workstations	Poka Yoke	IoT based Feedback, by vertical and horizontal integration	It improved visibility, flexibility, and speed of execution.
Job floor, Workshops, stores and offices standardization	5S + 1S (Safety)= 6S	Augmented Reality flexibility in time.	This resulted as flexibility in space and engagement of people with works and practices.

The study results in a comprehensive assessment of integration effects such as defect reduction, unnecessary motion reduction, machine downtime reduction, man-hours reduction, and delay avoidance. It also examines the sequence of application from inquiry to delivery,

ONLINE ISSN
3006-9726
PRINT ISSN
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and challenges the conventional approach of Lean by investigating the potential benefits of Industry 4.0. The integration identified success factors, barriers, and benefits, and allows managers to anticipate and resolve potential issues. Simulations are used to demonstrate improvements and gain leadership support, which is based on their engagement. It also reveals that teamwork between improvement and digitization teams can be encouraged to overcome integration barriers. Importantly, the study emphasizes that integrating Lean and Industry 4.0 relieves managers' concerns and facilitates decision-making. The integration also emphasizes the importance of training and digital literacy for future readiness, motivates HR departments to adapt hiring policies and develop appropriate training programs. The study shows how Industry 4.0 and Lean applications enable waste reduction by reducing repairs and ensuring cleanliness in accordance with 6S. It demonstrates how Industry 4.0 and Lean applications enable waste reduction by reducing repairs and ensuring cleanliness in accordance with 6S, more informed decision making, and resource consciousness. Simulations are used to demonstrate improvements and gain leadership support. Based on their engagement, teamwork between the improvement and digitization teams can be encouraged to overcome integration barriers. Importantly, the study emphasizes that integrating Lean and Industry 4.0 does not have to be expensive; it relieves managers' concerns and facilitates decision-making. The integration also emphasizes the importance of training and digital literacy for future readiness, motivates HR departments to adapt hiring policies and develop appropriate training programs. From an environmental standpoint, the study shows how Industry 4.0 and Lean applications enable waste reduction by reducing repairs and ensures cleanliness in accordance with 6S, more informed decision-making, and resource consciousness in manufacturing. It facilitates assessment of the environmental impact of machinery choices and leveraging Industry 4.0, and aligning production processes with environmental goals are examples of this. It emphasizes the interaction between Lean practices and digital tools. Socially, Lean and Industry 4.0 implementation necessitates improved communication between people and Industry 4.0 tools. It calls for governments and policymakers to support digital literacy training, infrastructure support, and upskilling initiatives, particularly for engineers. Academic institutions must also revise their programs in order to provide graduates with the necessary skills for Industry 4.0. Effective communication and interaction can be facilitated by user-friendly interfaces and tools. Unintended consequences and inefficiencies can result from failing to consider these interrelationships. To ensure its effective application, businesses must analyze the impact of each aspect. It provides insights into success factors, barriers, and benefits, assisting managers in making decisions. It also emphasizes the environmental, technological, and social implications of integration, promoting sustainability and readiness for the Industry 4.0 era.

6. Conclusions

This study examined the changes that Industry 4.0 has brought to the shipbuilding industry worldwide and presented a methodology for implementing the Shipyard 4.0 model in a Croatian case study shipyard. The study reveals that the incorporation of Industry 4.0, with the utilization of Lean System tools, plays a critical role in improvement of efficiency,

ONLINE ISSN
3006-9726
PRINT ISSN
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reduction of costs, and increase in productivity. The adoption of 5S can bring improvement in organization appearance because of sustainability and standardization. It has the potential to produce high-quality products with minimum losses and improved production, and can lead to greater customer satisfaction and increased profitability, reduced delays, defects, and reworks, improved inventory handling, optimal space utilization, and greater employee motivation and on-time delivery of products and services. The novel part of this research is the GT technique of lean tool, which is used for setting the schedules, the production of parts and components in the same family at the same time, reducing the time required to complete the production process. Further, the scheduling developed in the work study by using the shortest processing time (SPT) rule, schedules jobs based on basis of their shortest processing time, optimizes the production process, reduces setup time, minimizes inventory, and increases productivity. The findings of this study suggest that the implementation of a Lean System can significantly reduce the number of problems in various sections of shipyard production processes. However, the use of standardized procedures, efficient resource allocation, and proactive problem-solving techniques are among the key factors that contribute to the success of such systems. These findings can serve as a useful guide for shipyards looking to improve their production processes and minimize problems in the future.

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