Assessing Production Efficiency: A Case Study of the Ballast Water Treatment System in a Turkish Maintenance Shipyard

Ayhan Mentes, Ender Koç, Muhammed Alperen Güngör, Ümit Ağri

The installation and implementation of ballast water treatment systems (BWTS) are crucial for protecting marine ecosystems, preserving biodiversity, promoting human health and supporting global economic sustainability. This study evaluates the effectiveness of installing these essential systems, with a focus on enhancing production efficiencies in the manufacture and installation of BWTS pipes. We conducted a detailed assessment at a leading maintenance and repair shipyard in Turkey, guided by a team of experts. The aim was to optimize operational processes by identifying delays and bottlenecks in pipe production and installation. Using Arena Simulation, we pinpointed disruptions and inefficiencies within the production system. Based on this analysis, we developed and executed targeted improvements that led to significant improvements. Notably, the annual output increased from 23 to 41 units, reflecting a 78% increase in productivity. These improvements are of far-reaching importance and provide valuable strategies for increasing production efficiency in any pipe manufacturing. Our findings offer key insights into refining operational processes and boosting productivity in a variety of industrial contexts.

KEYWORDS

~ Ballast water treatment systems
~ Ship production
~ Production efficiency
~ Maintenance and repair shipyards
~ Arena

Istanbul Technical University, Faculty of Naval Architecture and Ocean Engineering, Department of Shipbuilding & Ocean Engineering, İstanbul, Türkiye
e-mail: mentes@itu.edu.tr
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1. INTRODUCTION

Ships play a pivotal role in facilitating much of international trade, necessitating the presence of shipyards around the world for their construction, maintenance and repair. Among these shipbuilding hubs, Turkey stands as a maritime nation that has attained a commendable level of expertise in this sector while continuing its growth trajectory (Turkish Chamber of Shipping, 2022).

The ship repair and maintenance sector plays a crucial role in maintaining the operational lifespan of vessels. To ensure safe navigation, maintain optimum comfort and meet regulatory requirements, every ship must undergo comprehensive surveys. In addition, ships often require repair services following incidents that result in damage. Given Turkey's advantageous location as a strategic bridge between Asia and Europe, its proximity to Europe and its extensive coastline, the country has become a major player in the ship maintenance and repair sector. Turkey's geopolitical location has made it a preferred destination for ships in need of maintenance and repair (Republic of Turkey, Ministry of Economy, 2018).

Production efficiency refers to the effective use of resources in the production of goods and services. In the competitive environment of repair shipyards, production efficiency is of utmost importance as the survival of these yards depends on their skillful management of factors such as cost, profit, quality and time. In order to increase productivity, both internal and external factors must be considered, which serve as pivotal parameters for improving production efficiency. The initial step to improvement is to identify the significance of these factors.

When examining the shipyard environment encompassing shipbuilding, maintenance and repair processes, it becomes apparent that studies on efficiency focus predominantly on shipbuilding. For instance,Song et al. (2009) have conducted studies on efficient shipbuilding that focus on medium-sized and small shipbuilding companies. Ozkok (2010) refers to the difficult competitive environment and urges manufacturing companies, especially shipyards, to scrutinize their production processes, increase production within specified timeframes, and focus on analyzing and improving production efficiency in Turkish shipyards.

Conversely, Gunbeyaz et al. (2018) examined the ship recycling industry, which operates in contrast to shipbuilding, and emphasize the transition phase that ship recycling is going through to adapt to new regulations. They emphasize the need for shipyard owners to invest in and develop their facilities. To offset these investments, they aim to optimize existing processes and enhance efficiency through the use of simulation programs.

Xue et al. (2019) identify construction technique, resource capability and management level as three critical factors in shipbuilding. They conduct a production efficiency analysis specifically focused on Chinese shipyards. Roque and Gordo (2020) explore the concept of efficiency in shipbuilding and propose suitable metrics to facilitate a comprehensive and systematic measurement of a shipyard's efficiency.

Lee et al. (2020) employ a production planning methodology to enhance the production planning process. They quantitatively evaluate this method using the DES simulation program and demonstrate its effectiveness in improving production efficiency. Okubo and Mitsuyuki (2022) propose a method that divides complex shipbuilding projects into four components: product, workflow, workplace and team. Through modeling and process simulation, they automatically generate realistic production schedules with the aim of streamlining operations.

Numerous techniques have been proposed to enhance production system efficiency, including standardization of production data, system integration, information optimization and innovation within the production system. Simulation technology is used to enhance the objectivity and increase the reliability of system outputs.

Ozkok (2013) employs Arena simulation software to illustrate how machine failures affect block production time in shipbuilding processes. Similarly, Ozkok and Helvacıoğlu (2013) use Arena simulation software to model all production processes of the double bottom block with the aim of improving block production time by eliminating bottlenecks during production.

The discharge of ballast water from ships entails significant ecological and economic risks that make the use of BWTS necessary. Ballast water often harbors a variety of aquatic organisms, including bacteria, viruses, small invertebrates, algae and larvae. If this ballast water is released into new ecosystems during loading or unloading, it poses the potential to introduce non-native and potentially invasive species entering the local environment. The arrival of invasive species can inflict economic losses by adversely affecting fisheries, aquaculture and the tourism industry, as well as disrupting local ecosystems and triggering ecological imbalances.

To mitigate these risks, international regulations such as the Ballast Water Management Convention established by the International Maritime Organization (IMO) mandate the installation of BWTS on ships. These systems facilitate the purification of ballast water by eliminating or neutralizing potentially harmful organisms before discharge. By treating the ballast water, the proliferation of invasive species and the subsequent ecological and economic consequences can be substantially reduced.

This study is unique in that no other study has analyzed the BWTS pipe fabrication and assembly process. Together with environmental awareness, the concept of the green ship and the green environment has become a very popular topic today. In this context, the IMO wants BWTS to be installed on ships. Shipyards are currently receiving heavy orders for BWTS assemblies and are very busy. In this study, by modeling the manufacturing and assembly process of BWTS pipes, the bottlenecks in this process are identified and the assembly process is shortened with the given suggestions. In this way, the shipyards can build BWTS in less time, build much more BWTS in a year and increase their revenue.

The primary purpose of this study is to evaluate the efficiency of the installation of BWTS, which play a crucial role in environmental protection, in a maintenance and repair shipyard in Turkey. It aims to identify any malfunctions and bottlenecks that occur throughout the entire process of pipe manufacturing and installation of the BWTS. By addressing these challenges, the study aims to expedite the necessary activities and integrate the proposed productivity-enhancing solutions into the system. To achieve this, the manufacturing and assembly of the BWTS tubes is modeled using the industry-standard Arena simulation software, which is known for its reliability and widespread use in both academic and industrial environments.

This paper will undertake the following key steps:

a) Maximizing production efficiency through iterative feedback in planning and production processes.
b) Implementing changes in BWTS pipe manufacturing and installation using the Arena program to enhance overall efficiency.
c) Conduct comprehensive measurements in the shipyard under the supervision of on-site experts.
d) Contribute to existing literature by conducting efficiency analysis specifically in maintenance-oriented shipyards.

The continuous development of the maintenance and repair sector requires the adoption of innovative solutions in the yards in order to optimize capacity utilization. Consequently, the shipyard in question will be better equipped to provide more efficient services. Given the significance of BWTS for the environment, this study not only benefits the environment but also contributes to the economy by streamlining the production process through the proposed solutions. Since increasing the capacity of the system is closely linked to the layout of the shipyard, a thorough analysis of the shipyard layout and the integration of innovations in accordance with the conditions of the facility is essential.

2. SIMULATION

Analyzing and evaluating complex production processes, such as in shipbuilding, poses significant challenges. When making investment decisions in such intricate contexts, it is often impractical to analytically determine the exact benefit of purchasing a new machine, for example. Instead, virtual environments are used to model complex real events and evaluate the effects of possible changes. In this context, simulation software has been developed to facilitate the modeling of realistic production processes in a computer environment. This software enables the creation of virtual representations of actual events, allowing for modifications that would not be feasible in reality.

The simulation software is built upon the principles of queueing theory. Performance measures, including the Average Waiting Time in the Queue (Wq), the Average Waiting Time in the System (W), the Average Number of Queues Waiting in the Queue (Lq) and the Average Number of Pieces Waiting in the System (L) are commonly used in simulation models (Ugurlu et al., 2022). These performance indicators serve as the basis for determining the structure of simulation models. Among them, Lq is particularly noteworthy as it reveals bottlenecks within the simulation model. A high Lq value in the buffer area indicates the presence of a bottleneck at this point.

The following Little's Law equations (Smith and Sturrock, 2022) are fundamental to understanding and quantifying the relationships in play:

$$L = \lambda W \quad (1)$$

$$L_q = \lambda W_q \quad (2)$$

$$W = W_q + E(S) \quad (3)$$

$$W_q = L/\lambda - E(S) \quad (4)$$

These equations establish the connections between the average number of pieces waiting in the queue (Lq), the average waiting time in the queue (Wq), the arrival rate (λ), the average number of pieces waiting in the system (L) and the average waiting time in the system (W). By employing these equations, valuable insights into the system's behavior and performance can be obtained, supporting decision making and potential improvements within the production process.

Arena is a robust software program designed specifically for modeling, simulating and analyzing complicated systems and processes. Widely utilized across various industries such as manufacturing, healthcare and logistics and provides users with a comprehensive platform to construct intricate system models encompassing equipment, personnel and resources. By simulating various scenarios, users can effectively evaluate the performance of the system under different conditions. For further insights into the features and capabilities of Arena in comparison to other simulation programs, see Table 1.

When using ARENA for simulation, the selection of the appropriate statistical distribution is crucial. Here are some methods to determine the most suitable distribution:

- Data Analysis: Start by analyzing the data through visual tools like histograms and Q-Q plots. This helps to identify patterns and determine if the data fits a particular distribution, such as a normal, exponential or uniform distribution.
- Mathematical Modeling: Use mathematical models to understand the behavior of the system. For example, if the system involves a time interval between events, an exponential distribution might be appropriate.
- Theoretical Knowledge: Leverage domain-specific knowledge to identify common distributions for similar systems. For instance, normal distributions are often used for processes involving random sampling.
- Experimentation and Simulation: Run simulations with various distributions to find out which one best matches the observed data. This trial-and-error approach can help refine the choice of distribution.
- Combining these methods usually leads to the most accurate results when selecting the appropriate statistical distribution.

Software	Cost Allocation Costing	Mixed Discrete Continuous Modeling	Real Time Viewing	Export Animation	Compatible Animation Software	3D Animation	Import CAD Drawings
AnyLogic	✓	✓	✓	✓	✓	✓	✓
Arena	✓	✓	✓	✓	✓	✓	✓
Enterprise Dynamics	✓	✓	✓	✓	✓	✓	✓
ExtendSim AT	✓	✓	✓	✓	✓	✓	✓
ExtendSim Suite	✓	✓	✓		✓	✓	✓
FlexSim	✓	✓	✓	✓		✓	✓
Process Simulator	✓	✓	✓			✓	✓
ProModel Optim.	✓	✓	✓			✓	✓
SAS Simulation			✓				
Simio	✓	✓	✓	✓	✓	✓	✓
SIMUL8	✓	✓	✓			✓	✓

Table 1. Comparison of simulation programs.

The significance of Arena stems from its profound capacity to assist organizations in making well- informed decisions and enhancing their operational efficiency. By leveraging Arena, users are able to thoroughly analyze and optimize their systems, identify bottlenecks and inefficiencies, and evaluate the repercussions of implementing changes in the system. Furthermore, it serves as a valuable tool for testing novel designs and strategies, forecasting outcomes and evaluating the potential return on investment associated with various projects. Consequently, Arena plays a pivotal role in enabling organizations to curtail costs, amplify efficiency and productivity and elevate their overall performance to new levels.

3. BALLAST WATER TREATMENT SYSTEM (BWTS)

The International Maritime Organization (IMO) serves as the specialized agency of the United Nations responsible for establishing global standards for ship safety, security and the protection of the environment from the adverse impacts of shipping (IMO, 2011). The Ballast Water Management Convention, adopted by the IMO, aims to prevent the spread of potentially harmful substances (IMO, 2004). Since 8 September 2017, ships have been required to manage their ballast water in such a way that aquatic organisms and pathogens are eliminated or neutralized before releasing it into new locations (IMO, 2022). This regulation contributes to prevent the spread of harmful pathogens and invasive species. BWTSs are integrated into new or existing ships to fulfill this requirement.

A BWTS is designed to remove or inactivate biological organisms present in the ballast water. As a developing technology, ballast water treatment encompasses a growing number of manufacturers, resulting in limited in-service experience with the available systems. It is generally recognized that no single system is universally suitable for all ship types. In the case of new ships, BWTS installation is typically carried out during construction, while operational ships undergo installation at repair shipyards.

The installation process for existing ships involves adding a new pipeline to the primary ballast line and incorporating purification devices. The specific pipes, equipment and methods employed vary depending on the characteristics of the ship. Factors such as the pipe diameter, the number of spools, and the installation location of the system are determined based on the ship's size, significantly influencing the installation timeline of the BWTS.

Compliance with IMO regulations mandates the installation of BWTS for ships operating in different seas, making the manufacture of BWTS pipes an ongoing task. When a ship arrives at a repair shipyard, the shipyard establishes communication and obtains the relevant data and drawings prior to the ship's arrival. The BWTS process begins with the drawings received by the shipyards, followed by material procurement, pipe production and galvanization. Once production is complete, the installation phase begins and after thorough testing and commissioning, the BWTS is delivered to the ship.

4. PRODUCTION EFFICIENCY OF BWTS PIPE MANUFACTURING AND ASSEMBLY

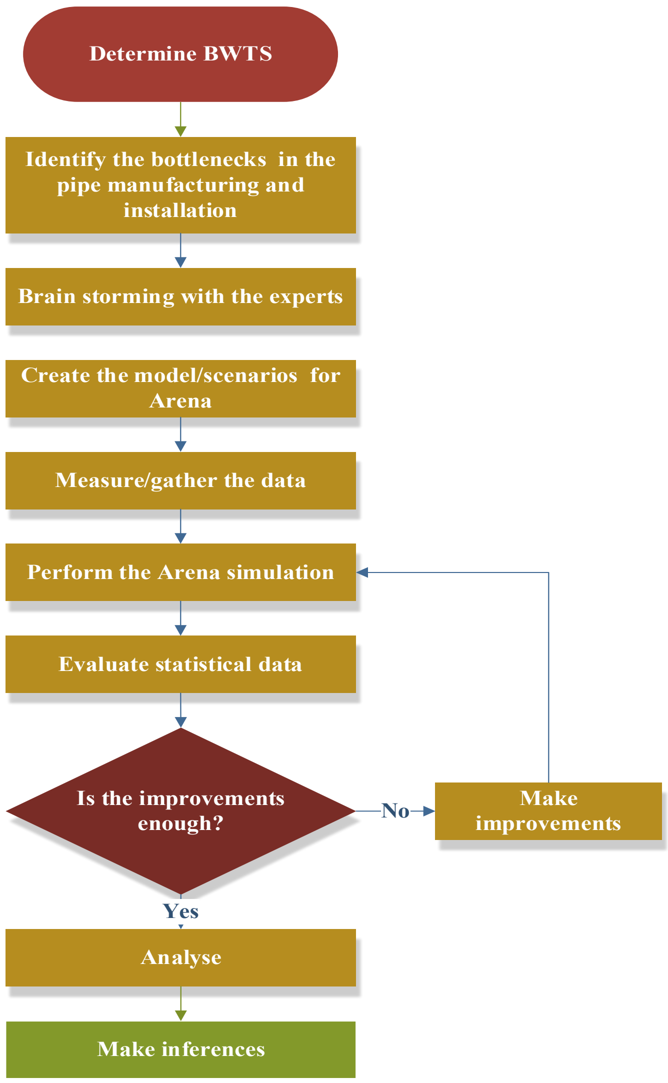
This study focuses on the analysis of process efficiency improvement of a BWTS manufactured and installed for a Handymax crude oil tanker in a maintenance and repair yard in Turkey. The focus is on the challenges related to piping issues, regardless of the technology used. The field data revealed that a significant portion of the BWTS installation involves the main and auxiliary piping networks. The study examines various factors affecting the BWTS production process to identify areas for improvement. To streamline the BWTS process and optimize efficiency, the study adopts the steps summarized in Figure 1 as a guide for process improvement.

The shipyard selected for this study is located in the Yalova Altınova Shipyards region, which is known for its extensive maintenance and cargo handling activities in Turkey. The investigation was conducted through on-site field studies and measurements in collaboration with experienced personnel from the facility. A team of three naval architects and ocean engineers and two planning and production engineers were involved in the data collection and analysis. The planning and production engineers have extensive expertise in their field and have at least 12 years of experience in various shipyards, enabling them to adapt to different environments and working conditions.

A notable observation made during the study was the lack of an operational culture in which processes that directly or indirectly impact productivity are systematically evaluated within each repair and maintenance shipyard. By implementing monitoring processes and collecting/measuring data, efficiency-enhancing measures can be introduced by identifying and rectifying errors. The development of a production line based on the observed processes and the data obtained holds considerable potential for the long-term profitability of the operation. With this in mind, the manufacturing and assembly process of a BWTS was comprehensively evaluated.

- The BWTS pipe installation processes are presented below.
- Reaching the drawings and data to the shipyard,
- Checking the drawing and preparing the material list,
- Ordering the required materials,
- Delivery of the materials to the storehouse,
- Handing over the material to the workshop,
- Cutting the pipes with a grinding machine,
- Welding of bent pipes,
- Spot welding between flange and pipe,
- Welding flange with electric arc welding
- Elbow pipes
- Elbow pipes welding with argon welding
- Electric arc welding
- Removing welding burrs on elbow pipes
- Fairlead pipe
- Fairlead opening
- Welding with argon welding
- Removing welding burrs from fairlead pipe
- Removing welding burrs,
- Transferring basket,
- Sending the pipes in the basket for galvanizing,
- Delivery pipes to shipyard and transferring to ship,
- Pipe installation,
- Testing.

The transfer of pipes between different processes is a crucial factor that affects the overall time required. To optimize efficiency, it is essential to assess the layout of the pipe workshop and carefully evaluate the associated transfer times. Figure 2 shows the layout of the pipe workshop relevant to this study and provides a visual representation of its configuration and organization.



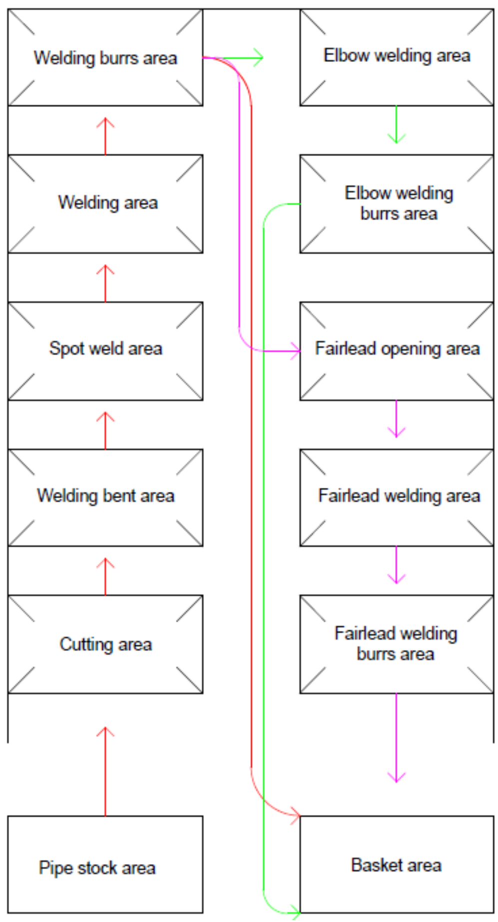


Figure 1. The flowchart of the BWTS process improvement.

Figure 2. An example of pipe workshop layout.

The production and installation processes for the BWTS pipes were identified through comprehensive examinations conducted at the designated repair shipyard. The entire workflow was closely monitored and the duration of each process was determined based on multiple measurements on different days to ensure accuracy. These time estimates were based on the assumption that a DN200 pipe system would be installed. The transfer time was calculated using the example shown in Figure 2. It was also assumed that an average of 200 spools would be used in the system. Based on these assumptions and the insights obtained through observations, Table 2 provides a detailed breakdown of the BWTS pipe production and installation processes, including the duration of each activity. Table 2 shows the activities required for manufacturing and installation of BWTS pipes in their respective operational sequence. The completion times given represent the average values obtained from the measurements of the individual activities. These activities and their respective completion times serve as input data for the relevant modules within the simulation model developed with the ARENA software environment.

Process	Time
Reaching the drawings and data to the shipyard	Starting of the process
Controlling drawing and forming a list of material	5 - 7 days
Ordering the materials required	1 - 2 days
Delivery of the materials to the storehouse	Connected with the previous process
Transferring the material to the workshop	2 hours
Transferring to the cutting area	3 minutes (per spool) (average duration)
Measuring and marking the cut	3 minutes (per spool) (average duration)
Cutting the pipes with a grinding machine	13 minutes (per spool) (min. duration)
Transferring to the welding bent area	3 minutes (per spool) (average duration)
Welding bent for the pipe	3 minutes (per spool) (average duration)
Transferring to the spot weld area	3 minutes (per spool) (average duration)
Spot weld between flange and pipe	10 minutes (per spool) (average duration)
Transferring to the welding area	3 minutes (per spool) (average duration)
Welding flange with electric arc welding	25 minutes (per spool) (average duration)
Transferring to the welding burrs area	3 minutes (per spool) (average duration)
Removing welding burrs	7 minutes (per spool) (average duration)
Elbow pipes	
Transferring to elbow area	3 minutes (per spool) (average duration)
Elbow pipes welding with argon welding	40 minutes (per spool) (average duration)
Electric arc welding	20 minutes (per spool) (average duration)
Transferring to welding burrs area	3 minutes (per spool) (average duration)
Removing welding burrs from elbow pipes	7 minutes (per spool) (average duration)
Fairlead pipe	
Transferring to the fairlead area	7 minutes (per spool) (average duration)
Fairlead opening	1 hour (per spool) (average duration)
Transferring to the welding area	3 minutes (per spool) (average duration)
Welding with argon welding	40 minutes (per spool) (average duration)
Transferring to the welding burrs area	3 minutes (per spool) (average duration)
Removing welding burrs from fairlead pipe	7 minutes (per spool) (average duration)
Transferring basket for pipe	12 minutes (per spool) (average duration)
Transferring basket for elbow pipe	8 minutes (per spool) (average duration)
Transferring basket for fairlead pipe	4 minutes (per spool) (average duration)
Sending the pipes in the basket for galvanizing	2 - 3 days (per system) (average duration)
Delivery of pipes to the shipyard and transfer to the ship	Connected with the previous process
Pipe installation	7 - 10 days (average)
Test	1 day (per system) (average)

Table 2. BWTS Pipe Installation Processes and Their Time.

The information collected was simulated using the Arena program, a discrete event simulation and automation software developed by Systems Modeling and acquired by Rockwell Automation in 2000 (Arena, 2020).

Discrete Event Simulation (DES) was selected for this study because it is suitable for modeling systems with discrete, event-driven changes. DES is characterized by:

Event-Driven Dynamics: It accurately simulates systems where changes occur at specific points in time, which is crucial for capturing event sequences and interactions.

Complex Systems: DES copes well with intricate systems with multiple components and interactions, allowing detailed analysis of resource allocation and process flows.

Resource Optimization: It enables efficient simulation of various scenarios to optimize resource usage and system performance.

Computational Efficiency: DES generally offers faster simulation speeds, which is an advantage for extensive analyzes and scenario tests.

In contrast, methods like Agent-Based Simulation (ABS) and Deterministic Simulation, while useful, either require more computational resources or may not capture the event-driven nature of our system as effectively as DES.

Simulation involves designing a model of a real system and conducting experiments to understand system behavior and evaluate different strategies. Simulations allow for more efficient observation of inputs, stages, and outcomes within an event. In the context of this study, the Arena software was employed to simulate the production process of manufacturing and installing BWTS pipes and to measure production performance. By running simulations, the shipyard can save time and resources by pre-testing real-life scenarios. The Arena Simulation Software enables the investigation of processes, inputs and outputs in the production line under various conditions. A modular test model is created in Arena, whose connecting lines define the asset flow path. Probability distributions are used to incorporate the randomness of the process and statistical data such as average queue length, minimum and maximum queue size and resource utilization time can be determined. The model also takes into account factors such as production errors, machine malfunctions, breaks, lunch hours, and specific working hours to ensure a realistic representation.

In this study, the processes and their respective durations from Table 2 were input into the Arena Simulation Program. The simulation was based on the assumption that a BWTS enters the system or arrives at the shipyard every 15 days. The simulation was designed for a period of 365 days. It was specified that each BWTS consists of 200 spools, with 20% of the produced spools being elbows and 20% being fairleads. In addition to the initial plan, the BWTS arrival time was reduced to 8 days instead of 15 days to evaluate the impact of improvements to the BWTS process. The system was operated accordingly and changes in production volume were evaluated based on the 365-day simulation results.

When using the Arena simulation software, it is important to consider various statistical distributions to model processes accurately. Among these distributions, the normal distribution was used specifically for modeling and optimizing the time spent on various tasks in the Pipe Installation Processes, as it effectively captures the variability associated with these durations. While the uniform distribution is valid for scenarios with equally probable outcomes, the normal distribution is particularly relevant in this case as it is suitable for processes that cluster around a mean time. Additionally, the exponential distribution can be considered for the analysis of waiting times, but the primary focus remains on the normal distribution for the tasks involved in pipe installation.

Figure 3 shows the model developed by the authors and input into the Arena simulation. The allocation of resources to each process is critical, including human resources and machinery such as staff and cranes. Figure 4 illustrates the resources allocated in the system.

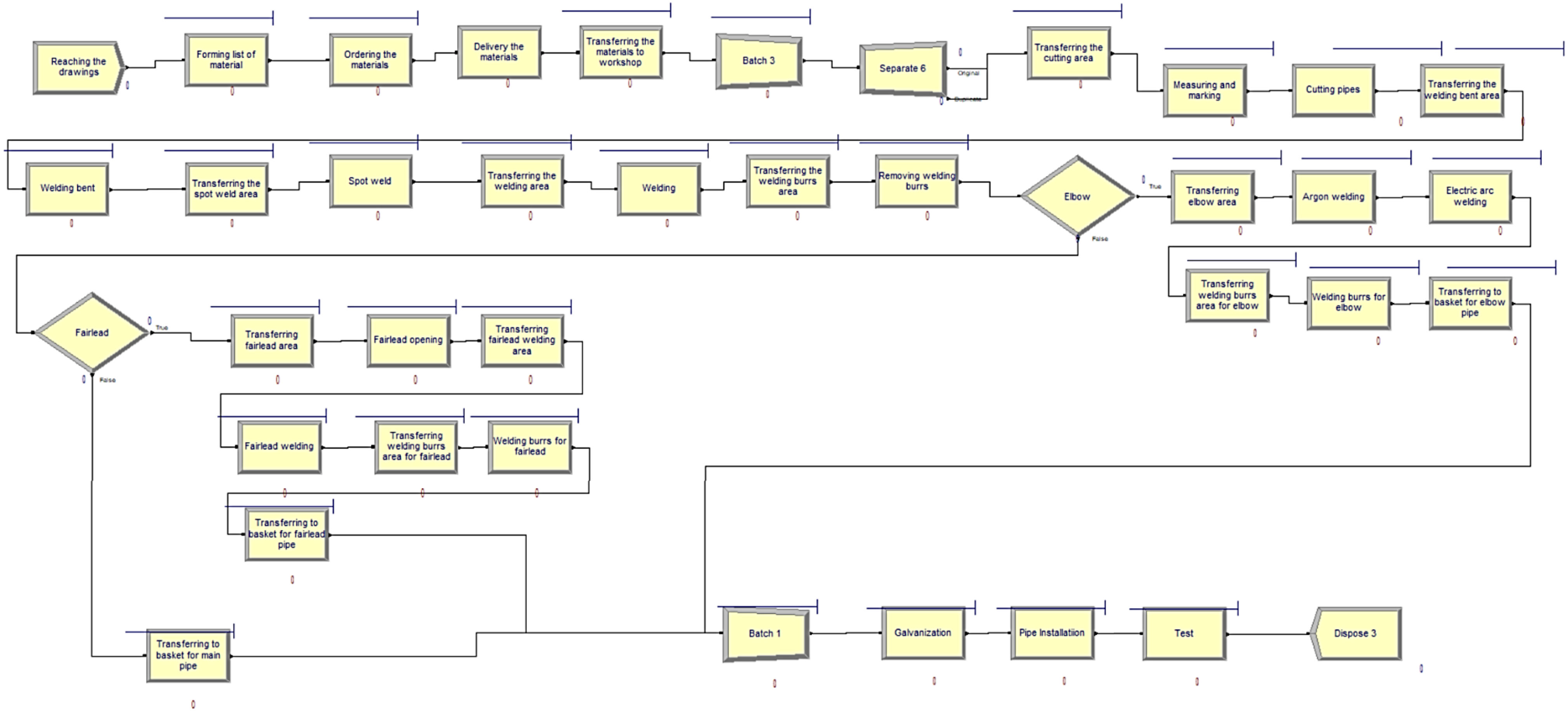


Figure 3. The flowchart of the processes entered the Arena Simulation Program.

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	Planning Engineer	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
2	Purschasing Staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
3	Forklift	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
4	Gantray crane	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
5	Cutting Staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
6	Welding bent staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
7	Spot weld staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
8	Welding staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
9	Welding burrs staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
10	Elbow welding staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
11	Fairlead staff	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
12	Other company	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
13	Staffs	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
14	Testing	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑

Figure 4. The resources assigned to Arena.

The Arena modeling utilized various modules, including Create, Process, Decide, Batch, Separate, and Dispose, each serving a specific purpose within the simulation. The reasons for using these modules is elaborated upon below:

- The Create module signifies the initiation of the process upon the arrival of BWTS drawings at the shipyard..
- The Process module facilitates the assignment of processes and corresponding durations to each task.
- The Decide module enables the separation of elbow and fairlead pipes from the main pipes.
- Batch and separate modules are responsible for signaling that only one product enters the system, followed by the production of 200 pipes for a BWTS.
- The Dispose module concludes the modeling after the test phase. This module marks the end of the process flow, as entities are removed from the simulation. It is essential to finalize each task using this module.

Based on the simulation outcomes, the system generated a total of 23 outputs. Table 3 shows the average and maximum queue numbers for each process.

Process	Average	Maximum Value
Cutting pipes	31.0672	131
Welding	29.4307	84
Measuring and marking	14.9918	131
Transferring to the cutting area	8.2	199
Transferring to the welding bent area	1.6728	26
Transferring to the spot weld area	0.7226	17
Transferring to the welding area	0.6297	7
Spot weld	0.5548	18
Fairlead welding	0.4715	5
Fairlead opening	0.3835	6
Transferring to the welding burrs area	0.3496	3
Transferring basket for the main pipe	0.1927	3
Electric arc welding	0.1235	3
Welding bent	0.0956	12
Argon welding	0.0807972	3
Transferring basket for elbow pipe	0.0642	3
Transferring to the welding burrs area for elbow	0.06342	3
Transferring to the elbow area	0.06298	3
Transferring to the fairlead area	0.06144	2

Transferring to the fairlead welding area	0.0604	2
Transferring basket for fairlead pipe	0.0597	2
Transferring to the welding burrs area for fairlead	0.0588	2
Removing welding burrs	0.0087822	1
Welding burrs for elbow	0.00543	1
Welding burrs for fairlead	0.0042	1
Forming a list of material	0	0
Galvanization	0	0
Ordering the materials	0	0
Pipe Installation	0	0
Test	0	0
Transferring the materials to the workshop	0	0

Table 3. The number of the queue for each process.

All processes have been allocated appropriate resources. Table 4 shows the resource names and their respective busy percentages. Table 4 provides insights into the labor resources used in the fabrication and installation of the pipes for the BWTS and the activity level of each employee during their working hours. For instance, the forklift was only in operation for 12.92 % of the total working time, while the gantry crane was used for around 63 %. This information allows us to observe the productivity of the labor force throughout the day in the ARENA simulation environment.

Resource	Busy
Cutting Staff	49.33%
Elbow welding staff	34.25%
Fairlead staff	52.10%
Forklift	12.92%
Gantray crane	63.30%
Other company	15.43%
Planning Engineer	48.70%
Purchasing Staff	99.70%
Spot weld staff	27.41%
Staffs	56.62%
Testing	63.14%
Welding bent staff	13.71%
Welding burrs staff	26.81%
Welding staff	68.58%

Table 4. The resources and percentage of busy.

5. RESULTS & DISCUSSION

To ensure the accurate representation of the real system in the simulation model, a thorough step-by-step monitoring of the entity flows was performed. The interactive debugger was used to trace the entities' progression through the system, starting with their entry into the system via the create module and ending with their exit via the dispose module. It was observed that the entities followed all the necessary steps in sequential order, confirming the fidelity of the system. The verification is deemed successful, indicating that the model actually represents the real system. However, in order to statistically compare and validate the output of the simulation model with the actual system output, data from the real system is required. Since this data collection process has not yet commenced and is not feasible in the current facility, consultations were held with experts to obtain validation through their approval.

Upon examining the output results of the system model created with the Arena Simulation Program, it was noted that certain processes had high queue numbers. Consequently, specific improvements were implemented with the aim of reducing the waiting queues. The target area for these improvements was determined by identifying the location with the highest queue occurrences in the previous model.

Analysis of the model results showed that the average number of queues for pipe cutting was approximately 131 (Table 3).

Accordingly, the first enhancement involved replacing the grinding machine with an electric saw for cutting the pipes. With this modification, the previous measurement and marking process was updated solely as a measurement step. The pipe cutting time using the grinding machine, which previously took at least 13 minutes (Table 4), was reduced to 9 minutes by using the electric saw. Similarly, the average time for measurement and marking, which was previously recorded as 3 minutes (Table 4), was also reduced to an average of 2 minutes with the revised procedure. As a result of this improvement, the number of queues and the waiting times for new entities are shown in Table 5.

Process	Average	Maximum Value
Welding	37.6967	121
Cutting pipes	16.3749	136
Transferring the welding bent area	8.3606	67
Transferring the cutting area	8.1607	199
Transferring the welding area	7.9977	41
Spot weld	7.4239	45
Transferring to the spot weld area	7.2731	42
Transferring to the welding burrs area	3.2615	17
Transferring basket for main pipe	1.7632	15
Fairlead welding	1.3672	11
Fairlead opening	1.1498	11
Welding bent	0.9099	28
Transferring to the fairlead area	0.632	7
Transferring elbow area	0.5147	7
Transferring fairlead welding area	0.4441	6
Transferring welding burrs area for elbow	0.3703	5
Transferring basket for elbow pipe	0.2791	5
Transferring welding burrs area for fairlead	0.2662	6
Electric arc welding	0.1899	7
Transferring basket for fairlead pipe	0.1863	6
Argon welding	0.1371	7
Removing welding burrs	0.0129	2
Welding burrs for fairlead	0.0065	1
Welding burrs for elbow	0.0064	1
Forming the list of material	0	0
Galvanization	0	0
Measuring and marking	0	0
Ordering the materials	0	0
Pipe Installation	0	0
Test	0	0
Transferring the materials to the workshop	0	0

Table 5. New queue waiting after the first improvement.

Significant changes in the number of queues were observed as a result of the initial improvement. Specifically, notable alterations were identified in the welding processes of the main pipes. The output analysis revealed approximately

37 entities were waiting in these welding procedures. Based on this finding, the second improvement entails replacing the electric arc welding method with a gas metal arc welding machine. On average, operations conducted with the electric arc welding took an average of 25 minutes, while the time was reduced to 17 minutes with the introduction of the gas-shielded welder. The results obtained after this improvement show the number of queues and the waiting times, which are shown in Table 6.

Process	Average	Maximum Value
Cutting pipes	16.348	135
Welding	13.759	75
Transferring the welding area	10.296	49
Transferring the welding bent area	8.839	68
Transferring the spot weld area	8.185	51
Transferring the cutting area	8.185	199
Transferring the welding burrs area	7.881	29
Spot weld	6.223	45
Transferring basket for main pipe	4.318	22
Fairlead welding	3.305	24
Fairlead opening	2.351	25
Transferring elbow area	1.508	12
Transferring fairlead area	1.371	13
Electric arc welding	1.048	15
Transferring welding burrs area for elbow	1.029	8
Welding bent	0.896	29
Argon welding	0.879	15
Transferring fairlead welding area	0.869	7
Transferring basket for elbow pipe	0.842	8
Transferring welding burrs area for fairlead	0.553	14
Transferring basket for fairlead pipe	0.411	14
Removing welding burrs	0.211	3
Welding burrs for elbow	0.009	1
Welding burrs for fairlead	0.005	1
Forming the list of material	0	0
Galvanization	0	0
Measuring and marking	0	0
Ordering the materials	0	0
Pipe Installation	0	0
Test	0	0
Transferring the materials to the workshop	0	0

Table 6. The new queue waiting after the second improvement.

The analysis of the results after the second improvement showed that the processes with the highest number of queues were pipe cutting and welding. As the pipe cutting process had already been improved and the installation of an additional electric pipe cutting saw would be costly, the focus shifted to improving the process with the next highest number of queues. This led to welding being identified as a target for improvement. However, as the improvement of this process would only take place in the next step, the focus shifted to optimizing the process with the third highest number of queues, which was transfer. The output analysis revealed waiting queues in the transfer processes, with an average of 8 to 10 entities waiting. To alleviate this situation, the proposed improvement was the introduction of a mobile crane. The average and maximum queue numbers resulting from the implementation of two cranes are also shown in Table 7.

Process	Average	Maximum Value
Welding	19.412	84
Cutting pipes	19.0822	155
Spot weld	10.2131	55
Transferring the cutting area	4.0683	198
Fairlead welding	1.9776	13
Fairlead opening	1.7359	13
Measuring and marking	1.3743	53
Transferring the welding bent area	0.8006	1
Welding bent	0.639	26
Electric arc welding	0.2692	4
Argon welding	0.1944	4
Transferring the spot weld area	0.075	1
Transferring the welding area	0.0228	1
Removing welding burrs	0.0154	1
Transferring the welding burrs area	0.0149	1
Welding burrs for elbow	0.0103	1
Welding burrs for fairlead	0.007	1
Transferring welding burrs area for elbow	0.0034	1
Transferring basket for main pipe	0.0033	1
Transferring fairlead welding area	0.002	1
Transferring basket for elbow pipe	0.002	1
Transferring welding burrs area for fairlead	0.0017	1
Transferring elbow area	0.0011	1
Transferring fairlead area	0.0011	1
Transferring basket for fairlead pipe	0.001	1
Forming a list of material	0	0
Galvanization	0	0
Ordering the materials	0	0
Pipe Installation	0	0
Test	0	0
Transferring the materials to the workshop	0	0

Table 7. The new queue waiting after the third improvement.

Based on the results obtained from this improvement, it is evident that the processes of welding, pipe cutting and spot weld are still experiencing waiting queues. To mitigate the waiting times in these areas, increasing the number of resources appears to be a viable solution. Therefore, the fourth improvement focuses on augmenting the workforce by increasing the number of welders involved in the welding and spot welding processes from 1 to 2. The average and maximum queue numbers resulting from this improvement are shown in Table 8.

Process	Average	Maximum Value
Cutting pipes	19.0822	155
Fairlead welding	4.9757	13
Transferring the cutting area	4.0603	198
Fairlead opening	3.7147	13
Welding	2.2215	84
Transferring the welding bent area	2.0422	1
Electric arc welding	1.9449	4
Argon welding	1.6357	4
Transferring the welding burrs area	1.5551	1
Transferring the welding area	1.4884	1
Transferring the spot weld area	1.452	1
Measuring and marking	1.3811	53
Transferring basket for main pipe	0.8893	1
Welding bent	0.5496	26
Transferring fairlead area	0.3018	1
Transferring elbow area	0.3004	1
Removing welding burrs	0.2462	1
Transferring welding burrs area for elbow	0.1666	1
Transferring fairlead welding area	0.1585	1
Transferring basket for elbow pipe	0.1568	1
Spot weld	0.14	55
Transferring welding burrs area for fairlead	0.0847	1
Transferring basket for fairlead pipe	0.08	1
Welding burrs for elbow	0.039	1
Welding burrs for fairlead	0.018	1
Forming a list of material	0	0
Galvanization	0	0
Ordering the materials	0	0
Pipe Installation	0	0
Test	0	0
Transferring the materials to the workshop	0	0

Table 8. The new queue waiting after the fourth improvement.

Based on the results obtained from the previous improvement show that the process with the highest number of queues is pipe cutting. However, due to the associated cost increase, this improvement is set aside, and attention is turned to the process with the next highest number of queues. Technological advancements alone do not offer a feasible solution for enhancing the fairlead welding process. Consequently, the transfer process is prioritized as the next area for improvement. As the installation of a third crane is not possible due to space constraints, the next process in line is the fairlead opening. The proposed improvement to this process is to use machine devices to open the fairlead instead of a blowtorch. This change will reduce the average opening time from 1 hour to 30 minutes, as verified through on-site measurements. The average and maximum number of waiting queues resulting from this improvement are shown in Table 9. Furthermore, Table 10 provides an overview of the updated resources and their corresponding busy percentages.

Process	Average	Maximum Value
Cutting pipes	19.0822	155
Transferring the cutting area	4.0659	198
Transferring the welding bent area	2.3166	33
Transferring the welding burrs area	1.9181	13
Transferring the welding area	1.8098	14
Transferring the spot weld area	1.7578	14
Electric arc welding	1.684	19
Welding	1.659	22
Argon welding	1.4475	19
Measuring and marking	1.3793	54
Transferring basket for the main pipe	1.0803	11
Welding bent	0.5533	25
Removing welding burrs	0.4513	15
Transferring elbow area	0.3787	7
Transferring fairlead area	0.3672	7
Transferring fairlead welding area	0.3555	4
Transferring welding burrs area for fairlead	0.3202	3
Transferring basket for fairlead pipe	0.2942	4
Transferring welding burrs area for elbow	0.2362	6
Transferring basket for elbow pipe	0.2222	4
Spot weld	0.1337	9
Welding burrs for fairlead	0.1216	4
Fairlead opening	0.0993	6
Welding burrs for elbow	0.0764	4
Fairlead welding	0.0255	9
Forming a list of material	0	0
Galvanization	0	0
Ordering the materials	0	0
Pipe Installation	0	0
Test	0	0
Transferring the materials to the workshop	0	0

Table 9. The new queue waiting after the fifth improvement.

Resource	Busy
Cutting staff	5.48%
Elbow welding staff	34.31%
Electric saw	24.66%
Fairlead CNC	16.32%
Fairlead staff	21.78%
Forklift	1.36%
Gantray crane	63.44%
Gas metal arc welding	46.58%
Other company	17.00%
Planning engineer	40.67%
Purchasing staff	9.83%
Spot weld staff	27.46%
Staffs	54.76%
Testing	6.31%
Welding bent staff	13.70%
Welding burrs staff	27.04%

Table 10. New resources and percentage of busy.

In the initial system configuration, the BWTS arrival times were scheduled every 15 days. Based on the simulation results obtained with this plan, the production of BWTSs was observed to be 23 units. However, in order to effectively evaluate the impact of the implemented improvements, it was necessary to modify the BWTS arrival times. Consequently, the arrival times were adjusted to occur every 8 days instead of 15 days. With this revised plan, the system continued its operation, resulting in an increase in the number of productions. Over a simulation period of 365 days, the total number of BWTS units produced reached 41. These improvements not only improved the efficiency of the system, but also contributed to increased production capacity.

Throughout the study, the focus of the improvements was on the stations where bottlenecks were identified. Each optimization step led to favorable outcomes, including reduced waiting times and improved processing durations within the overall process. The initial improvement involved substituting pipe-cutting with an electric saw instead of using a grinding machine, resulting in an average time saving of 5 minutes per pipe cut. The next improvement was to replace electric arc welding with a gas metal arc welding machine, which reduced the time needed to welding the pipes by 8 minutes. The third improvement was to increase the number of cranes from 1 to 2, speeding up all transfer processes by a factor of 2. In the fourth improvement, the number of spot welders and gas-shielded welding machines was increased from 1 to 2, reducing the duration of spot welding and welding processes by a factor of 2. Finally, a CNC (Computerized Numerical Control) machine was employed instead of a welding torch for opening the fairlead, resulting in a time saving of 30 minutes for each fairlead pipe. A summary of these improvements can be found in Table 11.

The system used	System to be used	Time earned
Pipe cutting with a grinding machine	Pipe cutting with an electric saw	5 minutes
Electric arc welding	Gas metal arc welding machine	8 minutes
Number of Cranes = 1	Number of Cranes = 2	-
The number of spot weld staff and gas metal arc welding machines is 1	The number of spot weld staff and gas metal arc welding machines is 2	-
Opening a fairlead with a blowtorch	Opening a fairlead with CNC	30 minutes

Table 11. Summary of improvements.

To further validate the effectiveness of these improvements, we conducted a statistical analysis comparing two datasets representing the percentage of busy resources before and after the implementation of the BWTS.

T-Test Results:

T-Statistic: -7.3522

P-Value: 1.3745e-06

The t-test results indicate a significant difference between the two datasets, with a p-value far below the 0.05 threshold. This suggests that the improvement measures taken are statistically significant.

Kolmogorov-Smirnov Test Results:

Test Statistic (D): 0.4464

P-Value: 0.0712

The Kolmogorov-Smirnov Test results show that the p-value is greater than 0.05, indicating that there is no statistically significant difference between the distributions of the two datasets.

Anderson-Darling Test Results:

For the First Dataset:

Test Statistic: 0.3175

Critical Values: [0.497, 0.566, 0.680, 0.793, 0.943] (at 15%, 10%, 5%, 2.5%, and 1% significance levels)

For the Second Dataset:

Test Statistic: 0.3186

Critical Values: [0.500, 0.569, 0.683, 0.797, 0.948]

The Anderson-Darling Test results indicate that the test statistics for both datasets are smaller than the critical values at the 5% significance level, confirming that both datasets can be considered normally distributed.

The T-Test indicates a statistically significant difference between the two datasets, affirming that the improvements implemented in the BWTS assembly line are effective.

The Kolmogorov-Smirnov Test shows no significant difference between the distributions, indicating the consistency of the data.

The Anderson-Darling test confirms that both datasets are normally distributed, which further confirms the robustness of the analysis.

Overall, the statistical tests support the conclusion that the improvements made to the BWTS assembly line are statistically valid, underpinning the reliability of the simulation results and demonstrating their positive impact on production efficiency. These findings provide crucial insights for refining operational processes and boosting productivity across diverse industrial contexts.

The installation of the BWTS encompasses both pipe production and installation processes. As previously mentioned, these improvements are not only applicable to shipyards involved in BWTS installation but also relevant to any company engaged in pipe production. The methods employed in these improvements are adaptable for implementation by any company.

Considering the long-term perspective, the investment in the equipment used for these improvements will prove to be cost effective and contribute to the company's profitability in the future. Embracing evolving technologies, these improvements prioritize the utilization of machinery over manual labor, thereby reducing production errors in future operations. Furthermore, they promote the health and safety of workers. By integrating various types of machines and systems that will be employed in future production, maximum efficiency and minimal errors can be achieved.

Analyzing the impact of the improvements implemented through simulation on the installed system, the annual production and installation of BWTSs in a workshop increased from 23 to 41 units. This represents a significant growth of approximately 78%, effectively doubling the production and installation capacity of shipyards. With this enhanced system feasibility, shipyards utilizing the improved production system can produce and install an additional 18 BWTSs per workshop per year. Considering that the improvements are primarily focused on pipe work, it becomes apparent that the acceleration and reduction of error margins can be achieved on various types of pipe-related tasks. These advantages enable shipyards to achieve their profitability goals and attract a larger customer base.

6. CONCLUSION

This study focusing on the examination of BWTSs and their installation efficiency, holds significant importance for addressing critical environmental concerns and ensuring sustainable maritime practices. The installation efficiency of BWTS is vital for several reasons. Firstly, it contributes to the protection of marine ecosystems by effectively reducing the ecological risks associated with the discharge of ballast water from ships. This mitigation prevents the introduction of non-native and potentially invasive species into the local environments, preserving biodiversity and maintaining the ecological balance. Secondly, efficient BWTS installation safeguards human health by minimizing the transmission of harmful bacteria, viruses and pathogens through ballast water. Thirdly, the study helps sustain the global economy by promoting compliance with international regulations such as the International Maritime Organization's Ballast Water Management Convention. By evaluating and improving the installation process, the study enhances operational efficiency, reducing potential delays and costs for shipyards. Ultimately, a comprehensive study of BWTS installation efficiency contributes to a greener, more sustainable maritime industry that protects ecosystems, human health and economic stability.

The pipe manufacturing and installation stage stands out as the most extensive and intricate phase in the BWTS process. This analysis conducted in a repair shipyard, based on thorough investigations and data, revealed that the high number of products in the queue and the low overall output were primarily attributed to manual labor-intensive production. To address this issue, the Arena Simulation Program was employed to assess the number of products waiting in the queue and determine the total output. The aim is to propose optimization solutions by evaluating the results obtained by entering the predecessor, successor and average times for each process into the program. Based on the results generated, the initial conditions and the proposed improvements are presented in Table 12, providing valuable insights to increase the efficiency and productivity of the BWTS pipe manufacturing and installation phase.

First Situation	Improvement
Pipe cutting with a grinding machine	Pipe cutting with an electric saw
Use of an electric arc welding	Use of gas metal arc welding machine
Number of cranes used 1	Number of cranes used 2
Number of resources for spot welding and gas metal arc welding 1	Number of resources for spot welding and gas metal arc welding 2
Opening the fairlead with a blowtorch	Opening the fairlead with a fairlead CNC

Table 12. Comparison between the first situation and improvements.

The simulation was used to identify delays and bottlenecks in pipe production and installation, and to optimise operational processes. Significant improvements were achieved as a result of these analyses. In particular, annual production was increased from 23 to 41 units, which corresponds to a 78% increase in productivity. These improvements are of far-reaching importance and provide valuable strategies for improving production efficiency in all areas of pipe manufacturing. Our findings provide important insights into improving operational processes and increasing productivity in various industrial contexts.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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