The Influence of Shipyard Layout on Sustainability Performance Based on the Triple Bottom Line through Operational Efficiency Mediation: A SEM-PLS Approach

Didik Hardianto[1*], Marjono[2], Anthon Efani[3], Andi Kurniawan[4]
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Abstract**—** The shipyard industry is a complex production system requiring an efficient and integrated facility layout. However, many shipyards have developed without optimal layout planning, leading to inefficiencies in material flow and production processes. This study examines the impact of shipyard layout on sustainability performance based on the Triple Bottom Line (TBL), with operational efficiency as a mediating variable, and evaluates the role of ISO-based integrated management systems as a supporting factor. This study adopts an explanatory quantitative approach using SEM-PLS, based on questionnaire data collected from purposively selected operational personnel. The results indicate that shipyard layout has a positive and significant effect on both operational efficiency and sustainability performance, either directly or indirectly through operational efficiency as the primary mediator. ISO-based management systems do not directly influence sustainability performance but contribute significantly to operational efficiency. These findings highlight operational efficiency as a key mechanism linking facility layout to sustainability performance and propose an integrative causal framework that combines structural, process, and outcome dimensions within a unified empirical model.

*Keywords***—** Shipyard layout; operational efficiency; sustainability performance; Triple Bottom Line; SEM-PLS.

[*]*Corresponding Author: didik.hardianto@hangtuah.ac.id*

I. INTRODUCTION

The shipyard industry represents a strategic sector within the global maritime transportation and logistics system, characterized by highly complex production processes and the integration of fabrication, assembly, outfitting, and repair activities across dynamic spatial and temporal dimensions. This complexity renders shipyards as highly interdependent production systems, in which each activity is closely interconnected and strongly influenced by the configuration of the production space [1], [2], [3], [4]. In this context, facility layout serves not merely as a physical arrangement but as a strategic element that plays a critical role in determining material flow effectiveness, process synchronization, and the optimization of production resource utilization [5], [6], [7].

However, industrial practices indicate that many shipyards have evolved without systematic and optimization-based layout planning. Such conditions tend to generate structural inefficiencies, including cross movement, bottlenecks, increased material handling distances, and imbalanced production flows, all of which negatively affect operational efficiency [8], [9], [10]. Furthermore, these inefficiencies may lead to increased energy consumption and operational waste, ultimately impacting the sustainability performance of production systems [11], [12], [13].

From an operations management perspective, facility layout is a long-term strategic decision that determines the efficiency structure of production systems. The literature suggests that optimally designed layouts can reduce material movement distances, minimize waiting times, improve facility utilization, and enhance coordination among production processes [1], [5], [6]. This significance becomes even more pronounced in the shipyard industry, which is characterized by large-scale products, long production cycles, and complex material flow patterns [2], [8]. In addition to conventional approaches, advancements in heuristic methods, metaheuristic algorithms, and multi-objective optimization techniques have been widely applied to improve production system layout performance [14], [15], [16], [17]. In the context of shipyards, several studies demonstrate that algorithm-based optimization approaches can significantly enhance space efficiency and improve material flow patterns [18], [19].

Operational efficiency in this context represents a critical variable reflecting the capability of a production system to optimize the use of resources, time, and production capacity. Improvements in operational efficiency not only reduce costs and increase productivity but are also associated with lower energy consumption and reduced production waste, thereby contributing to the environmental dimension of sustainability [11], [20], [21]. Thus, operational

Didik Hardianto, Post Graduate Program Enviromental Science Brawijaya University, Email: didik.hardianto@hangtuah.ac.id

Marjono, Department of Mathematics, Faculty of Mathematics and Natural Sciences, Brawijaya University, Malang, Email: marjono@ub.ac.id

Anthon Efani Department of Fisheries Agribusiness, Faculty of Fisheries and Marine Science, Brawijaya University, Malang, Email: anthonefani@ub.ac.id

Andi Kurniawan, Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, Brawijaya University, Malang, Email: andi_k@ub.ac.id

efficiency can be viewed as a conceptual bridge linking operational performance to sustainability outcomes in production systems.

With increasing global pressure toward sustainable industrial practices, the Triple Bottom Line (TBL), encompassing economic, environmental, and social dimensions, has emerged as a dominant paradigm for evaluating organizational performance [20], [21], [22]. Within this framework, sustainability is no longer considered an additional outcome but rather an integral component of long-term operational strategy [23], [24]. Previous studies indicate that operational efficiency is positively associated with sustainability performance through mechanisms such as emission reduction, energy optimization, and more effective waste management [11], [21], [25].

Previous studies in this domain can be broadly categorized into three main streams. First, studies on facility layout primarily focus on technical optimization, such as minimizing material handling distance, improving spatial efficiency, and enhancing production flow. Second, research on operational efficiency emphasizes process optimization, including time reduction, resource utilization, and workflow synchronization within production systems. Third, sustainability-related studies predominantly address outcome-based performance, focusing on environmental, economic, and social indicators within the Triple Bottom Line framework.

However, these research streams are often examined in isolation, with limited integration between structural design, operational processes, and sustainability outcomes. This fragmentation highlights a critical gap in the literature, particularly in complex production systems such as shipyards, where these elements are inherently interdependent.

Nevertheless, the integration of facility layout, operational efficiency, and sustainability performance remains relatively limited in the existing literature. Facility layout studies generally focus on technical optimization aspects, such as minimizing distance and material handling costs, without explicitly linking these improvements to sustainability impacts [16], [17], [26]. Conversely, sustainability research tends to emphasize outcome indicators without adequately considering production system design as a primary structural determinant [26], [27]. Moreover, empirical studies explicitly examining the mediating role of operational efficiency in the relationship between facility layout and sustainability performance remain scarce, particularly in the shipyard industry, which exhibits unique operational characteristics [12], [13], [28]. Recent studies also indicate that the integration of facilities and functions in the development of multipurpose shipyards in Indonesia continues to face significant technical and managerial challenges, underscoring the need for more systematic approaches in layout design and operational management [34]. Although some studies have addressed shipyard layout optimization, most remain focused on technical aspects and have not integrated operational efficiency and sustainability dimensions within a comprehensive empirical causal model [18], [19].

Conceptually, facility layout influences operational efficiency through the arrangement of material flows, movement distances, and coordination among production activities. Suboptimal layouts can lead to increased time and resource waste, ultimately reducing overall production system performance [9], [10]. In turn, higher operational efficiency has the potential to enhance sustainability performance by reducing energy consumption, emissions, and operational waste [11], [21], [25]. Additionally, several studies suggest that facility layout may also exert a direct influence on sustainability through more efficient and environmentally friendly production system design, although this mechanism has not been extensively tested within an integrated empirical framework [12], [13].

Based on these research gaps, this study develops an empirical model integrating shipyard facility layout, operational efficiency, and sustainability performance based on the Triple Bottom Line within a unified causal framework. Specifically, this study positions operational efficiency as a mediating variable that explains the mechanism through which facility layout affects sustainability performance. The novelty of this study lies in: (i) the simultaneous integration of structural (facility layout), process (operational efficiency), and outcome (sustainability performance) dimensions within a single causal model; (ii) the application of SEM-PLS to examine both direct and indirect effects simultaneously [29], [30], [31], [32]; and (iii) its application within the shipyard industry context, which remains relatively underexplored in the international literature [2], [12]. Accordingly, this study aims to analyze the effect of shipyard layout on sustainability performance based on the Triple Bottom Line, considering the mediating role of operational efficiency.

II. Method

This study employs an explanatory quantitative approach with a non-experimental, cross-sectional design to examine the causal relationships among shipyard layout (X), operational efficiency (Y_1), and Triple Bottom Line (TBL)-based sustainability performance (Y_2) [11], [12], [13], [20], [21], [22]. The research model is specifically designed to analyze the mediating role of operational efficiency in explaining the mechanism through which facility layout influences sustainability performance [16], [21].

The empirical analysis is conducted using Structural Equation Modeling–Partial Least Squares (SEM-PLS), which enables the simultaneous modeling of relationships among latent constructs, accommodates mediation effects, and does not require strict multivariate normality assumptions [29], [30], [31], [32]. This method is selected due to its suitability for predictive and exploratory research in complex production systems such as the shipyard industry.

The unit of analysis in this study is individuals directly involved in shipyard operational activities. Respondents are selected using purposive sampling based on the following criteria: (1) a minimum of two years of work experience, (2) direct involvement in production operations, and (3) an understanding of material flow and facility layout. These criteria are established to ensure that respondents possess adequate operational knowledge of shipyard production systems [11], [12].

The sample size is determined based on the general SEM-PLS rule of thumb, i.e., 5–10 times the number of indicators in the largest construct, to ensure the stability of model parameter estimation [29]. Data are collected through a structured questionnaire using a five-point Likert scale to measure respondents' perceptions of each research construct indicator [32].

TABLE 1.
RESPONDENT CHARACTERISTICS

Characteristic	Category	Number of Respondents	Percentage (%)
Position	Production Operator	51	68
	Supervisor	16	21
	Manager	8	11
Education	High School / Vocational	34	45
	Diploma	27	36
	Bachelor's Degree	14	19
Work Experience	5–7 years	24	32
	8–10 years	33	44
	>10 years	18	24

All constructs in this study are modeled as reflective constructs, including: (1) shipyard layout, representing the spatial configuration and material flow within the production system [1], [2], [3]; (2) operational efficiency, reflecting the system's ability to optimize time, resources, and production processes [20], [21]; and (3) TBL-based sustainability performance, encompassing economic, environmental, and social dimensions [20], [21], [22], [24], [25].

Data analysis is conducted in two stages using SmartPLS software. The first stage involves the evaluation of the measurement model (outer model), including tests of convergent validity (outer loadings > 0.70), internal consistency reliability (Cronbach's alpha, rho_A, and composite reliability > 0.70), and discriminant validity using the Fornell–Larcker criterion and the HTMT ratio [30], [31], [32]. The second stage involves the evaluation of the structural model (inner model), including hypothesis testing of causal relationships among constructs, coefficient of determination (R^2), effect size (f^2), and path significance using the bootstrapping technique [29], [31].

To minimize the potential for common method bias, this study applies several procedural remedies, including anonymous questionnaire administration, the use of varied indicator wording, and the separation of question structures across constructs. Furthermore, mediation analysis is conducted using bootstrapping to simultaneously test indirect effects, enabling a robust and inferential identification of the mediating role of operational efficiency [31], [32].

III. RESULTS AND DISCUSSION

A. *Respondent Characteristics*

The respondent characteristics presented in Table 1 indicate that the majority of respondents belong to the production operator category (68%), who are directly involved in operational activities and material flow within the shipyard. The dominance of this group has important methodological implications, as in complex production systems such as shipyards, understanding of facility layout, material flow patterns, and operational efficiency is largely shaped by practical, on-site experience [1], [2], [3]. Therefore, this respondent composition ensures that the data obtained reflect actual operational conditions rather than merely conceptual or normative perceptions.

In terms of work experience, the majority of respondents have more than five years of experience (76%), indicating substantial exposure to the dynamics of production processes and interactions among facilities. In the operations management literature, work experience is considered a critical factor in enhancing individuals' ability to identify system inefficiencies, including time waste, excessive material handling distances, and imbalances in workflow [20], [21]. Therefore, this characteristic strengthens the substantive validity of the operational efficiency construct measurement.

Furthermore, the variation in respondents' educational backgrounds reflects a combination of technical operational competence and managerial conceptual understanding. This condition is particularly relevant in Triple Bottom Line-based research, as sustainability evaluation depends not only on operational perceptions but also on the ability to comprehend the economic, environmental, and social implications of production systems [11], [13], [22]. Thus, the diversity of educational backgrounds supports the quality of the data in capturing the multidimensional nature of sustainability performance.

Overall, the respondent characteristics demonstrate a high level of representativeness of actual shipyard operational conditions. The combination of a dominant production operator group, sufficient work experience, and diverse educational backgrounds provides a strong empirical basis to ensure the external validity and practical relevance of the research findings within the context of the complex shipyard industry.

B. Measurement Model Evaluation (Outer Model)

The evaluation of the measurement model is conducted to ensure that all latent constructs exhibit adequate levels of validity and reliability prior to testing the structural relationships. In the SEM-PLS approach, the quality of the measurement model is a critical aspect, as the accuracy of causal relationship estimation largely depends on the ability of the indicators to represent latent constructs accurately and consistently [29], [30], [31]. Therefore, the evaluation is performed comprehensively through assessments of convergent validity, internal consistency reliability, and discriminant validity.

Based on Table 2, all indicators demonstrate outer loading values exceeding 0.70, indicating that each indicator makes a strong contribution to the formation of its respective latent construct. Substantively, within the shipyard layout construct, functional integration (0.861) and layout flexibility (0.829) emerge as the most dominant dimensions. This finding suggests that layout effectiveness is not solely determined by spatial configuration but also by the system's ability to be adaptive and integrated in supporting production flow. Thus, in the shipyard context, facility layout is not static but functions as a dynamic enabler of production system efficiency [1], [3].

For the operational efficiency construct, the production cycle time efficiency indicator exhibits the highest loading (0.901), highlighting the temporal dimension as the most critical factor in shipyard production systems. This result reflects the industry's strong dependence on activity synchronization and the minimization of waiting times between processes [20], [21]. Meanwhile, within the sustainability performance construct, energy efficiency (0.877) and waste management (0.851) serve as the primary contributors, emphasizing the dominance of the environmental dimension in evaluating operational sustainability. Overall, these results indicate that convergent validity is not only statistically satisfied but also consistent with the operational realities of the production system.

TABLE 2.
OUTER LOADING VALUES OF CONSTRUCT INDICATORS

Construct	Indicator	Indicator Description	Outer Loading
Shipyard Layout (X)	X1	Spatial coordination of facilities	0.773
	X2	Material flow alignment	0.795
	X3	Alignment with environmental and energy principles	0.768
	X4	Integration of shipyard functions	0.861
	X5	Layout flexibility	0.829
ISO-based Integrated Management System Effectiveness (M)	M1	Consistency of operational control	0.901
	M2	Integration of quality, environmental, and occupational health management	0.897
Operational Efficiency (Y_1)	Y11	Minimization of material travel distance	0.773
	Y12	Production cycle time efficiency	0.901
	Y13	Optimization of equipment and facility utilization	0.838
Sustainability Performance (Y_2)	Y21	Operational waste management	0.851
	Y22	Occupational health and safety	0.823
	Y23	Resource utilization efficiency	0.850
	Y24	Operational energy efficiency	0.877

TABLE 3.
INTERNAL RELIABILITY RESULTS OF CONSTRUCTS

Code	Construct	Cronbach's Alpha	rho_A (ρa)	Composite Reliability (ρc)	Interpretation
X	Shipyard Layout	0.865	0.875	0.902	Reliable
M	ISO-based Integrated Management System Effectiveness	0.762	0.762	0.894	Reliable
Y_1	Operational Efficiency	0.789	0.808	0.876	Reliable
Y_2	Sustainability Performance (Triple Bottom Line)	0.874	0.881	0.913	Reliable

Furthermore, the internal consistency reliability results presented in Table 3 indicate that all constructs exhibit Cronbach's alpha, rho_A, and composite reliability values above 0.70, demonstrating satisfactory internal consistency [29], [30], [31]. The consistently higher composite reliability values compared to Cronbach's alpha suggest that the SEM-PLS approach provides more stable reliability estimates for reflective measurement models [29], [32].

Substantively, the high reliability observed in the shipyard layout (0.902) and sustainability performance (0.913) constructs indicates that both constructs possess stable and homogeneous indicator structures, enabling them to consistently represent the underlying phenomena. This is particularly important, as these constructs serve as the primary variables in the research model. In addition, the high reliability of the ISO-based management system construct indicates that the integration of quality, environmental, and occupational health and safety aspects can be measured consistently, thereby reinforcing its role as an enabling variable within the structural model.

TABLE 4.
AVERAGE VARIANCE EXTRACTED (AVE) RESULTS

Code	Construct	AVE
X	Shipyard Layout	0.650
M	ISO-based Integrated Management System Effectiveness	0.808
Y_1	Operational Efficiency	0.704
Y_2	Sustainability Performance (Triple Bottom Line)	0.723

The Average Variance Extracted (AVE) results presented in Table 4 indicate that all constructs have values exceeding 0.50, implying that more than 50% of the variance in the indicators is explained by their respective latent constructs [29], [30], [31]. The highest AVE value is observed in the ISO-based management system construct (0.808), indicating a very high level of indicator homogeneity. In contrast, the relatively lower AVE value for the shipyard layout construct (0.650) reflects its inherent complexity and multidimensional nature.

This condition is consistent with the operational realities of shipyards, which are influenced by multiple technical, spatial, and operational factors. Therefore, rather than indicating a weakness, this variation reinforces the external validity of the construct by capturing the multifaceted nature of the shipyard production system [1], [2].

Discriminant validity, as presented in Table 5 (HTMT) and Table 6 (Fornell–Larcker), further confirms the robustness of the measurement model. All HTMT values are below the threshold of 0.90, indicating no issues related to discriminant validity among the constructs [31]. In addition, the Fornell–Larcker criterion shows that the square root of the AVE for each construct exceeds its correlations with other constructs, confirming that each construct possesses a clearly distinct empirical identity [29], [30].

Conceptually, this distinction is essential, as each construct plays a different role within the production system: facility layout as a structural determinant, operational efficiency as a process mechanism, management systems as a control factor, and sustainability performance as the system outcome [1], [11], [20].

Overall, the results of the measurement model evaluation indicate that all constructs satisfy the required criteria for validity and reliability in SEM-PLS. Beyond demonstrating statistical robustness, these findings also confirm the conceptual alignment between the indicators and the operational phenomena under investigation. Therefore, the measurement model provides a strong empirical foundation and is deemed suitable for structural model analysis, allowing the estimation of causal relationships to be interpreted in a scientifically sound, stable, and robust manner [1], [11], [20].

TABLE 5.
DISCRIMINANT VALIDITY RESULTS USING HTMT

Construct Relationship	HTMT Value
X ↔ M	0.570
Y_1 ↔ M	0.655
Y_1 ↔ X	0.806
Y_2 ↔ M	0.547
Y_2 ↔ X	0.838
Y_2 ↔ Y_1	0.743

TABLE 6.
FORNELL–LARCKER CRITERIA

Construct	M	X	Y_1	Y_2
M: ISO-based Integrated Management System Effectiveness	0.899			
X: Shipyard Layout	0.476	0.806		
Y_1: Operational Efficiency	0.511	0.682	0.839	
Y_2: Sustainability Performance (Triple Bottom Line)	0.451	0.743	0.637	0.850

C. Collinearity Assessment

Collinearity assessment is conducted to ensure that no multicollinearity exists among the predictor constructs in the structural model, which could otherwise lead to biased estimates, instability in path coefficients, and distortions in causal relationship testing. In the Partial Least Squares Structural Equation Modeling (SEM-PLS) approach, collinearity is commonly evaluated using the Variance Inflation Factor (VIF), which reflects the degree of redundancy among predictor variables in explaining endogenous constructs [29], [30].

The collinearity test results presented in Table 7 indicate that all VIF values range from 1.000 to 2.038. These values are consistently well below the conservative threshold of 5 and even satisfy the more stringent criterion of less than 3 recommended in recent SEM-PLS literature [29]. Therefore, it can be concluded that there is no significant indication of multicollinearity in the proposed structural model, and the parameter estimates can be considered stable and unbiased.

TABLE 7.
COLLINEARITY TEST RESULTS (VIF)

Structural Relationship	VIF
M → Y_1	1.294
M → Y_2	1.412
X → M	1.000
X → Y_1	1.294
X → Y_2	1.950
Y_1 → Y_2	2.038

From a methodological perspective, the absence of multicollinearity indicates that each exogenous construct in the model—namely shipyard layout (X) and the effectiveness of ISO-based integrated management systems (M)—provides a unique contribution (non-redundant explanatory power) in explaining the endogenous variables, particularly operational efficiency (Y_1) and sustainability performance (Y_2). This is important because, in mediation models, high collinearity among predictors can distort the estimation of both direct and indirect effects, thereby reducing the validity of causal inferences [31].

From a substantive perspective, these results further strengthen the conceptual validity of the research model. Although shipyard layout, ISO-based management systems, and operational efficiency are theoretically embedded within an interconnected production system, they are empirically shown to play distinct structural roles. Shipyard layout functions as a structural determinant that shapes spatial configuration and material flow patterns [1], [2], [3], ISO-based management systems act as control and standardization mechanisms for operational processes [13], while operational efficiency represents the process outcome resulting from the interaction of these factors [20], [21].

Therefore, the collinearity test results not only confirm the statistical adequacy of the model but also reinforce construct distinctiveness and the clarity of the theoretical roles of each variable within the causal framework. Accordingly, the structural model analysis can proceed with a high level of confidence in the stability, validity, and accuracy of parameter estimation [29], [30], [31].

D. Structural Model Evaluation (Inner Model)

The structural model evaluation is conducted to examine the causal relationships among latent constructs and to assess the predictive capability of the model in explaining endogenous variables. In the Partial Least Squares Structural Equation Modeling (SEM-PLS) approach, evaluation is not solely based on the significance of path coefficients but also includes the coefficient of determination (R^2), effect size (f^2), and mediation testing using robust bootstrapping procedures [29], [30]. [31], [32]. This approach enables the simultaneous analysis of both direct and indirect relationships within complex models. The estimated structural model is illustrated in Figure 1, while the results of the analysis are presented in Tables 8–11.

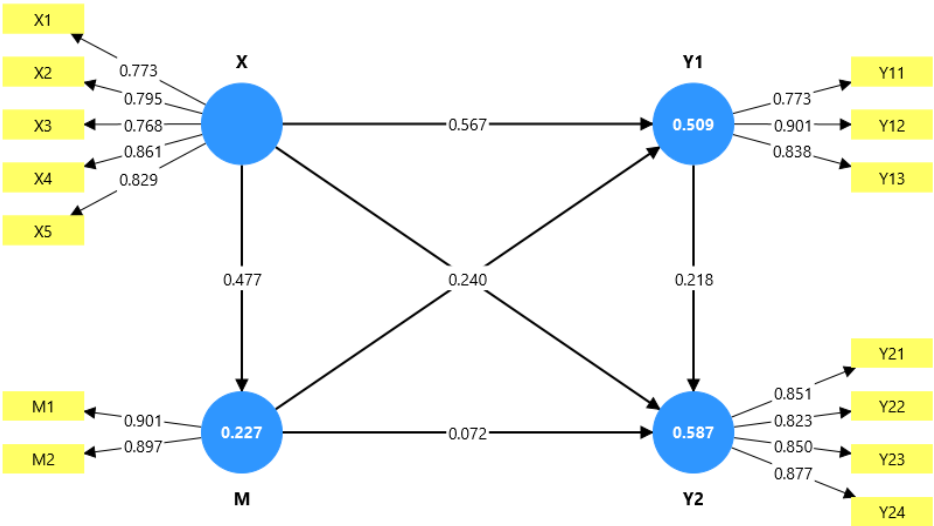

Figure. 1. SEM-PLS Structural Model

Path Coefficients

The estimated path coefficients presented in Table 8 indicate that shipyard layout (X) has a positive and significant effect on all key endogenous constructs, namely operational efficiency (Y_1; $\beta = 0.567$; $p < 0.001$), sustainability performance (Y_2; $\beta = 0.560$; $p < 0.001$), and the effectiveness of integrated management systems (M; $\beta = 0.477$; $p < 0.001$).

TABLE 8.
PATH COEFFICIENT RESULTS

Relationship	Path Coefficient (β)	t-statistic	p-value	Decision
$M \rightarrow Y_1$	0.240	2.890	0.004	Significant
$M \rightarrow Y_2$	0.072	0.736	0.462	Not Significant
$X \rightarrow M$	0.477	5.542	0.000	Significant
$X \rightarrow Y_1$	0.567	6.093	0.000	Significant
$X \rightarrow Y_2$	0.560	5.765	0.000	Significant
$Y_1 \rightarrow Y_2$	0.218	2.052	0.040	Significant

These findings confirm that facility layout serves as a primary structural determinant in shipyard production systems, directly influencing both operational performance and sustainability outcomes. Conceptually, this result reinforces the literature suggesting that facility design constitutes a strategic foundation for optimizing material flow and integrating production processes [1], [2], [3]. Furthermore, these findings extend existing theoretical perspectives by demonstrating that structural design plays a more fundamental role than traditionally assumed, particularly in complex production systems where spatial configuration directly governs process efficiency and resource utilization.

Furthermore, operational efficiency (Y_1) is found to have a positive and significant effect on sustainability performance ($\beta = 0.218$; $p = 0.040$), indicating that improvements in process efficiency directly contribute to the achievement of Triple Bottom Line-based performance. This finding confirms that operational efficiency functions as a transformational mechanism that converts operational advantages into economic, environmental, and social benefits [21]–[23].

More specifically, this relationship can be explained by the fact that efficiency improvements reduce process waste, energy consumption, and idle time, which are closely associated with environmental and economic sustainability dimensions in shipyard operations.

In contrast, the effectiveness of ISO-based integrated management systems (M) has a significant effect on operational efficiency ($\beta = 0.240$; $p = 0.004$), but does not have a direct effect on sustainability performance ($\beta = 0.072$; $p = 0.462$). This result suggests that management systems primarily act as operational enablers rather than direct drivers of sustainability. In other words, their contribution to sustainability is indirect, operating through improvements in operational efficiency, which is consistent with the literature on the role of managerial practices in production systems [13], [21].

This may be attributed to the nature of management systems, which emphasize standardization, compliance, and procedural control rather than directly modifying physical production processes, thereby limiting their immediate impact on sustainability outcomes.

TABLE 9.
COEFFICIENT OF DETERMINATION (R^2)

Endogenous Construct	R^2	Category
M	0.227	Weak
Y_1	0.509	Moderate
Y_2	0.587	Moderate

Coefficient of Determination (R^2)

The coefficient of determination (R^2) values presented in Table 9 indicate that the model demonstrates adequate explanatory power. Operational efficiency (Y_1) has an R^2 value of 0.509, while sustainability performance (Y_2) has an R^2 value of 0.587, both of which fall within the moderate range. These results suggest that the model possesses sufficient predictive power in explaining the primary endogenous variables [29].

Meanwhile, the R^2 value for the effectiveness of the management system (M) is 0.227, which falls within the weak category, indicating that this variable is influenced by external factors not included in the model. Thus, the management system functions as a supporting variable with a limited contribution to the overall causal structure of the study.

Effect Size (f^2)

The effect size (f^2) analysis presented in Table 10 indicates that shipyard layout (X) exerts a large effect on both operational efficiency ($f^2 = 0.506$) and sustainability performance ($f^2 = 0.389$), as well as a moderate effect on the effectiveness of integrated management systems ($f^2 = 0.294$). These findings further confirm that facility layout is the dominant factor within the production system.

TABLE 10.
EFFECT SIZE (F^2) RESULTS

Relationship	f^2	Category
$M \rightarrow Y_1$	0.091	Small
$M \rightarrow Y_2$	0.009	Very Small
$X \rightarrow M$	0.294	Medium
$X \rightarrow Y_1$	0.506	Large
$X \rightarrow Y_2$	0.389	Large
$Y_1 \rightarrow Y_2$	0.057	Small

In contrast, operational efficiency (Y_1) demonstrates a small effect on sustainability performance ($f^2 = 0.057$), although it remains statistically significant. This suggests that its role is more appropriately interpreted as a mediating mechanism rather than a primary direct driver. Meanwhile, the effect of management systems on sustainability performance is negligible ($f^2 = 0.009$), reinforcing its position as an enableing variable within the model.

Mediation Analysis

The mediation test results presented in Table 11 indicate that operational efficiency (Y_1) serves as a significant mediator in the relationship between shipyard layout (X) and sustainability performance (Y_2), with an indirect effect of $\beta = 0.124$ ($p = 0.049$). This result confirms that improvements in facility layout contribute to sustainability performance not only directly but also indirectly through enhanced operational efficiency.

Given that the direct effect of shipyard layout on sustainability performance ($X \rightarrow Y_2$) remains significant, the mediation can be classified as partial mediation [31]. This finding suggests that the influence of shipyard layout operates through two complementary pathways: (1) a direct structural effect on sustainability performance and (2) an indirect effect mediated by operational efficiency. Accordingly, operational efficiency functions as a key mediating mechanism that translates layout design into sustainability outcomes.

TABLE 11.
MEDIATION EFFECTS (BOOTSTRAPPING)

Mediation Path	Path Coefficient	t-statistic	p-value	Decision
$M \rightarrow Y_1 \rightarrow Y_2$	0.052	1.521	0.128	Not Significant
$X \rightarrow Y_1 \rightarrow Y_2$	0.124	1.965	0.049	Significant
$X \rightarrow M \rightarrow Y_1$	0.115	2.238	0.025	Significant
$X \rightarrow M \rightarrow Y_2$	0.034	0.709	0.479	Not Significant
$X \rightarrow M \rightarrow Y_1 \rightarrow Y_2$	0.025	1.333	0.182	Not Significant

This finding provides empirical evidence that sustainability performance in shipyard systems is not solely driven by structural design, but is critically mediated by the efficiency of operational processes. In other words, while facility layout establishes the structural foundation of the production system, its effectiveness in achieving sustainability goals depends on how efficiently operational processes are executed.

In contrast, the mediation pathway involving the management system is not supported. Although the indirect relationship from shipyard layout to operational efficiency through the management system ($X \rightarrow M \rightarrow Y_1$) is significant, this effect does not extend to sustainability performance (Y_2). This indicates that the management system primarily contributes to operational improvements without generating additional sustainability impacts. Therefore, its role is better interpreted as an operational enabler rather than a sustainability driver within the proposed model.

Structural Model Implications

Overall, the structural model evaluation yields three key implications. First, shipyard layout emerges as the most dominant structural determinant in enhancing both operational efficiency and sustainability performance. Second, operational efficiency acts as a key mediating variable (partial mediator) that bridges the relationship between facility layout and sustainability. Third, ISO-based integrated management systems function as an enabling factor, strengthening operational efficiency but not exerting a direct influence on sustainability performance.

These findings provide important contributions to the literature by demonstrating that sustainability in the shipyard industry is not solely driven by managerial practices but is strongly influenced by the structural design of production systems. This study extends the existing literature in three main ways: (a) by integrating facility layout, operational efficiency, and sustainability within a unified causal model; (b) by providing empirical evidence of the partial mediating role of operational efficiency; and (c) by identifying the pathway of layout → efficiency → sustainability as the dominant mechanism in shipyard production systems.

Accordingly, layout optimization is not only relevant in the context of productivity improvement but also serves as a key lever for achieving integrated operational sustainability [1], [3], [21].

E. Discussion

The findings of this study provide robust empirical evidence on the structural and process mechanisms that shape sustainability performance in shipyard production systems. Overall, the results indicate that shipyard layout acts as a primary structural driver, operational efficiency serves as a key mediating mechanism, and ISO-based integrated management systems function as operational enablers within a unified causal framework.

First, shipyard layout is found to have a strong and significant influence on both operational efficiency and sustainability performance. This highlights the critical role of spatial configuration, material flow organization, and functional integration in determining production system performance. In shipyard environments characterized by large-scale and highly interdependent production activities, facility layout directly governs material movement efficiency, process synchronization, and operational coordination [1], [2], [6]. Therefore, layout should not be interpreted merely as a physical arrangement, but as a strategic structural element that fundamentally determines production system effectiveness. From a theoretical perspective, this finding extends prior literature by reinforcing the argument that facility design constitutes a core determinant of production efficiency and competitiveness in maritime systems [1], [3], [5]. While previous studies have emphasized operational planning and managerial control, the present study demonstrates that structural configuration itself plays a more fundamental role in shaping system-wide performance outcomes in complex industrial environments such as shipyards.

Second, operational efficiency is found to have a significant positive effect on sustainability performance and acts as a partial mediator between shipyard layout and sustainability outcomes. This indicates that the influence of layout operates through both direct and indirect pathways, with operational efficiency serving as a key transformation mechanism that converts structural advantages into sustainability performance. This relationship can be explained by the fact that improvements in operational efficiency reduce resource consumption, material waste, and process inefficiencies, which are directly associated with sustainability performance in production systems [20], [25]. In addition, efficient operations enhance energy utilization and minimize unnecessary production activities, thereby contributing to economic and environmental dimensions of the Triple Bottom Line framework [18], [21]. Thus, operational efficiency represents a critical bridge connecting production system design and sustainability outcomes.

Third, the effectiveness of ISO-based integrated management systems significantly influences operational efficiency but does not have a direct effect on sustainability performance. This suggests that management systems primarily function as operational enablers rather than direct sustainability drivers. Their role lies in standardizing procedures, improving process control, and enhancing organizational discipline, which collectively contribute to improved operational efficiency. This finding is consistent with prior research indicating that managerial and institutional frameworks influence sustainability outcomes indirectly through operational improvements rather than direct structural changes in production systems [19], [20]. In other words, management systems alone are insufficient to generate sustainability improvements without corresponding enhancements in physical system design and operational configuration.

Furthermore, the structural model confirms that the dominant mechanism in shipyard production systems follows a structure–process–outcome logic, where facility layout (structure) influences operational efficiency (process), which subsequently determines sustainability performance (outcome). This integrated perspective addresses the fragmentation in previous studies, which tend to examine layout optimization, operational efficiency, and sustainability performance in isolation [6], [18].

Beyond the shipyard context, these findings may also be applicable to other large-scale, project-based, and spatially complex industries such as offshore construction and heavy manufacturing systems, where interdependencies between spatial design, operational flow, and performance outcomes are equally critical [2], [5].

In summary, this study contributes to the literature by providing an integrated empirical framework that links facility layout, operational efficiency, and sustainability performance. It demonstrates that achieving sustainability in shipyard production systems requires not only effective managerial systems but also optimized structural design and efficient operational processes. This integrated perspective offers a more comprehensive understanding of sustainability mechanisms in complex industrial systems.

IV. Conclusion

This study confirms that shipyard layout is a primary structural determinant that significantly enhances both operational efficiency and Triple Bottom Line-based sustainability performance. The spatial configuration of facilities, material flow organization, and the integration of production functions play a strategic role in shaping overall production system performance.

Operational efficiency is identified as a key mediating variable (partial mediator) in the relationship between facility layout and sustainability performance. This finding indicates that the advantages of layout design are not only directly realized but are also translated into improved economic, environmental, and social outcomes through enhanced process efficiency. Thus, operational efficiency serves as a transformational mechanism linking production system design to sustainability outcomes.

In contrast, ISO-based integrated management systems do not exhibit a direct effect on sustainability performance but significantly influence operational efficiency. This suggests that management systems function as operational enablers rather than primary drivers of sustainability. The mediation analysis further reveals that the most influential pathway lies in the indirect relationship between layout, operational efficiency, and sustainability performance, whereas pathways involving management systems are relatively weak.

From a theoretical perspective, this study contributes to the literature by integrating facility layout, operational efficiency, and sustainability performance into a unified empirical causal framework, while providing empirical evidence of the partial mediating role of operational efficiency. The findings extend existing research by demonstrating that sustainability in shipyard systems is not solely driven by managerial practices, but is fundamentally shaped by the structural design of production systems.

From a practical perspective, the results highlight that layout optimization, driven by operational efficiency, constitutes a key strategy for improving sustainability performance in shipyards. Accordingly, management should prioritize the development of integrated and adaptive layouts that minimize material handling inefficiencies and enhance process synchronization. Management systems should be implemented with a focus on strengthening operational efficiency as the primary pathway to achieving sustainability.

This study has several limitations. First, the cross-sectional design restricts the ability to capture the dynamic evolution of operational and sustainability performance over time. Second, the model is limited to facility layout, operational efficiency, and management systems, and does not fully incorporate external factors such as technological advancement, policy frameworks, and regulatory pressures. Future research is therefore encouraged to adopt longitudinal approaches, incorporate additional variables such as digitalization, lean manufacturing, and green technologies, and expand the scope to different types of shipyards to enhance generalizability.

Overall, the findings highlight that sustainability performance in shipyard systems is primarily driven by structural design, while operational efficiency acts as the key mechanism translating design into sustainable outcomes. This emphasizes the necessity of integrating spatial design and operational processes as a unified strategy for sustainable shipyard development.

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