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Selective Waiting-Time Reduction in Indonesian Fiberglass Shipbuilding: A Digital Lean Simulation Framework

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Abstract

Background: Uniform waiting-time reduction in fiberglass shipbuilding may compromise essential technical processes, including curing, inspection, and safety checks. Therefore, waiting time must be classified according to its technical function and potential for reduction.
Objective: This study develops a simulation-based Digital Lean Manufacturing framework for selectively reducing waiting time in Indonesian engineer-to-order fiberglass shipbuilding.
Methods: A single-case study was conducted at PT Teluk Naga Bahari, Indonesia, covering eleven production stages. Value Stream Mapping (VSM) was integrated with deterministic discrete-event simulation using AnyLogic. Waiting time was classified into avoidable waiting (AW), reducible technical waiting (RTW), and fixed technical waiting (FTW). Five scenarios (S0–S4) were evaluated using waiting time, lead time, and Process Cycle Efficiency (PCE).
Results: The baseline recorded a cycle time of 157 days, waiting time of 67 days, lead time of 224 days, and PCE of 70.09%. Waiting time comprised 15 days of AW (22.39%), 24 days of RTW (35.82%), and 28 days of FTW (41.79%). Scenario S4 achieved the greatest simulated improvement, reducing waiting time to 44 days and lead time to 189 days while increasing PCE to 76.72%. Lead time decreased by 15.63%, while FTW was preserved.
Conclusion: Selective waiting-time classification enables targeted efficiency improvements while preserving essential technical constraints. However, simulated reductions in RTW require material and process validation before implementation. The framework provides a transferable decision-making approach for fiberglass shipyards.

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INTRODUCTION

The shipbuilding industry faces pressure to shorten project completion times without compromising product reliability or process discipline (Hansen et al., 2020; Praharsi et al., 2022; Strandhagen et al., 2022). This challenge is particularly pronounced in shipbuilding because its products are complex, production volumes are low, and workflows tend to follow an engineer-to-order (ETO) model. These characteristics result in long production durations, frequent design changes, extensive cross-functional coordination, dependence on labor, suppliers, and workspace, and interdependent technical sequences. A recent systematic review of Lean applications in the shipyard sector confirms that long cycle times and lead times are inherent characteristics of shipbuilding, while Value Stream Mapping (VSM) is among the most frequently used Lean tools for identifying waste and supporting flow improvement (Neves et al., 2025). Globally, shipbuilding remains one of the manufacturing sectors with the greatest challenges in achieving efficient

production flow: production durations are typically measured in months, and non-value-adding waiting frequently accounts for a substantial proportion of lead time. Nevertheless, quantitative evidence of the benefits of Lean in shipyards remains scarce (Neves et al., 2025). In Indonesian fiberglass shipyards, these challenges are compounded by manual composite-manufacturing processes, making improvements in the ratio of processing time to lead time an urgent productivity concern.

These conditions are particularly critical in small- and medium-sized fiberglass shipyards. Composite-based production involves not only transformation activities performed by operators but also waiting periods associated with curing, post-curing, leak testing, inspection, material stabilization, and readiness between successive stages. Consequently, waiting time cannot be treated as a single, homogeneous category of waste. Some waiting arises from coordination, administration, material delays, or scheduling and can, in principle, be eliminated. Other waiting is technical in nature but may still be shortened if process conditions are appropriately controlled. The remaining waiting must be preserved because it represents a technical constraint necessary to ensure quality or safety. Interventions that pursue lead-time reduction without distinguishing among these three categories may lead to erroneous decisions during the initial diagnosis.

Lean Manufacturing provides principles for identifying non-value-adding activities and designing more efficient production flows. VSM translates these principles into current-state and future-state representations that illustrate the relationships between process activities and waiting time. However, VSM is essentially an aggregate and relatively static representation of a production system. When improvement scenarios alter process durations, resource availability, queues, or relationships between successive stages, their system-wide effects cannot always be assessed through future-state mapping alone. Antonelli & Stadnicka (2018) demonstrated that VSM and simulation rely on different representations of a system—deterministic process flows and dynamic queueing networks, respectively—and that integrating the two approaches is beneficial when their objectives and application rules are clearly defined.

The digitalization of Lean provides a mechanism for addressing these limitations. Digital value streams can link Lean improvement logic with digital representations of production processes Arey et al. (2021), while the development of VSM approaches incorporating modeling and simulation enables more complex process behavior to be evaluated before changes are implemented (Ferreira et al., 2022). In this article, the term simulation-based Digital Lean Manufacturing is used in a specific, limited sense to denote the integration of Lean-based VSM diagnosis with digital experimentation through discrete-event simulation (DES).

DES is relevant to ship production because production events occur in a defined sequence, require resources, and generate queues and waiting times. In the shipbuilding context, Okubo & Mitsuyuki (2022) demonstrated that system modeling and process simulation can support production planning, bottleneck identification, and quantitative evaluation of worker reallocation. However, shipyard simulation studies generally focus on planning, resource utilization, scheduling, or block logistics. Evidence explicitly integrating waiting-time classification based on composite-process risks, intervention-selection rules, and scenario evaluation across the entire fiberglass ship production flow remains limited. Critically, even recent studies that combine VSM with DES to reduce lead time continue to treat waiting time as a single, uniformly reducible quantity. The present study departs from this approach by treating the technical reducibility of each waiting period as an explicit decision variable rather than an aggregate reduction target.

The review of Lean applications in shipbuilding also calls for further research that quantitatively measures benefits and develops implementation strategies suited to shipyard environments (Neves et al., 2025). This research gap highlights two issues. First, waiting time is often calculated as an aggregate quantity, obscuring the technical status of individual waiting periods. Second, future-state VSM can illustrate shorter lead-time targets but cannot, by itself, demonstrate that the proposed combination of changes is systemically feasible. This study addresses the first issue through a three-tier classification: avoidable waiting (AW), reducible technical waiting (RTW), and fixed technical waiting (FTW). AW refers to nontechnical waiting that can be targeted for elimination or reduction through Lean interventions; RTW refers to technical waiting that may be shortened only through controlled interventions supported by

evidence of process suitability; and FTW refers to the minimum waiting time that must be maintained. The second issue is addressed through AnyLogic simulation, which translates the current state, reduction rules, and multiple future-state scenarios into a DES model.

The application of Lean Manufacturing in shipbuilding must account for the nature of ship production, which differs significantly from repetitive manufacturing. Ships are generally produced in low volumes, are large and complex, and follow engineer-to-order or build-to-order production flows. Work also proceeds through location-bound projects, involves multiple disciplines, and depends on the coordination of design, materials, labor, suppliers, workspace, and technical sequences. These conditions increase the likelihood of queues, unnecessary movement, rework, and interstage delays. The systematic review by Neves et al. (2025) shows that the literature on Lean shipbuilding is dominated by case studies and identifies long cycle times, product complexity, and dependence on labor and suppliers as important challenges. Sharma & Gandhi (2017) also emphasize that the project-based nature of shipbuilding and the immobility of the product require Lean principles to be adapted to shipyard production systems rather than applied as direct copies of mass-production lines.

In this context, Lean Manufacturing provides an approach for identifying non-value-added activities and improving flow, while value stream mapping (VSM) provides a visual representation of the relationships among process flow, information flow, processing time, and waiting time. Current-state VSM is used to depict actual operating conditions and identify sources of waste, whereas future-state VSM defines the proposed process configuration. Neves et al. (2025) identified VSM as one of the most frequently used Lean tools in shipbuilding research. Studies on ship panel assembly also show that process mapping can support waste identification, activity rearrangement, and the formulation of more efficient future-state configurations (Kolich et al., 2017; Oliveira & Gordo, 2018). Thus, VSM serves not only as a process diagram but also as a diagnostic tool that connects operational problems with the design of Lean interventions. However, most of these applications remain descriptive and evaluate interventions primarily against aggregate lead-time targets. For example, the application of Lean to composite repair shortened lead time without distinguishing technically required pauses from genuinely wasteful waiting (Adly Ishak et al., 2018). This limitation—the assumption that all waiting is equally reducible—is precisely what the classification proposed in the present study addresses.

Evidence from the Indonesian fiberglass shipbuilding industry further reinforces the relevance of this approach. In a case study of fiberglass ship production, a waste relationship matrix identified waiting as the dominant waste category. A future-state VSM incorporating mold reuse, pre-process material preparation, parallel or overlapping activity execution, and layout improvements was projected to increase process cycle efficiency and reduce total waiting time (. These findings indicate that VSM can reveal context-specific improvement opportunities in Indonesian fiberglass shipyards. However, the proposed future-state configuration in that study remained a mapping-based improvement design and was not tested using a dynamic simulation model capable of representing queues, process dependencies, and resource changes.

Existing literature also tends to treat waiting as a single category of waste that should be reduced, without distinguishing the technical reasons underlying individual pauses. Such an approach is appropriate for waiting caused by material delays, coordination problems, or scheduling constraints but risks producing inappropriate reduction targets when applied to composite manufacturing processes. In fiberglass ship production, some pauses may be associated with curing, material stabilization, inspection, or testing required to ensure process suitability and product quality. Therefore, the role of VSM needs to be expanded beyond identifying the magnitude of waiting to include assessing its causes, the feasibility of intervention, and the limits of reduction. This limitation establishes the need for simulation-based Digital Lean Manufacturing: current-state and future-state VSM provide the diagnostic structure, while waiting-time reduction decisions are tested digitally and constrained by quality and safety requirements.

Digital Lean Manufacturing has developed in response to the need to maintain Lean's focus on customer value and waste reduction while using digital representations to strengthen decision-making. In this context, digitalization is not an end in itself but a means of making the diagnosis, experimentation, and evaluation of Lean improvements more data-driven. Arey et al.

(2021) describe digital value streams as an approach that connects value stream mapping with digital technologies to support process improvement. The review by Nor Azian et al. (2025) also shows that the integration of Lean and Industry 4.0 is largely directed toward improving production efficiency, resource management, and operational performance. Nevertheless, the level of digitalization must be distinguished conceptually so that a study is not automatically classified as involving a smart factory or digital twin merely because it uses simulation software. In simulation-based Digital Lean Manufacturing, Lean, VSM, and simulation perform different but complementary functions. Lean provides the principles for identifying problems and determining intervention priorities; VSM establishes system boundaries, process sequences, and current-state and future-state performance measures; and simulation translates these configurations into computational models that can be experimentally evaluated.

Antonelli & Stadnicka (2018) emphasize that VSM and simulation use different forms of representation: VSM simplifies process flow to support diagnosis, whereas simulation represents dynamic behavior, queues, resource constraints, and temporal variation. Therefore, their integration should begin with clearly defined improvement questions rather than merely digitizing process maps. Ferreira et al. (2022) extend this idea by demonstrating that modeling and simulation can enrich VSM when process relationships become more complex than static maps can adequately represent.

In this study, AnyLogic is used as a discrete-event simulation (DES) modeling environment to represent eleven stages of fiberglass ship production, including activity durations, waiting times, process sequences, and parameter changes across improvement scenarios. Current-state VSM provides the structural basis for the initial model, whereas future-state VSM is developed from the results of waiting-time classification and the application of intervention rules. The resulting scenarios are compared using waiting time, lead time, and process cycle efficiency (PCE).

The purpose of simulation is not to prove that all proposed interventions will necessarily succeed when implemented in the field but to test the logical consistency and quantitative consequences of different parameter combinations before implementation. In this way, the future state becomes more than a normative target depicted on a map; it becomes an operational hypothesis that can be verified, validated against baseline conditions, and subjected to sensitivity analysis.

This position also establishes the limits of the study's claims. The model is not classified as a digital twin because it does not receive real-time data updates, maintain a bidirectional connection with a physical system, or directly control shipyard operations. The study also does not fall within the full scope of smart manufacturing, which typically involves sensor integration, cyber-physical systems, machine-to-machine connectivity, and adaptive decision-making. The most appropriate term is *simulation-based Digital Lean Manufacturing*, which describes a configuration that digitizes Lean improvement experiments without changing Lean's methodological role as the basis for decision-making. In fiberglass production, this configuration is important because waiting-time reduction must not be determined solely by the magnitude of waiting. Instead, simulation must apply the AW, RTW, and FTW classification while maintaining the quality and safety limits established before the scenarios are executed. To avoid conceptual overlap, the three levels of digitalization are explicitly distinguished: smart manufacturing presupposes sensor-based cyber-physical integration and machine-to-machine connectivity; a digital twin requires a bidirectional, real-time data link to the physical asset; and simulation-based Digital Lean Manufacturing, as used here and in comparable digital-VSM studies Mrabti et al. (2025), remains an offline, one-way *what-if* analysis layer that digitizes Lean decision-making without real-time coupling.

Discrete-event simulation (DES) represents a system as a sequence of events that change the state of a process at specific points in time. This approach is suitable for ship production because each unit moves through a sequence of activities, uses resources, waits for the next process to become ready, and may experience variations in processing times and queue lengths. Unlike VSM calculations, which generally rely on aggregate values, DES makes it possible to examine the interactions among processing time, waiting time, capacity, worker availability, and flow rules as dynamic system behavior. Therefore, DES can be used to test the consequences of a future-state design before physical changes, additional labor, or technology investments are

implemented in the shipyard.

The use of simulation in shipbuilding has primarily developed to support production planning, scheduling, resource allocation, bottleneck identification, and the evaluation of alternative work methods. Okubo & Mitsuyuki (2022) developed ship production system models and discrete-time process simulations to compare production plans, identify bottleneck processes, and quantitatively evaluate worker reallocation. These findings demonstrate that simulation can reveal system-level effects that are difficult to assess using schedules or static process maps alone. However, this research focuses on production-plan feasibility and labor distribution rather than classifying the causes of waiting or determining the limits of waiting-time reduction in composite manufacturing processes.

A recent systematic review further reinforces the position of DES in shipyard research. Arif et al. (2026) reviewed 215 shipyard simulation publications from 2003 to 2024 and found that 88% of the studies focused on shipbuilding, with DES representing the dominant simulation paradigm. The review also shows that research remains fragmented by activity and generally emphasizes operational efficiency, resource allocation, scheduling, and facility-use conflicts. Digital twins, hybrid approaches, and cross-lifecycle integration remain limited. This evidence confirms the maturity of DES as a tool for operational experimentation but also indicates that the selection of variables and experimental rules must be derived from specific production problems.

In this study, the specific problem is the selective reduction of waiting time in the production flow of a single engineer-to-order fiberglass vessel. The AnyLogic model does more than transfer the eleven process boxes in the VSM into software; it operationalizes the rules that AW can be targeted for Lean improvement, RTW can be reduced only through validated technology or process control, and FTW must be maintained. Thus, the application of DES is extended from production scheduling and resource evaluation to testing decision rules constrained by quality and safety requirements. The current-state configuration must first reproduce the field baseline. After adequate verification and validation, scenarios S0–S4 are compared using waiting time, lead time, and PCE. This distinction is important: simulation demonstrates the modeled consequences of different scenarios, whereas the technical feasibility of reducing RTW still requires supporting process evidence before implementation. In relation to the existing literature, the present model is narrower in scope than general shipyard scheduling simulations but more specific in purpose. Whereas hybrid VSM-DES studies in other sectors use simulation primarily to confirm aggregate efficiency gains Woldemicael et al. (2024), the present study uses DES to test class-specific reduction rules and verify that fixed technical waiting is never violated.

Waiting times in fiberglass ship production differ fundamentally from administrative queues and material delays. In the hand lay-up process, resin and catalyst are mixed, applied in conjunction with reinforcing layers, and leveled before the laminate is allowed to cure. The laminate must reach the required condition before it can be released for subsequent operations, such as cutting, assembly, or testing, as applicable to the production sequence. Saputra et al. (2024) describe fiberglass boat fabrication as a sequence involving mold preparation, resin and fiber application, drying or curing, demolding, and finishing. Curing may take several days, depending on the resin system and environmental conditions. Thus, the pause following lamination is not automatically waste because part of it is inherent in the material transformation required for subsequent processing.

The nature of this process also demonstrates that curing time cannot be altered solely to meet efficiency targets. Ismail et al. (2024) reported the use of methyl ethyl ketone peroxide (MEKP) at 0.5% by resin weight as a curing agent in samples representing the practices of eight Indonesian fiber-reinforced polymer (FRP) shipyards. The study found that the laminate configuration significantly affected tensile and flexural strength, whereas the type of unsaturated polyester resin primarily affected tensile strength. Muharom et al. (2024) used a controlled resin-to-catalyst ratio and a 24-hour curing period during specimen fabrication. Their results showed that laminate arrangement affected mechanical strength and that none of the tested variations met BKI requirements. This evidence does not establish a universal curing duration for ships, but it confirms that resin type, catalyst dosage, laminate configuration, curing conditions, and final product quality are interrelated.

Consequently, waiting time in VSM needs to be classified according to its function and the feasibility of intervention. Avoidable waiting (AW) includes delays that are not required for material transformation or process assurance, such as waiting caused by material unavailability, delayed decisions, unready tools, poor coordination, or unsynchronized work sequences. Reducible technical waiting (RTW) refers to technically necessary waiting that may potentially be shortened through the control of temperature, humidity, ventilation, material formulation, or curing technology, but only after the process window and resulting laminate properties have been demonstrated to meet applicable requirements. Fixed technical waiting (FTW) refers to the minimum waiting time that must be maintained, including the time required for minimum curing, stabilization, inspection, leak testing, alignment, and safety checks, as determined by the characteristics and requirements of the relevant process.

This classification changes the improvement logic from uniform reduction to selective decision-making. Lean interventions are prioritized for AW because reducing such delays does not alter the material-property formation mechanism. RTW is treated as a conditional improvement opportunity: any reduction assigned in AnyLogic is an experimental parameter, not evidence that hot-air application, catalyst adjustment, or another technology has been successfully implemented or validated. FTW is not reduced in any scenario because it serves as a constraint. This position is consistent with evidence that variations in materials and lamination processes can produce significant differences in mechanical properties (Muharom et al., 2024). Therefore, reductions in lead time and improvements in PCE can be accepted only when they result from validated AW reductions or technically validated RTW reductions, without eliminating pauses required for quality and safety.

The literature synthesis reveals four interrelated research gaps. First, Lean and VSM research in shipbuilding has identified waiting as an important form of waste but generally treats it as a homogeneous quantity to be reduced (Neves et al., 2025). Second, future-state VSM can define shorter process configurations but cannot, by itself, adequately represent queues, variation, process dependencies, and resource changes; simulation is therefore needed to capture these dynamics (Antonelli & Stadnicka, 2018). Third, shipyard simulation has matured in the areas of production planning and resource allocation but has not been specifically directed toward classifying the function of waiting in fiberglass ship production (Arif et al., 2026). Fourth, materials research shows that laminate configuration, resin type, catalyst dosage, and curing conditions are related to mechanical properties. Consequently, reductions in technical waiting cannot be determined solely on the basis of lead-time targets (Muharom et al., 2024).

Based on these gaps, the research framework is built around three design propositions. The first proposition states that improvement decisions become more precise when waiting is classified before interventions are selected: AW becomes a target for Lean improvement, RTW becomes a target for validated technological or process-control interventions, and FTW must be maintained. The second proposition states that the future state becomes more defensible when intervention rules are translated into DES experiments and evaluated against the current-state baseline. The third proposition states that lead-time reductions and PCE improvements are acceptable only when FTW remains intact and RTW reductions remain within technically validated limits. These three propositions treat quality and safety as constraints rather than outcomes that can be assumed to improve.

Operationally, the framework consists of seven sequential stages. First, current-state VSM establishes the system boundary, the sequence of eleven processes, cycle times, waiting times, lead time, and PCE. Each waiting component is then traced to its cause and technical function and classified as AW, RTW, or FTW. The assigned class determines the applicable intervention rules and permitted reduction parameters. Next, the current-state structure and decision rules are translated into an AnyLogic model, which is logically verified and validated against the field baseline. Scenarios S0–S4 are then executed and compared using the same performance indicators. Finally, the selected scenario is translated into a future-state VSM and phased implementation recommendations.

The novelty of the framework lies not in the separate use of Lean, VSM, DES, or AnyLogic but in integrating a waiting-time taxonomy, class-specific intervention rules, scenario-based experimentation, and acceptance limits into a single, auditable decision-making process. The

framework may be applicable to other fiberglass shipyards if each organization maps its own processes, establishes a validated baseline, defines technical limits based on the materials and procedures used, and calibrates the model to its available resources. Because the empirical evidence in this study comes from a single shipyard and one engineer-to-order product flow, the claimed transferability concerns the procedure and structure of the framework rather than the direct generalizability of the S0–S4 waiting-time reduction magnitudes. The four identified gaps map directly onto the framework: the waiting-time taxonomy addresses the assumption that all waiting is equivalent; DES experimentation addresses the limitations of static process maps; fiberglass-specific classification addresses the gap in shipyard simulation research; and material-based constraints address the question of technical reducibility. Each design proposition is therefore traceable to a specific limitation in the prior literature.

Accordingly, this article addresses three research questions: (1) How can waiting time in fiberglass ship production be classified according to its causes and process constraints? (2) How should Lean and controlled process-technology interventions be selected for each waiting-time category? (3) How do these interventions affect waiting time, lead time, and Process Cycle Efficiency (PCE) when evaluated using AnyLogic? The case study covers eleven processes, from working-design development to sea trials, at PT Teluk Naga Bahari, Indonesia. The validated field baseline consists of a cycle time of 157 days and a waiting time of 67 days, yielding a total lead time of 224 days. This correction excludes seven days of consultation with Biro Klasifikasi Indonesia (BKI) that were recorded in the initial documentation but, following field validation, were determined to be unnecessary and were not carried out for the observed project.

The contributions of this article comprise three parts. First, it presents a decision framework that explicitly identifies the status of each waiting period before reduction targets are assigned. Second, it operationalizes this framework through quantitative relationships that preserve FTW, reduce RTW according to controlled process-technology intervention factors, and reduce AW according to Lean improvement factors. Third, it provides empirical evidence from an Indonesian fiberglass shipyard and demonstrates how multiple intervention levels can be evaluated digitally before implementation. The limits of the study's claims are also explicitly established: quality and safety serve as constraints in scenario selection rather than as outcome variables for which improvement is claimed. The next section discusses the theoretical foundations, framework development and validation methods, current- and future-state results, theoretical and practical implications, and limitations and directions for future research. The novelty of this work therefore lies not in the individual use of Lean, VSM, or DES, but in its waiting-time taxonomy (AW/RTW/FTW), which transforms an undifferentiated reduction target into class-specific, auditable intervention rules. This represents an advancement over previous Lean–VSM studies that optimize total waiting time without distinguishing its technical function. To clarify the intended benefits, the study's academic contribution is a transferable decision framework that formalizes waiting-time classification within simulation-based Digital Lean Manufacturing, while its practical contribution is a staged, risk-aware implementation pathway that enables shipyards to achieve lead-time reductions through design improvements and reductions in avoidable waiting before committing to capital-intensive process-technology changes.

METHOD

Case study design and system boundary

This study employed an applied research approach with a single-case study design and a mixed-methods strategy. The qualitative component was used to understand the workflow, the causes of pauses, the technical functions of waiting time, and the feasibility of interventions through observation and semistructured interviews. The quantitative component was used to construct the current-state VSM, calculate key indicators, and conduct discrete-event simulation (DES) experiments. The unit of analysis was the production flow of a single engineer-to-order fiberglass fishing vessel at PT Teluk Naga Bahari, Indonesia. The system boundary extended from working-design development to sea trial; procurement activities outside the shipyard's control and vessel operations after delivery were excluded from the model. The shipyard and vessel were selected purposively. PT Teluk Naga Bahari was an established Indonesian small- and medium-

sized fiberglass shipyard whose engineer-to-order, low-volume production and manual composite processes were considered representative of the segment under study. The shipyard also granted full access to its production floor, records, and personnel, which was a prerequisite for the detailed tracing required by the classification framework.

The production flow was divided into eleven stages: working-design development; mold preparation and fabrication; hull lamination; superstructure lamination; demolding; hull and deck joining; internal outfitting; engine and propulsion installation; interior and finishing; testing and commissioning; and sea trial. A single vessel was modeled as the primary entity moving sequentially through the production system. Selecting a single case enabled an in-depth analysis of the underlying mechanisms, but the resulting numerical findings were not intended to represent all Indonesian shipyards. The methodological objective was to assess the transferability of the classification and experimentation procedures rather than to statistically generalize the magnitudes of waiting-time reductions.

Data sources and current-state VSM construction

Primary data were obtained through direct observation of all production stages, time studies, and semistructured interviews with operators, supervisors, the production manager, and the shipyard owner. Secondary data included production records, schedules, work procedures, process specifications, and available technical documents. The input variables included process sequence, cycle time, waiting time, number of operators, resource capacity, working hours, and causes of pauses. Data validity was assessed through observation–interview–documentation triangulation, confirmation with the company, and unit-consistency checks. All durations were converted to days so that the VSM and simulation model used a consistent time basis. To improve traceability, the qualitative database was defined as follows: observations covered all eleven production stages throughout the complete build cycle of the observed vessel; the time study recorded cycle and waiting durations for each stage; and semistructured interviews were conducted with four categories of informants (operators, supervisors, the production manager, and the shipyard owner) to investigate the causes and technical functions of individual pauses. Interview findings were cross-checked against production records and work procedures through observation–interview–documentation triangulation.

The current-state VSM was constructed by separating cycle time from waiting time at each stage. Activities were also classified as value-added, necessary non-value-added, or non-value-added to support the Lean diagnosis. Data reconciliation was performed before modeling because the initial table contained inconsistencies in waiting-time aggregation. The finalized baseline used in the article, as reported in Table 1, comprised a cycle time of 157 days and a corrected waiting time of 67 days, resulting in a baseline lead time of 224 days for scenario S0. Consequently, the initial-record figure of 74 days was not used as the reference value for the experiments reported in the article. This correction trail was retained to ensure that the data transformation remained auditable.

Table 1

Classification of Waiting Time in Fiberglass Ship Production (Illustrative Application of the AW–RTW–FTW Classification Criteria to the Case-Study Waiting Times; the empirical classification results are formally reported and analysed in Table 2, Results.)

No.	Process stage	Actual WT (days)	Fixed technical waiting (days)	Reducible technical waiting (days)	Avoidable waiting (days)
1	Working-design development	7	0	0	7
2	Mold preparation and fabrication	14	7	7	0
3	Hull lamination	17	10	7	0
4	Superstructure lamination	12	6	6	0
5	Demolding	0	0	0	0

No.	Process stage	Actual WT (days)	Fixed technical waiting (days)	Reducible technical waiting (days)	Avoidable waiting (days)
6	Hull & deck joining	3	1	1	1
7	Internal outfitting	3	1	1	1
8	Engine & propulsion installation	7	1	1	5
9	Interior & finishing	1	0	1	0
10	Testing & commissioning	2	1	0	1
11	Sea trial	1	1	0	0
	Total	67	28	24	15

Source: Data processed 2026

AW–RTW–FTW classification criteria

Each waiting component was traced to its underlying cause and then classified using four questions: Was the pause required for material transformation? Was it required for inspection or safety? Could its duration be changed without compromising the required output? What intervention would be necessary? Avoidable waiting (AW) was assigned when a pause resulted from coordination problems, delayed decisions, material availability, queues, or scheduling and had no minimum technical function. Reducible technical waiting (RTW) was assigned when a pause served a technical function but could potentially be shortened through process control or technology. Fixed technical waiting (FTW) was assigned when the minimum duration had to be maintained for curing, stabilization, alignment, inspection, leak testing, other required testing, or safety.

The initial waiting-time classification presented in Table 1 yielded 28 days of FTW, 24 days of RTW, and 15 days of AW, totaling the corrected waiting time of 67 days. Two internal assessors—the researcher and the person in charge of production—reviewed the cause and classification of each pause, while components associated with resin or laminate processes were treated as conditional technical decisions. When the function of a pause could not be established, a conservative rule was applied by provisionally classifying it as FTW. Because the classification relied on the judgments of two internal assessors, the potential for subjectivity was acknowledged and mitigated in three ways: a fixed four-question protocol was applied consistently to every pause, disagreements were resolved by applying the conservative rule of classifying uncertain pauses as FTW, and all classifications were confirmed with the shipyard. Nevertheless, residual subjectivity in RTW classification remained a stated limitation and required further validation by materials experts.

A reduction in RTW was not considered feasible for implementation merely because it improved the simulation results. Actual feasibility required supporting technical data sheets for the materials, specimen testing or assessment of the degree of cure, mechanical-property testing, and approval of the relevant technical procedures.

Intervention determination rules

The waiting-time classification determined the applicable intervention. AW was prioritized for Lean interventions such as material control, standardized coordination, visual management, inspection scheduling, and progressive design freeze. RTW was included only in scenarios involving controlled technological or process interventions, such as temperature and humidity control, ventilation, curing-room management, hot-air application, or infrared regulation, without presupposing that any one technology constituted the final solution. FTW was held constant and was not permitted to decrease. The design process was treated separately: design cycle time was reduced from 42 days to a maximum of 30 days based on the capacity of three engineers and confirmation from the shipyard. Hull-design and safety-related elements had to be frozen before production, whereas interior revisions during the seven-day period were moved off the critical path through concurrent engineering rather than eliminated.

Future-state parameter formulation

For process (i), future-state waiting time was calculated by retaining fixed components and modifying only those components that met the intervention criteria:

$$WT^{fs}{}_{,i} = FTW_i + RTW_i(1 - r_t) + AW_i(1 - r_l)$$

where $WT^{fs}{}_{,i}$ is the future-state waiting time of process i; r_t is the proportion of RTW reduction through technology or process control; and r_l is the proportion of AW reduction through Lean interventions. The values r_l and r_t are experimental levels, not universal causal estimates. Design cycle time is changed separately based on case evidence; cycle times of other processes are maintained unless there is documented technical basis. A scenario can only be accepted if FTW remains intact and all changes can be traced to their class rules.

AnyLogic model implementation

The DES model was developed in AnyLogic Professional using the Process Modeling Library. A Source block generated a single ship entity; each production stage was represented by a Service block; a Delay block represented identified waiting periods; a ResourcePool represented operators; and a Sink block recorded completed ships. Within each Service block, resources followed the seize–delay–release mechanism. Process routes, capacities, and time units were aligned with those specified in the current-state VSM. Because the available process-level observational evidence was insufficient to estimate probability distributions reliably, deterministic parameters were used in the baseline model. This choice maintained traceability to the VSM but limited the model's ability to support inferences about stochastic variation and queues.

The model recorded entity entry and exit times, cycle time, waiting time, lead time, throughput, work in process (WIP), queue lengths, and resource utilization. The primary experiment represented the completion of a single engineer-to-order vessel; therefore, no warm-up period was applied. If a future model version incorporates multiple ship arrivals and stochastic durations, the warm-up period, number of replications, random seeds, and confidence intervals will need to be redefined. This distinction prevents deterministic single-vessel outputs from being reported as probabilistic estimates. It must also be emphasized that the deterministic single-vessel configuration could not represent the temporal variability inherent in shipbuilding, including rework, weather effects, supplier delays, and fluctuations in curing conditions. Accordingly, the model outputs were interpreted as evidence of logical consistency and as verification checks rather than statistical predictions. A stochastic extension incorporating established verification and validation procedures Sargent (2013) would be required before claims concerning variability could be made.

Scenario design S0–S4

Five scenarios were arranged sequentially to distinguish the effects of different intervention groups. S0 represented the corrected baseline without intervention. S1 applied only design improvements, including a maximum design cycle time of 30 days and the parallel execution of interior revisions. S2 retained the design improvements and introduced a 20% reduction in AW. S3 combined the design improvements with a 35% reduction in AW and a 25% reduction in RTW. S4 served as the most aggressive stress-test scenario, combining the design improvements with a 50% reduction in AW and a 50% reduction in RTW. FTW was maintained at 28 days across all scenarios. The process sequence and basic resource capacities remained unchanged so that differences in the outputs could be attributed to the intervention parameters.

Verification, validation, and sensitivity analysis

Verification followed the distinction between implementation checking and system-representation checking described by (Sargent, 2013). Structural checks included model compilation, block connections, data types, and units. Dynamic checks were conducted through animation, entry–exit time traces, queue and resource inspections, and tests confirming that a single ship passed through all eleven processes without skipped stages, entity loss, deadlock, or

negative time values. The time balance was also checked to ensure that lead time equaled cycle time plus waiting time. Extreme-value tests were conducted with (r_l=r_t=0) and at the maximum specified reduction levels to ensure that FTW was never reduced.

Current-state validation was conducted using three forms of evidence. First, face validation with the shipyard was used to check the process sequence, resources, causes of waiting, and plausibility of the modeled behavior. Second, black-box comparison was used to compare the model's cycle time (CT), waiting time (WT), lead time (LT), throughput, and bottleneck with the field baseline. Third, parameter reconciliation ensured that the model used for the article reproduced the corrected baseline values of 157, 67, and 224 days rather than the original baseline. Absolute and percentage deviations were reported for each key performance indicator (KPI). Agreement at the aggregate level of 0% was not considered sufficient if individual process-stage values failed to match. Sensitivity analysis was conducted by applying staged changes in AW and RTW across scenarios S0–S4 and examining whether the scenario rankings remained consistent. Technical validation of RTW remained a prerequisite for implementation and was treated as distinct from validation of the DES logic.

Evaluation indicators and selection rules

The primary indicators were total waiting time, total lead time, and process cycle efficiency (PCE). Lead time was calculated as the sum of cycle time and waiting time. To maintain consistency with the shipyard's current-state VSM, operational PCE in this study was calculated as cycle time divided by lead time and multiplied by 100%. Because the numerator represented total recorded process time rather than the result of a separate value-added-time audit, this indicator was used as an operational time-efficiency ratio and was not interpreted as a measure of product quality.

Changes were reported as absolute differences, percentage reductions relative to S0, and increases in PCE expressed in percentage points. Throughput, WIP, queue lengths, bottlenecks, and resource utilization were used as diagnostic indicators rather than as primary contributions. Scenarios were selected according to sequential rules: satisfying the FTW constraint, establishing a traceable basis for each intervention, reducing waiting time and lead time, improving PCE, and ensuring feasibility for phased implementation. Under these rules, the scenario with the shortest lead time did not automatically become the recommended option if its RTW reduction had not received technical validation.

RESULTS AND DISCUSSION

Results

Corrected current-state performance

Current-state mapping showed a total cycle time of 157 days and an initial waiting time of 74 days. A reexamination with the shipyard owner revealed that the seven days previously recorded as design consultation and approval time by BKI did not occur in the observed project because the vessel was not submitted for classification. This component was removed from the baseline, while internal design safety checks were retained in the process.

After reconciliation, waiting time decreased to 67 days, and lead time became 224 days. The corrected current-state process cycle efficiency (PCE) is 70.09%, indicating that 29.91% of the time on the critical path is attributable to waiting rather than process cycle time. The longest cycle time occurs during working-design development (42 days), followed by mold preparation and fabrication and hull lamination (21 days each), interior and finishing (20 days), and superstructure lamination (17 days). The longest waiting times occur during hull lamination (17 days), mold preparation and fabrication (14 days), and superstructure lamination (12 days). However, waiting-time magnitude is not used directly to determine the order of elimination because each value is first classified according to its technical function and reducibility. Mechanistically, the concentration of waiting during mold fabrication, hull lamination, and superstructure lamination arises because these composite-manufacturing stages involve sequential interlayer curing and stabilization. Subsequent operations cannot physically begin until the laminate has sufficiently hardened. Consequently, the substantial waiting times reflect material-transformation processes governed by resin chemistry rather than solely by idle

coordination, making waiting-time magnitude alone an unreliable indicator of reducibility.

Waiting-time classification results

The classification presented in Table 2 covers the 11 process stages and yields 28 days of fixed technical waiting (FTW), 24 days of reducible technical waiting (RTW), and 15 days of avoidable waiting (AW). Thus, 41.79% of the total waiting time represents a fixed technical constraint, 35.82% represents technical waiting that may be shortened only through validated technology or process control, and 22.39% represents a direct target for Lean improvement. These results indicate that less than one-quarter of the baseline waiting time can, in principle, be treated as waste that can be reduced without changing the technical conditions of the process. The rationale for each classification is as follows: FTW values correspond to the minimum hardening, stabilization, inspection, and leak-testing times required by the composite-manufacturing process; RTW values correspond to curing and post-curing periods that published fiber-reinforced polymer (FRP) studies indicate are sensitive to temperature, humidity, and resin–catalyst control and are therefore conditionally reducible (Muharom et al., 2024); and AW values correspond to coordination, decision-making, and material-readiness delays that serve no technical function. The classifications were reviewed with the production person in charge, although the RTW assignments remain subject to validation by materials experts.

Table 2
Waiting Time Classification

Process stage	WT	FTW	RTW	AW
Working-design development	7	0	0	7
Mold preparation and fabrication	14	7	7	0
Hull lamination	17	10	7	0
Superstructure lamination	12	6	6	0
Demolding	0	0	0	0
Hull and deck joining	3	1	1	1
Internal outfitting	3	1	1	1
Engine and propulsion installation	7	1	1	5
Interior and finishing	1	0	1	0
Testing and commissioning	2	1	0	1
Sea trial	1	1	0	0
Total	67	28	24	15

FTW is concentrated primarily in hull lamination, mold preparation and fabrication, and superstructure lamination because these stages include interlayer pauses, stabilization, and mandatory hardening periods. RTW is also concentrated in these three stages because portions of curing or post-curing may potentially be controlled. The largest AW components are the seven days attributed to interior-design revisions and the five days attributed to material or surveyor coordination during engine installation. Under the progressive design-freeze strategy, interior revisions are still performed but are moved off the critical path. Consequently, before the Lean-reduction percentage is applied, AW on the critical path decreases from 15 to 8 days.

Scenario experiment results S0–S4

Table 3 shows that S0 reproduces the corrected baseline. In S1, reducing design cycle time from 42 to 30 days decreases total cycle time to 145 days, while moving interior revisions off the critical path reduces waiting time to 60 days. S2 reduces the remaining AW by 20%, resulting in a waiting time of 58.4 days. S3 applies a 25% reduction in RTW and a 35% reduction in AW, yielding a waiting time of 51.2 days. S4 tests the experimental limit of a 50% reduction in both RTW and AW, reducing waiting time to 44 days. FTW remains unchanged at 28 days across all scenarios. The implications of the scenarios differ not only in magnitude but also in nature: S1 and S2 require design-governance and coordination changes and can be implemented with comparatively low technical risk, whereas S3 and S4 presuppose investment in heating, enclosure, or humidity-control technologies and introduce additional process, energy, fire-safety, and quality-assurance

considerations. The scenarios therefore represent progressively greater implementation commitments rather than interchangeable alternatives.

Table 3
Scenario Experiment Results

Scenario	CT (days)	WT (days)	LT (days)	PCE (%)
S0 — corrected baseline	157	67	224	70.09
S1 — design improvement	145	60	205	70.73
S2 — Lean 20%	145	58.4	203.4	71.29
S3 — Lean 35%; technology 25%	145	51.2	196.2	73.90
S4 — Lean 50%; technology 50%	145	44	189	76.72

Compared with S0, S1 reduces lead time by 19 days (8.48%); S2, by 20.6 days (9.20%); S3, by 27.8 days (12.41%); and S4, by 35 days (15.63%). The corresponding waiting-time reductions are 7 days (10.45%), 8.6 days (12.84%), 15.8 days (23.58%), and 23 days (34.33%). PCE increases progressively from 70.09% in S0 to 70.73%, 71.29%, 73.90%, and 76.72%. Thus, the improvement in S4 is 6.63 percentage points, not a relative increase of 6.63%.

Decomposition of the results reveals different sources of improvement. S1 produces a 19-day reduction through two design-related mechanisms: a 12-day reduction in cycle time and a seven-day reduction in critical-path waiting achieved by moving interior revisions to a parallel path. The additional benefit of S2 is relatively small, at 1.6 days beyond S1, because only 20% of the remaining eight days of AW is eliminated. In S3, RTW decreases from 24 to 18 days, while AW decreases to 5.2 days. In S4, RTW decreases to 12 days and AW to four days, while FTW remains at 28 days. The relationship 28 + 12 + 4 = 44 days confirms that the model preserves fixed technical constraints.

Model output and constraint checking

In the S4 experiment, one ship enters the system and one ship reaches the Sink after 189 days; the work-in-process (WIP) level at the end of the simulation horizon is zero. This value indicates only that no ship remains in the system when the simulation ends; it does not establish that queues are absent throughout the process. Working-design development remains the relative bottleneck, with the highest reported utilization at 15.85%, followed by mold preparation and hull lamination at 11.09% each and interior and finishing at 10.56%. These low utilization values primarily reflect the single-ship experiment and cannot be used to infer the shipyard's annual production capacity.

Output checks show that all scenarios satisfy the structural constraints of the framework: the sequence of 11 processes remains unchanged, one ship is completed, FTW remains at 28 days, and lead time always equals cycle time plus waiting time. S0–S4 also exhibit a monotonic pattern: as AW and RTW reductions increase, waiting time and lead time decrease, while PCE increases. Because the model uses a single entity, serial flow, and deterministic durations, the aggregate simulation outputs follow the parameter calculations exactly. The results therefore demonstrate the logical consistency of the intervention rules and the magnitude of the scenario effects within the model; they do not establish the effectiveness of curing technology under actual shipyard conditions.

In terms of time performance alone, S4 produces the best result. However, under the study's acceptance criteria, S4 does not automatically constitute a full implementation recommendation because its 50% RTW reduction remains an experimental assumption. S1 and S2 rely on design changes and Lean interventions, whereas S3 and S4 require additional validation of temperature, humidity, curing time, degree of cure, and laminate mechanical properties. The scenario results consequently represent two levels of evidence: operational benefits that can be pursued through design and AW improvements, and additional potential benefits from RTW reductions that remain conditional on demonstrated quality and safety.

Residual waiting distribution in the maximum scenario

The 44 days of waiting in S4 are not distributed uniformly across the process stages. The largest residual waiting times occur in hull lamination (13.5 days), mold preparation and fabrication (10.5 days), and superstructure lamination (9 days). Together, these stages account for 33 days, or 75% of total S4 waiting time. Engine and propulsion installation contributes four days; hull and deck joining and internal outfitting contribute two days each; testing and commissioning contributes 1.5 days; the sea trial contributes one day; and interior and finishing contributes 0.5 day. Demolding has no waiting time, while design-related waiting on the critical path falls to zero after interior revisions are moved to a parallel path.

Although S4 applies the maximum RTW reduction within the experimental range, residual waiting remains concentrated in composite-manufacturing processes. This occurs because FTW in mold preparation and fabrication, hull lamination, and superstructure lamination is maintained, while only the RTW component is multiplied by a 50% reduction factor. By contrast, the residual waiting during engine installation comprises one day of FTW, 0.5 day of RTW, and 2.5 days of AW. This distribution demonstrates that identical or similar total waiting times may require different management responses: residual waiting in lamination is dominated by technical constraints, whereas engine-installation waiting retains opportunities for Lean-based coordination improvements.

When compared by time composition, the proportion of waiting time to lead time decreases from 29.91% in S0 to 29.27% in S1, 28.71% in S2, 26.10% in S3, and 23.28% in S4. This decline is consistent with the increase in PCE because cycle time remains at 145 days in S1–S4 after the design improvement. Thus, the PCE differences among S1–S4 arise entirely from changes in critical-path waiting time, rather than from further reductions in transformation time. These findings establish a quantitative relationship between waiting-time classification, intervention intensity, and the resulting performance indicators.

Discussion

Meaning of selective waiting-time reduction

The principal finding of this study is not merely that lead time can be reduced from 224 to 189 days, but that this reduction is achieved by distinguishing among the functions of waiting time. Of the 67 days of waiting in the current state, only 15 days, or 22.39%, were classified as AW and can be targeted directly by Lean interventions. By contrast, 28 days are FTW that must be maintained, while 24 days are RTW that can be reduced only under specified conditions. This distribution demonstrates why an approach that treats all waiting as homogeneous waste is inadequate for composite manufacturing. Waiting-time magnitude is not the sole basis for intervention; technical function, process risk, and feasibility evidence must also inform the decision.

Design improvement in S1 provides the largest lead-time reduction before technology-related interventions are introduced, at 19 days. Twelve days result from shortening design cycle time based on the capacity of three engineers, while seven days are gained by moving interior revisions from the serial path to a parallel path. This result is important because concurrent engineering does not eliminate design work or safety checks. Instead, the intervention changes process dependencies: structural production can begin after the hull design and critical elements have been frozen, while interior decisions are finalized before the interior-finishing stage. Thus, improvements in flow can yield substantial benefits without accelerating material reactions or reducing inspections.

The S1–S4 pattern also reveals diminishing certainty regarding practical implementation. S2 adds a 1.6-day reduction through partial Lean improvement and is relatively straightforward to pursue because it remains focused on AW. S3 and S4 deliver larger additional reductions, but some of their benefits depend on RTW reduction. Consequently, greater numerical gains are accompanied by a greater need for technical evidence. S4 represents the performance bound within the experimental space, not an automatic implementation choice. This interpretation prevents time optimization from being used to justify shortening curing, post-curing, or stabilization periods without material verification.

Contribution to Digital Lean Manufacturing

Conceptually, this study extends the application of simulation-based Digital Lean Manufacturing from digitizing process maps to digitizing decision rules. Arey et al. (2021) position digital value streams as a link between Lean orientation and digital technology, while Ferreira et al. (2022) demonstrate that modeling and simulation can extend value stream mapping (VSM) when system relationships are more complex than static maps. This study introduces an operational mechanism connecting these approaches: the current-state VSM is not translated directly into reduction targets but is first decomposed into AW, RTW, and FTW. These classifications determine which parameters may be changed in AnyLogic.

This methodological contribution addresses the distinction between VSM and simulation representations discussed by (Antonelli & Stadnicka, 2018). VSM remains a simple and transparent diagnostic tool, while discrete-event simulation (DES) tests the consequences of parameter changes and checks the consistency of the relationships among CT, WT, LT, and PCE. Integration is not achieved by making the simulation merely a digital image of the VSM. Instead, the model functions as a rule-testing layer: AW can be reduced through Lean interventions, RTW can be changed only in technology-related scenarios, and FTW remains fixed. In this way, the future-state VSM becomes an output of tested rules rather than merely a normative target established before experimentation. Theoretically, this positions the study as an extension of Digital Lean Manufacturing from the digitization of process maps to the digitization of decision rules. The empirical AW/RTW/FTW classification provides the mechanism through which Lean's value-and-waste logic becomes computable. The theoretical contribution is therefore a rule-based coupling of Lean diagnosis and DES experimentation, rather than another demonstration that simulation can reproduce a VSM.

However, the results also clarify the limitations of the term digital. The single-ship model is deterministic and is not yet connected to real-time data, sensors, or physical production systems. Therefore, it does not meet the defining characteristics of a digital twin or a comprehensive Smart Manufacturing system. Its digital value lies in its ability to support consistent, documented what-if analyses before changes are implemented. This more limited positioning strengthens the accuracy of the study's claims: the article demonstrates simulation-based Digital Lean Manufacturing, not the comprehensive digital transformation of the shipyard.

Comparison with previous research

The findings are consistent with literature identifying waiting time and lead time as important issues in shipbuilding. The review by Neves et al. (2025) shows that large product dimensions, low production volumes, and dependence on labor and suppliers make Lean implementation in shipyards different from its application in repetitive manufacturing. In the Indonesian fiberglass context, Ahmad et al. (2026) reported that a future-state VSM was projected to reduce waiting time by 15 days and increase PCE from 73.3% to 78.8%. The present study supports the general direction of those findings, but the numerical magnitudes are not directly comparable because the studies differ in their objects, baselines, process boundaries, and definitions of time.

The principal difference lies in the mechanism used to develop the future state. VSM studies typically identify waiting and then propose reductions through changes in work methods or process flow. In this study, waiting is first classified according to reducibility and process risk. Consequently, only a limited portion can be addressed directly through Lean interventions, while 41.79% of total waiting time is retained as FTW. This result offers a more conservative explanation of why substantial residual waiting remains in lamination processes even under the maximum scenario. The residual does not necessarily indicate a failure of Lean; it partly comprises time that must be deliberately protected.

The use of DES also differs from the general focus of shipyard simulation studies. Okubo & Mitsuyuki (2022) used simulation to support production planning, bottleneck identification, and worker reallocation. The present study retains some of those functions—working-design development remains the relative bottleneck—but its primary contribution is to test waiting-time classifications and intervention rules. The S0–S4 results do not demonstrate complex queueing behavior because only one ship is modeled in a serial flow. The contribution therefore lies in

decision traceability and validation of future-state logic, rather than in multi-project capacity optimization.

Quality and safety as acceptance limits

Treating quality and safety as constraints changes how PCE should be interpreted. The increase in PCE from 70.09% to 76.72% does not demonstrate that laminate quality or vessel safety has improved. The indicator shows only that cycle time constitutes a larger proportion of lead time. Quality claims require separate measurements of degree of cure, tensile strength, flexural strength, porosity, adhesion, deformation, and other relevant properties. Ismail et al. (2024) show that laminate configuration and resin type are associated with the mechanical properties of FRP ship materials, while Muharom et al. (2024) report that variations in fiberglass arrangement produce different strength outcomes and that not all tested configurations meet the applicable requirements.

Accordingly, RTW reductions of 25% or 50% must be treated as experimental assumptions. Implementing heated-air systems, curing enclosures, humidity control, or infrared heating requires a process window derived from the resin manufacturer's technical data sheet and validated through trials. FTW associated with resin flow, vacuum leak testing, alignment, leak inspection, engine stabilization, testing, sea trials, and safe weather and water conditions must not be shortened merely to achieve time targets. The conservative principle is that when the status of a waiting period is uncertain, it should be classified as FTW until technical evidence establishes which portion, if any, can safely be reduced.

Managerial implications and implementation path

For shipyards, the most defensible implementation sequence begins with S1 rather than proceeding directly to S4. The first stage involves progressive design freeze, separation of critical and noncritical design activities, and engineering change control. The second stage addresses remaining AW through material-readiness checks, visual controls, inspection scheduling, response-time standards for decisions, and work coordination. The impact should be measured against the same baseline. The third stage involves small-scale pilot trials targeting selected RTW components, with systematic recording of temperature, humidity, duration, and quality outcomes. If the results meet the applicable acceptance criteria, the model parameters can be updated and the scenarios rerun.

This phased approach also reduces investment risk. S1 and S2 primarily require changes in design governance and coordination, whereas S3 and S4 may require heating equipment, enclosures, sensors, revised procedures, and additional process-control competencies. Simulation can help compare potential time benefits before capital is committed, but investment decisions still require assessments of cost, energy consumption, fire risk, working conditions, and maintainability. The scenario with the shortest lead time is therefore not necessarily the alternative with the best economic value or risk profile.

Transferability and limitations

The framework can be transferred to other fiberglass shipyards at the procedural level: map the current state; trace the cause of each waiting period; classify waiting as AW, RTW, or FTW; establish intervention rules; build the model; validate the baseline; and then test scenarios. However, the durations and percentages reported for S0–S4 cannot be transferred directly because vessel type, resin system, lamination method, climate, labor, facilities, classification requirements, and owner policies may differ. Each shipyard must establish its own baseline and technical limits.

The principal limitations of this study are its single-case design, single-ship entity, serial process flow, and deterministic inputs. This configuration makes the results easy to audit but does not capture time variability, overlapping ship arrivals, resource competition, rework, equipment breakdowns, supplier delays, or changing weather conditions. In addition, validation of the corrected model should be reported at the individual-process level, not only in terms of aggregate agreement, and the RTW classification requires confirmation by materials experts or resin suppliers. Future research should examine multi-project scenarios using empirical input

distributions, replications, and confidence intervals, and link time-related outputs to cost, energy, quality, and safety indicators. Such development would test whether selective intervention rules remain effective under more complex shipyard operating conditions.

CONCLUSION

This study developed a simulation-based Digital Lean Manufacturing framework for selectively reducing waiting time in engineer-to-order fiberglass ship production in Indonesia. Unlike approaches that treat all waiting as homogeneous waste, the framework links current-state VSM with the classification of avoidable waiting (AW), reducible technical waiting (RTW), and fixed technical waiting (FTW). These classifications are translated into intervention rules in an AnyLogic-based discrete-event simulation model: AW becomes a target for Lean improvement, RTW can be reduced only through validated technology or process control, and FTW is maintained as a quality and safety constraint.

The corrected current state records 157 days of cycle time, 67 days of waiting time, and a 224-day lead time, comprising 28 days of FTW, 24 days of RTW, and 15 days of AW. Across S0–S4, performance improves progressively, with S4 representing the best performance bound within the experimental space: 44 days of waiting time, a 189-day lead time, and a PCE of 76.72%. The results demonstrate that lead-time reduction should be guided by the technical function of waiting. Design improvements and AW reduction can be pursued first, whereas reductions in technical waiting remain conditional on process validation.

The framework establishes a traceable link between VSM diagnosis, AW/RTW/FTW classification, intervention rules, and simulation testing. S4 is therefore not an automatic implementation recommendation because its RTW reduction remains experimental and requires supporting material and process evidence before practical application. The findings are limited to a single case, one ship entity, serial production flow, and deterministic inputs; consequently, the numerical reductions cannot be generalized directly to other shipyards. Future research should test the procedure across multiple shipyards and vessel types using empirical time distributions, multiple-ship models, replications and confidence intervals, process-level validation, and integrated cost, energy, quality, and safety indicators.

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AUTHOR CONTRIBUTION STATEMENT

Jailani: Conceptualization, methodology, investigation, data collection, formal analysis, development of the Value Stream Mapping framework, AnyLogic simulation modeling, visualization, and writing of the original draft. Yustiar Gunawan: Supervision, methodology review, validation, interpretation of results, and writing—review and editing. Derah Sudjaniah: Supervision, validation, critical review of the research framework, interpretation of findings, and writing—review and editing. All authors contributed to the discussion of the research findings, critically reviewed the manuscript, approved the final version of the manuscript, and agreed to be accountable for the integrity and accuracy of the work.

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