Application of the DMAIC tool for the improvement of the ship careening process in a Latin American shipyard

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***Abstract*– Six Sigma is a work methodology that allows companies to measure their operational efficiency, reduce defects in their processes, and improve their management. It is based on quality control and seeks to reduce variability and defects in the delivery of a product or service to the customer. The methodology can be applied to any type of process and organization.**

This article deals with the application of DMAIC tool in the process of ship careening in a Latin American shipyard, Ecuadorian Navy Shipyards (Astinave). The research was conducted to optimize response times in the management of the development of maintenance, careening, and repair activities. Currently, the process takes an average of 20 to 25 days.

The article analyzes the delay in the arrival of materials and other inconveniences that result in the accumulation of unproductive time in the process. The DMAIC model was adapted, which stands for define, measure, analyze, improve, and control, for which different statistical and quality tools were used to obtain savings in the stay of the vessels.

The sequence of the process was first to diagnose the initial situation, for which statistical data of the vessels that entered the shipyard were used, then the measurement method was determined using techniques and tools that helped to identify causes for the subsequent analysis of the problems detected. Objectives were achieved with performance metrics. Finally, an action plan was proposed to provide quality, solutions, and control of the problems.

Keywords—Six Sigma, careening, DMAIC model, shipyard, quality.

I. Introduction

At present, globalization has brought benefits to companies because they have been able to enter new markets and technological advances. However, companies must face challenges to preserve or maintain their business competitiveness. In this context, a necessary condition is quality, which seeks excellence in the results of organizations. The present research refers to the optimization of the ship careening process in a shipyard company by applying the Six Sigma system, which is based on the DMAIC methodology that allows the development of improvements, which stands for define, measure, analyze, improve, and control [1].

In the ship repairing industry, the careening of a vessel consists of repairing or composing the hull of a ship. During the careening process in the Ecuadorian Navy shipyards (Astinave), under study, some problems can delay the delivery of the work, either in the dry dock or docks. The investigation of this problem was carried out due to the interest of knowing the causes of the delivery of the works to the shipowner out of the time agreed with the shipyard, to establish indicators and a work plan to evaluate the process, reduce waiting times, costs and maintain the continuity of the improvement of the process over time.

Among the problems that cause delays is the lack of availability of materials, which sometimes results in significant delays. Also, modifications in the works that have been agreed upon at the beginning of the process, such as additional repairs or requested improvements that require extra time, as well as the reduction of works requested at the start of work that instead shorten the vessel's stay in docks or dry dock. Other types of problems are work-related accidents and weather-related problems such as heavy rains that interrupt outdoor work and affect the pace of repairs in the shipyard. It is worth mentioning that statistical tools and quality techniques were used for the analysis of these problems at each stage of the model applied.

Finally, in this article, a proposal for the implementation of the Six Sigma methodology to the careening process in the Astinave shipyard was elaborated to determine improvements in the critical areas of the process and propose effective solutions to optimize its efficiency, effectiveness and support the success of the company. See Fig. 1.

The Fig. 1 presents the working diagram used to solve the problem of downtime in the ship careening process at Astinave to avoid delays and additional costs. The process of the research work could be applicable to other shipyards with similar problems and they could adapt it to their own operations in order to foster collaboration between researchers and professionals in the ship repairing industry.

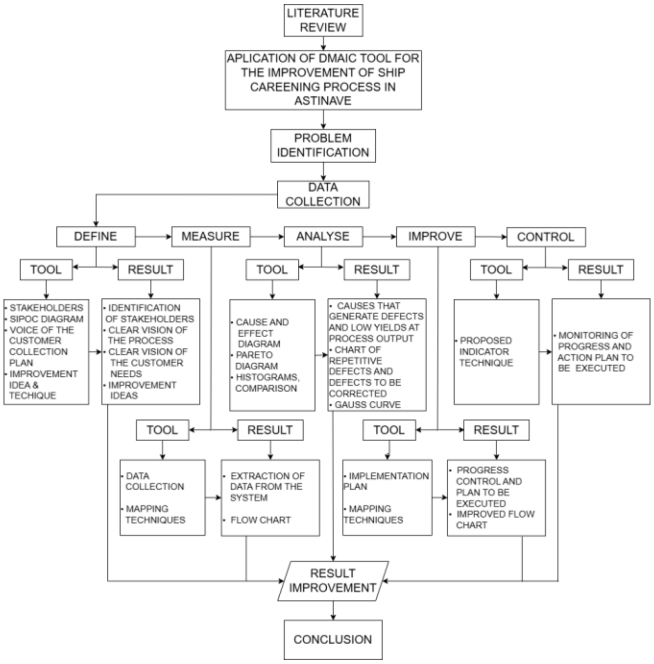

Fig. 1 Working Diagram to solve the problem.

II. General Characteristics of Shipyard and Careening works

The shipyard under study is Astinave, its headquarters is in Guayaquil, Ecuador. It has a dry dock, and workshops (center plant) for ship repairing, and careening. Besides, it has floating docks (south plant) for careening and repairing. Also, it has a Posorja plant that will have the installed capacity to serve vessels up to 125 m in length. The service activities generated by the shipyard are shipbuilding, ship repairing, ship careening, naval repowering, defense systems, port solutions, offshore solutions, and industrial solutions, see Fig. 2, Fig. 3 and Fig. 4 [2].

Fig. 2 Astinave Center Plant

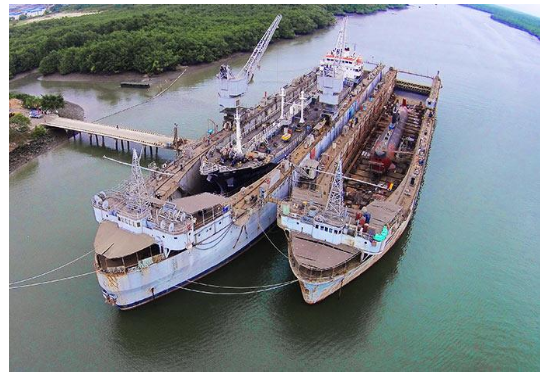

Fig. 3 Astinave South Plant

Fig. 4 Astinave Posorja Plant

III. Naval Careening in Astinave

Astinave serves vessels of up to 4000 tons of lift, 120 m in length, 16,5 m in breadth and 7 m in draft. The careening works carried out by the shipyard are:

A. Treatment and Painting cleaning and paint application work on metal surfaces: Washing at medium and high pressure of water to eliminate salts or marine contaminants using a Hydrowasher. The shipyard also has electric an pneumatic painting machines to apply paint and protect the metal from corrosion wear.

B. Habitability, Equipment and Accessories: Preparation and maintenance of furniture, equipment and accessories for working and work areas, ceilings and bulkheads. Besides, thermal and acoustic coating.

C. *Auxiliary Systems:* Maintenance, repair and preparation of auxiliary systems in cooper nickel, carbon steel, stainless steel, copper an PVC pipes. Provision of services in ciruits of wastewater, fuel, salt water, drinking water, pneumatic system, hydraulic, cooling and exhaust gas. Also, maintenance and repair of pipes, manifolds and valves of different types.

D. Electronic System

Maintenance and installation of equipment and navigation aid systems for vessels. Maintenance and installation of Printed Current Cathodic Protection system, Maintenance and installation of Communication System.

E. Electrical Systems Installation: Maintenance and repair of electrical systems on vessels of the Ecuadorian Navy and the industrial and commercial sector.

F. *Propulsion and Government Systems:* The shipyard has specialized personnel to carry out the disassembly, maintenance and installation of fixed-pitch and variable-pitch propulsion systems for ship propulsion. Also, it provides maintenance to the mechanical and hydraulic circuits of the government systems.

G. Metal-Mechanical: Maintenance and repair of the elements of the propulsion and governance system of the vessels. The shipyard repairs and machines propeller shafts, fixed pitch propellers, baron shafts, among other elements. Besides, the shipyard machines and install synthetic and metal bearings in the propulsion and steering systems. Astinave carries out the manufacturing and machining of industrial parts, impellers and pump accessories.

H. Hull and Structure: Ironing and structural change work on ships applying different welding processes. Astinave works in metallic materials such as: carbon steel, stainless steel, bronze and aluminum [2].

III. Six Sigma and DMAIC Methodology

Six sigma is a business philosophy focused on customer satisfaction, which uses the DMAIC methodology to decrease process variation and significantly improve quality. Statistical and administrative tools are used, and improvements are developed following these steps:

Define: the problem, the value to the client, the team and the project.

Measure: performance through a process map in which the reliability of the data is determined.

Analyze: identify the sources of variation and the roots of the problem.

Improve: develop changes to improve performance.

Control: maintain the improvements made [1].

By applying the DMAIC, solutions are proposed that could bring many different benefits not only to the company but also to other entities [3].

Research shows that the use of Six Sigma tools can be guided by two different patterns: the first one is associated with the use of design-oriented tools and the second one is based on non-design-oriented tools, both related to project duration time, and cost [4]. Currently, some studies relate Lean Six Sigma with the concepts of In-industry 4.0 and Circular Economy [5].

It is worth mentioning in the medical area that Six Sigma methodology is used to facilitate the quality control of glucose meters in hospitals [6] and this methodology can improve the quality of life and reduce the incidence of postoperative complications percutaneous coronary [7]. Besides, it can be expressed that this methodology is used in research carried out by clinical chemical laboratories be more profitable [8].

Six Sigma methodology is also used in Additive Manufacturing to reduce variability because it requires process design optimization when a new product is manufactured [9]. Besides, Six Sigma applies to engineering when materials must be selected in a simple and rapid approach driven by customers and the environment [10] and to ensure the leanness of the supply chain system [11]. However, it must be mentioned that Six Sigma focuses on improving business processes by using statistical measurements to evaluate changes in performance [12].

In the area of education, it can be expressed that in Saudi Arabia universities are oriented towards developing the educational structure and methods by applying the Six sigma methodology and the lean six sigma approach. In addition, collaborative research work is being carried out with other regional and international universities for its application [13]. Studies show that to achieve Six Sigma, organizations need to understand the causes of process variability, perform cause-effect analysis and evaluate its costs. Moreover, the proposed solutions could benefit not only the company but also entities involved in its operation [14]. Also, the Lean Six Sigma approach the vulnerability of a population to an earthquake [15].

IV. Discrete and Continuos variables

A random variable is a function that assigns a number to each elementary event of a random experiment. Random variables are classified into discrete and continuous. A discrete variable can only take isolated numerical values, fixed in consecutive, there can be none in between. A continuous variable can take any numerical value within an interval, so that between any two of them there is always another possible value.

In real-world systems, missing data is very common. However, efficient imputation methods and algorithms are now available that solve this problem for continuous and discrete variables [16].

V. Methodology

Table I below shows the proposed development of the careening process improvement project at the Astinave shipyard, following the Six Sigma DMAIC methodology, indicating the tools used and the results for the stage: Define, Measure, Analyze, Improve, and finally Control.

TABLE I
PROPOSAL FOR THE DEVELOPMENT OF THE PROJECT

Item	Tool	Result
1	Stage Define	
	Stakeholders	Identification of careening stake holders
	SIPOC diagram tool	Clear vision of the process
	Voice of the customer collection	Clear vision of the customer

	plan Improvement ideas technique	needs Improvement ideas
2	Stage Measure	
	Data collection plan technique Mapping technique	Extraction of data from the system Flow chart
3	Stage Analyse	
	Cause and effect diagram Pareto diagram Histograms and comparisons	Causes that generate defects and low yields at process output Chart of repetitive defects and defects that need to be corrected Gauss curve
4	Stage Improve	
	Implementation plan Mapping technique	Progress control and plan to be executed Improved flow chart
5	Stage Control	
	Proposed indicator technique	Monitoring of progress and action plans to be executed

VI. Results

In the Define stage, the first step was to identify the parties interested in executing the careening or who influenced the shipyard internally or externally. The power of influence can be A, B, and C, from highest to lowest, also indicating how much the project impacted this stakeholder: high, medium, low. See Table II.

TABLE II
STAGE DEFINE: STAKE HOLDERS

Item	Stakeholders		
	Role in the company	Power/Influence	Impact of the Project on the stakeholder
1	Production Management (Planning)	A	High
2	Customers (shipowners) and Suppliers	A	High
3	Classification Societies and Certification companies	B	Medium
4	Partnerships of foreign shipyards and universities	C	Low

To have a clear idea of the careening process, the SIPOC diagram (suppliers, inputs, process, outputs, customers) is shown in Fig. 5. The careening process starts with the shipowner's request for work requirements to the Planning Department, and then the shipyard replies with an estimated budget for the requested work. After reviewing all the requests, a careening schedule for drydocking and docks is drawn up. After the vessel is dry-docked, it is inspected to see if additional work is required. The work is carried out under the supervision of inspectors and the shipowner's technical representative. The process ends with the delivery of the finished work, the careening report and, the invoice given to the client.

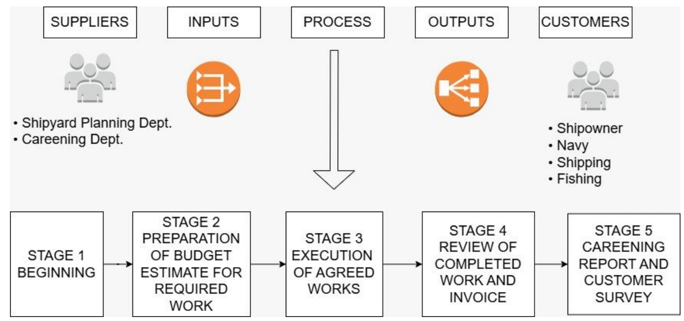

Fig. 5 SIPOC Diagram Tool. Vessel careening process in dry dock or dock.

The technique called Voice of the Customer Collection Plan clearly defines the data collection plan that allows understanding the customer's voice. It is crucial to know what customers expect during the hull maintenance process so that it can be designed considering their needs. According to common practice and experiences in hull maintenance work at Astinave, it is known that customers have expectations regarding hull maintenance or repair work on their vessels. They desire the tasks to be performed with high-quality standards and within the established deadlines. Shipowners expect the shipyard to employ advanced techniques and technologies with skilled labor, and follow safety regulations not only for the vessel but also for the personnel. Additionally, customers expect effective and continuous feedback between the shipyard and their technical representative to avoid work interruptions. It is worth mentioning that shipowners highly value clear and transparent communication about the progress of the work and costs.

The Table III presents the Voice of the Customer Collection Plan technique to understand customer satisfaction. The table includes reactive sources that focus on the feedback provided by the customer after receiving the service and proactive sources which involve the measures taken to anticipate and improve customer satisfaction before and during the service.

TABLE III
STAGE DEFINE: VOICE OF THE CUSTOMER COLLECTION PLAN TECHNIQUE

Item	Type		
	Customer	Reactive Sources	Proactive Sources
1 2 3 4 5	Navy Shipping/Logistic Fishing vessel Tanker ship Tourism vessel	Satisfaction surveys Comments and reviews Post-sales follow-up	Initial meetings and planning On-site visits and Audits Personalisation of the service

		Analysis of complaints and claims	

In the Measure stage, the Data collection plan technique was used to define the variables to be measured and their type, information that was extracted from the shipyard's statistical system, and data from the ships that entered the dry dock and docks in 2022, 2023 and 2024. (See Table IV, Fig. 6, Fig. 7, Fig. 8, and Fig. 9).

TABLE IV
STAGE MEASURE: DATA COLLECTION PLAN

Item	Type		
	Variables to be measured	Type of Variable	How will you measure it
1	Length of ship.	Quantitative, continuous	Annually
2	Planning and execution time of the work in the careening process.	Qualitative, continuous	Annually
3	The number of ships that entered the dry dock and docks	Quantitative, discrete	Anually
4	Type of ships and cause of entry to dry dock and docks.	Qualitative	Annually

By using the Improvement ideas technique and knowing the problems of the process, the improvement ideas were formulated, analyzed, and evaluated. Also, the area of impact and the person responsible for their development and implementation were established, see Table V.

TABLE V
IMPROVEMENT IDEAS TECHNIQUE

Item	Type		
	Ideas for improvement	Impact Area	Responsible
1	Improve the procurement of materials from the warehouse.	Department of careening	Head of careening
2	Determine time indicators for careening.	Planning department	Head of Planning
3	Improve feedback mechanism to the owner or technical representative.	Department of careening	Head of careening
4	Decrease transportation time of propulsion and steering system components from docks to workshops.	Production Management	Production Manager

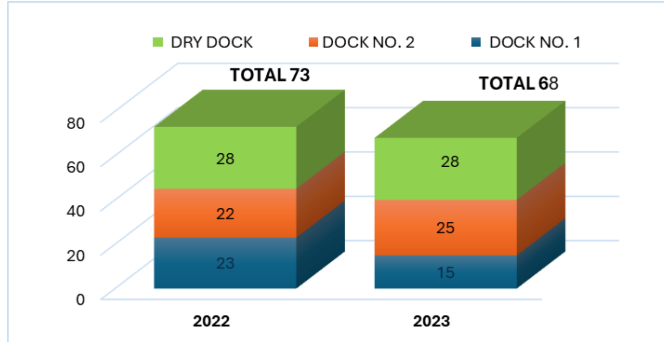

Fig. 6 Number of vessels entering dry dock and docks for careening in years 2022 and 2023.

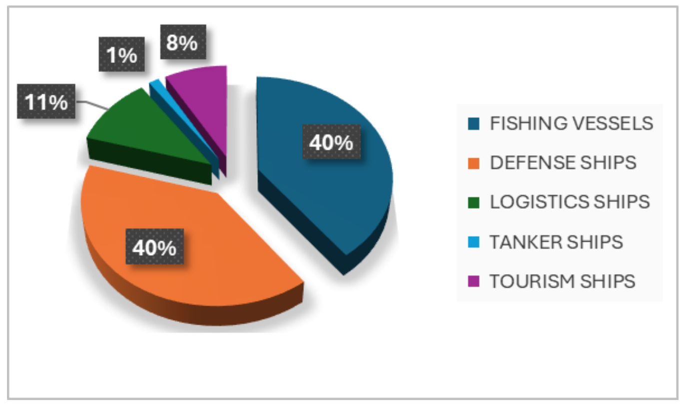

Fig. 7 Percentage by type of activity of vessels that entered the dry dock and docks for careening in 2022.

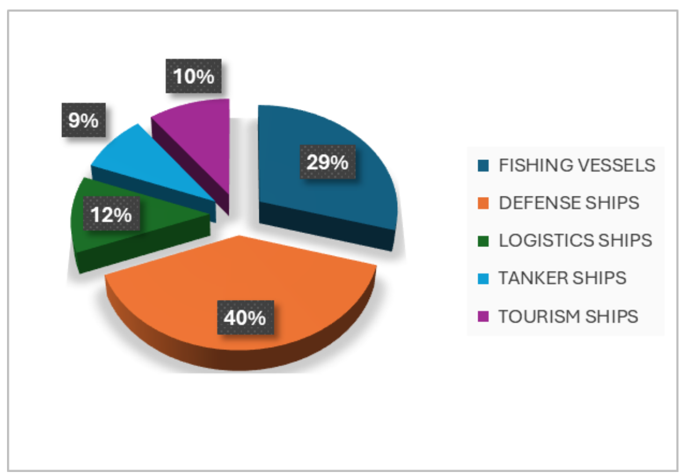

Fig 8. Percentage by type of activity of vessels that entered the dry dock and docks for careening in 2023.

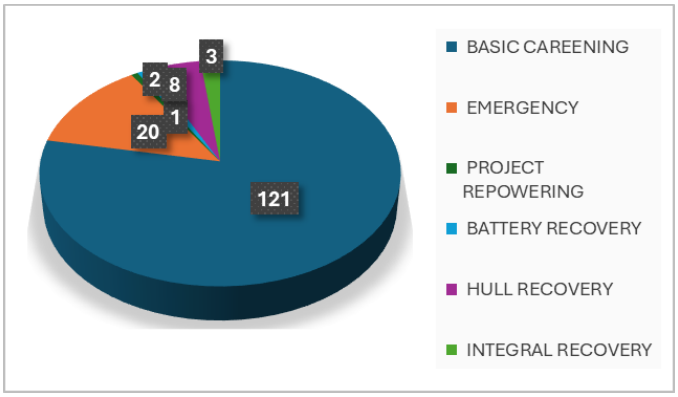

Fig. 9. Reason for entrance to docks and dry docks. Years 2022-2023-2024.

In measuring the problem, it is crucial to understand the operation of the ship's Careening process upon entering a dock or shipyard. For this reason, the mapping technique was applied, which involves a clear and comprehensible representation of the workflow. This representation was developed by the researchers and personnel from the Astinave shipyard involved in the process. Through mapping, the entire process can be analyzed from the shipowner's perspective, revealing an average preparation time before entry of 10 to 15 days and an estimated careening time of 20 to 25 days. (See Fig. 10).

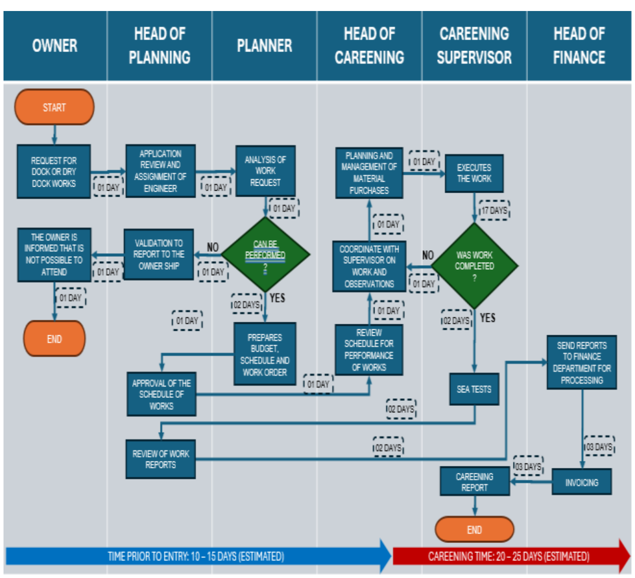

Fig. 10. Flow chart of the careening process.

The process begins with the work request made by the shipowner for entry into the dock or shipyard. The request is reviewed by the Planning Manager and assigned to the responsible engineer or planner, who analyses the required work and assesses whether it can be carried out by the shipyard. If the planner concludes that the shipyard cannot perform the requested work, the planner requests validation of the response from the Planning Manager, who then informs the shipowner that the requested work cannot be accommodated. If the response is positive, the planner prepares the budget, schedule, and work order. The planner then seeks approval of the work schedule from the Planning Manager.

Following the process, all documentation is sent to the Careening Manager, who reviews the work execution schedule, coordinates with the supervisor on the tasks and any observations that arise, and manages the work planning, including the purchase of materials.

Afterward, the Careening Supervisor receives the work order, the ship enters the dock, and the tasks are performed. If the work is not fully completed, the supervisor coordinates with the Careening Manager to plan the remaining tasks and purchase the necessary materials. If the work is completed, the ship is undocked, sea trials are conducted, and the completed work reports are reviewed.

The completed work reports are sent to the financial department for settlement and billing. Finally, the process concludes with the preparation of the careening report by the shipyard and its delivery to the shipowner.

In the Analyse stage, the Cause-effect diagram tool was used to identify the reasons for unproductive times in the careening process, considering the factors involved, such as machinery, environment, labour, raw materials, and methods. (See Fig. 11).

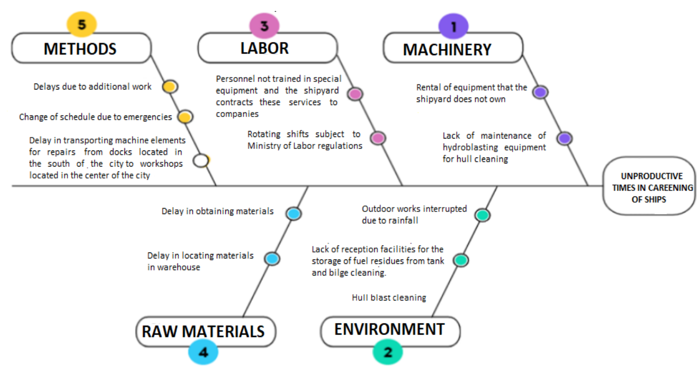

Fig. 11. Cause – effect diagram for ship careening process.

As shown in Fig. 11 at point 1, the shipyard does not have all the equipment and specifically needs to contract services for non-destructive testing, such as radiography.

Previously at Astinave, hydroblasting was used for hull surface cleaning, a more environmentally friendly method, but due to the high cost of spare parts and lack of maintenance, this equipment is no longer used. Currently, sandblasting is used, which is noisier and harmful to health due to dust inhalation. Additionally, this cleaning alternative requires hearing protection and an efficient ventilation system.

Reviewing point 2 of the diagram, it is known that Astinave is not sufficiently prepared to prevent pollution caused by ships because it does not have reception facilities for storing waste fuel from tank and bilge cleaning, which are highly polluting as indicated in Annex I of the MARPOL Convention in rules 12 and 38 [17]. However, through duly certified environmental managers, the shipyard manages the transport of these pollutants to be processed, a service charged to the customer as specified in the shipyard's regulations regarding the entry of ships into the dock, which must enter with clean tanks and bilges.

In this context, it is worth mentioning that Ecuador is a signatory to the MARPOL Convention, making it necessary to fulfill the commitment and promote the creation of maritime awareness and environmental culture through communication programs, action plans, and campaigns that highlight the real importance of preventing ship-caused pollution [18].

Reviewing point 3 of Fig. 11, the staff must be trained on special equipment required by the shipyard and modernize the equipment currently in use. Therefore, it would be beneficial to invest in training to reduce downtime and improve productivity. In this context, professional certifications are also required. Additionally, considering that the shipyard's rotating shifts are subject to Ministry of Labor regulations, the shipyard should hire more personnel to reduce unproductive times.

According to point 4 of Fig. 11, material problems could be solved by recommending the shipowner provide the materials. The placement of materials in the warehouse would be facilitated by applying the 5S methodology to organize and improve efficiency during the management of shipyard operations and production, its application brings many advantages and benefits for any kind of industry [19].

In point 5 of Fig. 11, delays caused by additional work requested by the shipowner are often urgent and require immediate attention and action to be resolved, consequently interrupting the planning of time allocated to other vessels. In these cases, it is necessary to be flexible in the decisions made by both the shipyard and the clients.

Finally, delays caused by transporting machinery for repairs between the south and central plants can be reduced by investing in repair workshops at each shipyard plant, which would help improve service efficiency and customer satisfaction.

Then, in the analyse stage, the Pareto diagram technique was used, as shown in Table VI, to identify the most recurring defects in the careening process, the problems and causes were organized from the most important to the least important. This technique is called the 80/20 Rule, where 80% of the problems come from 20% of the causes. (See Fig. 12).

TABLE VI
DEFECTS BY STAGES ORDERED FROM HIGHEST TO LOWEST.

Item	Type		
	Defect	Category/Cause	Frequency
1	Shipowner asks for less work than contracted.	A/Change of scope of work due to ship´s inspection at the dock	26
2	Shipowner asks for more work than contracted.	B/Change of scope of work due to ship`s inspection at the dock	8
3	Materials not available to complete work.	C/Delay in the acquisition of materials	5
4	Climatic factors affect the execution of works.	D/Hazardous conditions for workers. Machines and equipment do not work properly under adverse weather conditions	2

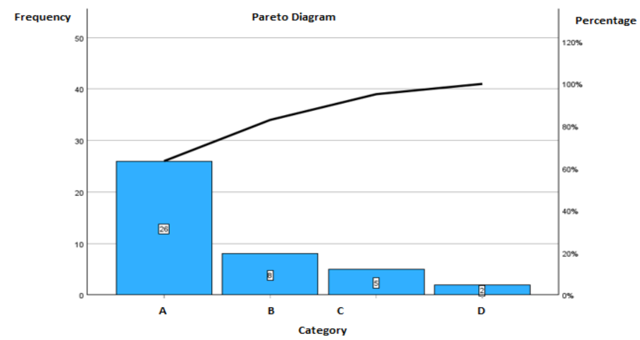

Fig. 12. Pareto diagram of the ship careening process at Astinave.

Considering the quantitative (length) and qualitative variables (work planning time, work execution time), using the software SPSS (Statistical Package for Social Sciences) and the statistics of the careening report of 155 vessels that entered the docks and dry dock for basic careening, emergency, project repowering, battery recovery, hull recovery and integral recovery in the years 2022, 2023 and 2024, Table VII below was prepared.

TABLE VII
QUANTITATIVE AND QUALITATIVE VARIABLES

Item			
	Length	Work planning time	Work execution time
1.Valid data	155	155	155
2.Missing data	0	0	0
3.Mean	52,4550	31,06	30,54
4.Standard deviation	23,47083	85,617	85,348
5.Variance	550,880	7330,33	7284,328
6.Range	98,50	922	922
7.Minimum	14,50	2	2
8.Maximum	113,00	924	924

Also, the histogram and the respective Gaussian curve that describes the data distribution of the frequency of entry of the vessels as a function of the quantitative variable, length, are presented. (See Fig. 13). According to the graph, ships between 55.55 and 63.75 m in length have the highest frequency, which is equal to 26.

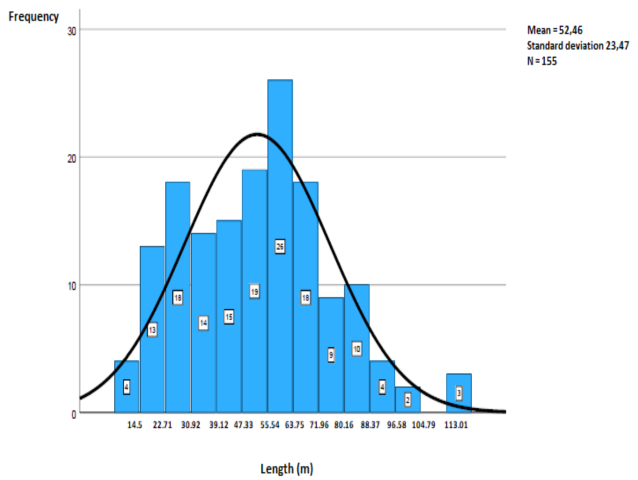

Fig. 13. Histogram L vs Frequency, Gaussian curve.

Also, the histogram of the qualitative variable Work execution time for the careening process, is shown in Fig.14.

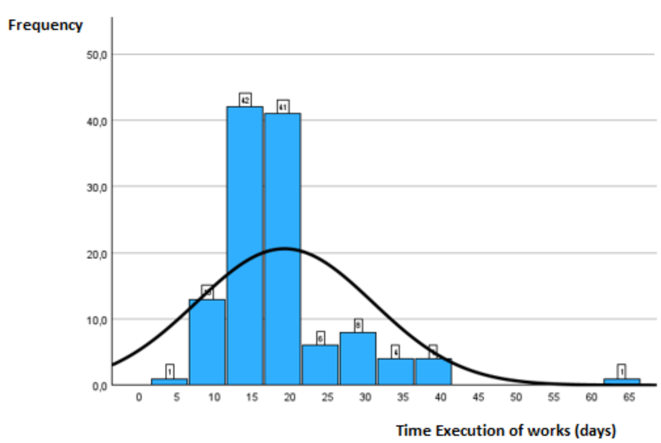

Fig. 14. Histogram of Work execution time for careening process.

In addition, a comparison was made between the Work planning time and Work execution time for careening process can be seen in Fig. 15. The graph shows a similar behavior over time, except for small biases in the planned time, which is due to defects that are corroborated in the Pareto diagram.

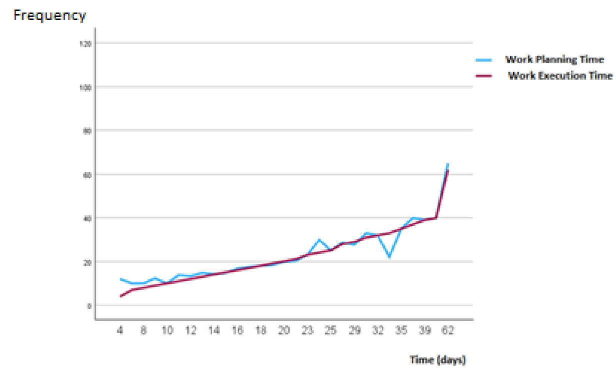

Fig. 15. Comparison between Work planning time and Work execution time.

In the improvement stage, the Implementation plan for the year 2024 is presented in Table VIII, which monitors the progress of the action plans to be executed.

TABLE VIII
IMPLEMENTATION PLAN YEAR 2024-2025

Item	Improvement Action	Priority Date	Responsible Advance
1	Establish that the shipowner shall provide the material.	High (1/10/2024-1/11/2024)	Production Manager 50%
2	Acquire quality control equipment, machinery for docks and train personnel.	High (1/10/2024-1/11/2025)	Production Manager 25%
3	Determine and standardize time indicators for each process activity.	Medium (1/10/2024-1/11/2024)	Head of Careening 0%
4	Construct reception facilities for the storage of fuel wastes.	Low (1/10/2024-1/11/2025)	Production Manager 0%

After identifying areas for improvement and bottlenecks, the following presents the optimized mapping, with an average preparation time before entry of 7 to 10 days and an estimated careening time of 17 to 20 days. (See Fig. 16).

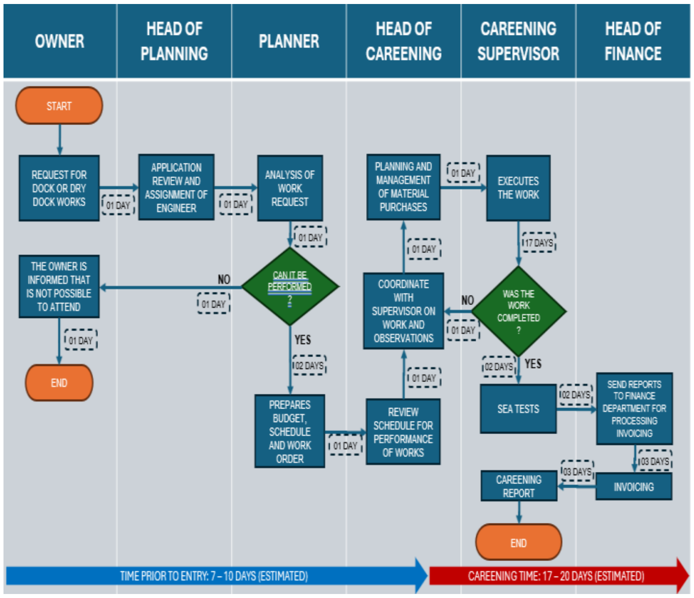

Fig. 16. Improved flow chart of the careening process.

In the control stage, it is showed the indicators established to evaluate the process and verify the continuity of the improvement over time. See Table IX.

TABLE IX
PROPOSED INDICATOR

Indicator	Objective	Metric
Percentage of vessels complying with the time plan	Keeping track of vessels that met the planned schedule	Vessels complied x 100 /Total Number
Actual process response time by vessel type	Keeping track of the actual response time of each type of careening vessel	Actual response time x 100/average time
Actual process cost reduction by vessel type	Keeping track of the actual cost made by the shipyard for each type of careening ship.	Actual cost of the process x 100/Average cost
Percentage of personnel training	Keeping track of the workers trained in the process	Number of trained workers x 100/Total number of workers

IV. CONCLUSIONS

It is concluded that in 2022, 73 vessels entered the shipyard for careening, of which 28 were at the dry dock, 23 at dock No. 1 and 22 at dock No. 2. 40% of these were fishing vessels. In 2023, 68 vessels entered the shipyard for careening, of which 28 were at the dry dock, 15 at Dock No. 1 and 25 at Dock No. 2, and 40% were defense vessels. Besides, from 2022 to 2024, 121 ships entered dry dock and docks for basic careening.

The Cause-effect diagram indicated that there is a delay in the acquisition of materials, so it could be established that the shipowner should provide them. Another cause that slows down the process is the contracting of work to companies that have equipment that the shipyard does not own or that lack maintenance and training staff. Therefore, the purchase of equipment for recurring work is suggested, as well as the training of personnel.

In addition, the transportation of machine elements from ships in docks (south plant) to be repaired in the shipyard (center plant) causes unproductive time, so the adequacy of workshops in docks is suggested, for which a cost-benefit study should be carried out.

It is considered relevant to build reception facilities for the storage of fuel residues from tank and bilge washing, to contribute to the International Maritime Organization (IMO) regulations for the preservation of the marine environment in accordance with the Marpol Convention.

The proposed implementation plan and control measures are essential to ensure that process improvements are sustainable over time. Periodic evaluation is also required to ensure efficiency and effectiveness.

It is recommended to implement the Six Sigma methodology in other service activities of the shipyard such as shipbuilding, repowering, defence systems, port solutions, offshore solutions, industrial solutions, etc., to improve customer satisfaction, reduce errors, and make decisions based on statistical data.

It would be advisable that this proposal for the application of DMAIC in the ship careening process be carried out in the shipyard in order to statistically evaluate the downtime at each stage after its application.

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REFERENCES

[1] Socconini, L., Reato, C.: Lean Six Sigma Sistemas de Gestión para liderar empresas. 1st edn. Marge Books. España. (2019).
[2] ASTINAVE homepage, https://astinave.com.ec, last accessed 2024/06/06.
[3] Smętkowska, M., & Mrugalska, B. Using Six Sigma DMAIC to improve the quality of the production process: a case study. Procedia-Social and Behavioral Sciences, 238, 590-596, (2018).
[4] Choo, A.: Solving problems efficiently in R&D projects: An empirical study of the application of six sigma tools in an industrial research center. IEEE Transactions on Engineering Management 69(6), 2530-2543 (2019).

[5] Skalli,D., Charkaoui, A., & Cherrafi, A. : Assessing interactions between Lean Six Sigma, Circular Economy and industry 4.0: toward an integrated perspective. IFAC-Papers OnLine, 55(10), 3112-3117 (2022).

[6] Huang, Y., Loveday, C., & Vincent, A.: Potential use of Six Sigma metrics in the quality control review of hospital glucose meters. Heliyon, 10(17), (2024).

[7] Che, S., Sun, Y., Li, H., Miao, R., Wang, J., & Chen, F.: Analysis of the Application Value of the Six Sigma Methodology in Nursing Management after Percutaneous Coronary Intervention. In The Heart Surgery Forum (Vol. 27, No. 9, pp. E1044-E1051), (2024).

[8] Thakur, V., et al.: Use of a Lean Six Sigma approach to investigate excessive quality control (QC) material use and resulting costs. Clinical Biochemistry, 112, 53-60, (2023).

[9] Sithole, C., Gibson., I. & Hoekstra, S.: Evaluation of the applicability of design for six sigma to metal additive manufacturing technology. Procedia CIRP, 100, 798-803, (2021).

[10] Maidin, N. A., Sapuan, S. M., Mastura, M. T., & Zuhri, M. Y. M: Materials selection of thermoplastic matrices of natural fibre composites for cyclist helmet using an integration of DMAIC approach in six sigma method together with grey relational analysis approach. Journal of Renewable Materials, 11(5), 2381-2397, (2023).

[11] Makinde, O., Selepe, R., Munyai, T., Ramdass, K., & Nesamvuni, A.: Improving the supply chain performance of an electronic product-manufacturing organization using DMAIC approach. Cogent Engineering, 9(1), 2025196, (2022).

[12] Wang, C. N., Nguyen, T. D., Nguyen, T. T. T., & Do, N. H.: The performance analysis using Six Sigma DMAIC and integrated MCDM approach: A case study for microlens process in Vietnam. Journal of Engineering Research, (2024).

[13] Al-Otaibi, S. A: Implementation of Six-Sigma methodology to achieve a competitive edge in Saudi universities. Studies of Applied Economics, 39(10), (2021).

[14] Smetkowska, M. & Mrugalska, B.: Using Six Sigma DMAIC to improve the quality of the production process: a case study. Procedia-Social and Behavioral Sciences, 238, 590-596 (2018).

[15] D. Caamaño and N. Mendieta, “Lean Six Sigma Aplicado a la Reducción de Riesgos Sísmicos. Caso de estudio en Ecuador”, Montego Bay, Jamaica:17th LACCEI International Multi- Conference for Engineering Education, and Technology, LACCEI 2019. Latin American and Caribbean Consortium of Engineering Institutions, 2019.

[16] Li, M., Liu, Y., Zheng, Q., Li, G., & Qin, W: An evolutionary computation classification method for high-dimensional mixed missing variables data. Electronics Letters, 59(24), e13058, (2023).

[17] International Maritime Organization: International Convention for the Prevention of Pollution from ships, 1973 and Protocol 1978. MARPOL 73/78. Consolidated Edition International Maritime Organization, London, United Kingdom (2011).

[18] Mendieta, N.: Does Ecuador Prevent Pollution Caused by Ships? Pan-American Conference of Naval Engineering, pp. 385-394. Springer International Publishing (2017).

[19] Arabi, S., Bajjou, M.S., Chafi, A., & El Hammoumi, M.: The implementation of Lean Manufacturing Tools in Morocco: A Study on Small and Medium-Sized Enterprises. In 2024 4th International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET), pp. 1-6. IEEE (2024).