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Development of a novel integrated value engineering and risk assessment (VENRA) framework for shipyard performance measurement: a case study for an Indonesian shipyard

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ABSTRACT

Shipyard industries affect the performance of manufactured ships. A designed ship needs well-performed shipbuilders to construct the ship following quality, timeline, budget, and environmental impact of future challenges. Shipyard performance measurement, including shipbuilding, ship repair, and ship conversion, will remain important as it is a powerful tool for strategic enhancement. This study proposes a conceptual and transdisciplinary framework for shipyard performance measurement through integrated Value Engineering and Risk Assessment (VENRA). The framework comprises five criteria groups: Technical, Business, External, Personnel Safety, and Environment, assessed by integrated fuzzy DEcision-MAking Trial and Evaluation Laboratory (DEMATEL) and Weighted Evaluation Technique (WET) methods and applied to an Indonesian shipyard. 'Shipyard's manufacturing facility' and 'Manufacturing/building strategy' are the most critical factors, while 'Personnel' and 'Technology Level' significantly influence other criteria. The framework can determine the shipyard's lowest score within the prioritised criteria and sub-criteria to evaluate the cause–effect link and prioritise steps to improve performance.

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1. Introduction

The function of the ship in exploration and global growth is well chronicled, but the infrastructure behind the ship, the shipyard, is typically forgotten or overlooked. The role of shipyards in producing or repairing vessels worldwide must be considered because it affects the produced ship's performance, which should be in accordance with customer's expectations (Bruce and Garrard 2013) and compliance with the challenging greenhouse gas (GHG) emissions reduction in the marine sector (IMO 2019).

On the one hand, the technical capability of shipyards exerts influence on the accuracy and quality of ship products (Basic 2019), such as in the propeller quality alignment case, which is affected by the installation process (Guo et al. 2018). The hull-form accuracy produced during manufacturing also has a negative impact on the speed reduction caused by poor hull-form shape accuracy. Although the distortion can be corrected, it takes more time and money and compromises the ship's structural integrity. Whatever the best and most advanced ship is designed, it requires the best-performing shipyard to execute the manufacturing process.

In addition, both the ship owner and the shipyard strongly consider economic aspects, such as production time, budget estimation mainly driven by labour and material costs and the effectiveness in organising the human resources. Appropriate shipyards with sound business management can achieve this economic aspect to gain a proper margin for the shipyard and satisfy customer expectations. The ship material supply chain, mainly the imported materials purchased, is also essential in the shipyard manufacturing process as this disruption can also impact the economics of the ship's manufacturing costs and time.

Furthermore, shipyard personnel safety standards, such as the ones originating from ISO (International Organization for Standardization) and OHSAS (Occupational Health and Safety Assessment Series), and their implementation within shipyards are required. A study of occupational safety in shipbuilding (Efe 2019) is an example of an effort to reduce the possibility of injury or death of personnel while working in the shipyard. Moreover, shipbuilding and ship repair sectors have not been considered yet concerning the GHG emissions-reducing targets by the International Maritime Organization (IMO 2019). GHG emissions contribution from shipyards is estimated at 2% for shipbuilding and 1% for ship repair (Chatzinikolaou and Ventikos 2014). However, no comprehensive and effective regulation governs the shipbuilding cycle (Pulli et al. 2013). With this respect, reducing GHG emission targets needs to be considered for the future greener shipyards in the marine sector.

On the other hand, a holistic design covering multiple dimensions or aspects is more important from a comprehensive standpoint. This point of view is not limited to the ship design process (Papanikolaou 2019). Shipyards, as manufacturers, should also consider implementing a holistic manufacturing process as they can improve the consideration of impacts in every aspect, including technical capabilities, business considerations, supply chain, safety, and environmental risk.

Determining the aspect of 'what industry performance should be through a number of criteria' can be executed through performance measurement tools. Performance measurement is essential to achieving a more competitive industry to maximise value, quality, flexibility, and cost. The proper critical selection of factors also

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influences determining aspects of what company performance should be evaluated as they impact how the measurement is conducted, affecting the company's strategic decision-making process (Harbour 1999).

To the best of the authors' knowledge, the existing models used for shipyard performance are mainly one-dimensional, including either technical (Pires and Lamb 2008; Pires et al. 2009) or financial (Gavalas et al. 2022). The model also uses simple measurements such as man-hour per Compensated Gross Tonnage (CGT) (Roque and Gordo 2021), which only consider the person-hour record and the ship size and type factors. The Data Envelopment Analysis (DEA) model used, such as from Rabar et al. (2022), who analysed the dry-docking performance, needs adequate data and input-output ratio and cannot analyse the criteria ranking. Concerning the model needing to involve several parameters and multi-dimensional attributes, a multi-criteria decision-making (MCDM) method is proposed for modelling.

This research aims to develop multi-dimensional criteria using a novel integrated VENRA framework for shipyard performance measurement. The VENRA criteria framework consists of Technical, Business, External, Personnel Safety and Environment groups with a number of criteria in each group and sub-criteria in each criterion. The proposed framework can measure shipyard performance through multi-dimensional attributes by analysing the criteria ranking within the shipyard's assessment score. The framework is applied in an Indonesian shipyard case to demonstrate the approach's effect.

The remaining sections are organised as follows. Section 2 examines the literature and critically analyses performance measurement in ship manufacturing, integrated Value Engineering and Risk Assessment, and fuzzy MCDM. Section 3 describes the proposed VENRA framework, followed by a shipyard case study and results in section 4. Section 5 presents the discussion part, and the conclusion in Section 6.

2. Literature and critical review

2.1. Shipyard performance measurement models

Initially, the shipyard performance model used productivity using man-hours per CGT to compare the shipyard's competitiveness in different regions. CGT is a tool developed by the UK in the 1960s to consider the workmanship content in different ship types and sizes, which has the latest version in 2007 by the Organization for Economic Co-operation and Development (OECD) (OECD 2007). Many researchers still used this model as a tool for shipbuilding productivity predictor (Lamb and Hellesoy 2002), comparing shipyards in different regions (Koenig et al. 2003) and measuring shipbuilding productivity (Roque and Gordo 2021). However, it cannot accommodate other influencing factors such as technology level, personnel safety, and environmental conditions.

The DEA model, which was introduced by Farrell (1957) and Charnes et al. (1978), has flexibility as it can include various input-output factors in the measurements. DEA has been used for shipbuilding performance benchmarking (Pires et al. 2009), proposing a scientific method for measuring productivity (Krishnan 2012), analysing performance indicators in shipbuilding competitiveness (Fareza 2020) and comparing technical gaps in productivity (Chao and Yeh 2020) in combination with meta-frontier. In the ship repair and maintenance sector, DEA has also been applied to measure and evaluate the efficiencies of various maintenance and repair operations (Mayo et al. 2020) and used for dry-docking performance measurement with different variables (Rabar et al. 2022). However, DEA is a non-dimensional parameter that cannot compute the weight importance factor. In addition, the number of Decision-Making Units (DMUs) should be at least twice the number of inputs and outputs (Golany and Roll 1989; Cook et al. 2014) or at least three DMUs per combined input-output number (Banker et al. 1989). With this regard, performance measurement needs other methods to eliminate these gaps.

The more comprehensive approach for shipyard performance is using the MCDM model, which can include various criteria and determine the ranking of those criteria. The MCDM model can also be integrated with Fuzzy Set Theory (FST) from Zadeh (1965) to eliminate subjectivity, making the assessment more naturally linguistic. The fuzzy MCDM approach has been applied in the marine and maritime industries for performance measurement or assessment.

Pinto et al. (2020) proposed a fuzzy qualitative factors model for technology and industrial location for Brazilian shipyards to rank the critical qualitative factors affecting naval shipbuilding performance. Baso et al. (2020) proposed internal and external environmental criteria for shipyards' competitiveness based on the Blue Ocean Strategy concept, prioritising the criteria through a linguistic Likert scale from experts, resulting in the shipyards' strategy decisions for the east region of Indonesia. Gavalas et al. (2022) evaluated shipbuilding performance indicators on a balanced scorecard criteria model focusing on business and financial indicators. Gayathri et al. (2022) developed an evaluation of port performance based on operational and financial aspects. Sahin et al. (2021) proposed a fuzzy MCDM based on a game-theoretic model to accommodate shipowner preferences and the challenges of shipyard selection for new shipbuilding based on technical aspects. Lazakis and Ölçer (2016) used fuzzy group MCDM to determine the optimal ship repair and maintenance method through suggested technical and cost attributes.

The fuzzy MCDM method has improved the measurement process by considering various factors, prioritising the weighted importance level, and assessing a more comprehensive dimension in shipyard performance measurement. However, the applications of this model for shipyard performance measurement are still limited and include a single dimension in either the technical (Sahin et al. 2021) or financial (Gavalas et al. 2022) dimensions. Concerning the safety and environmental impact in shipyards, the studies are also analysed in a single dimension, such as the analysis of occupational safety in shipbuilding (Efe 2019) and the study of energy management framework in shipbuilding to net zero emission (Vakili et al. 2022). A study by Ramirez-Peña et al. (2020) concerning the shipbuilding supply chain also uses a single dimension. Developing shipyard performance criteria that include multiple dimensions is required because it allows for a more comprehensive measurement of the shipyard in multi-dimensional parameters.

2.2. Integrated value engineering and risk assessment

The framework used to develop the multi-transdisciplinary dimension of factors is needed to integrate the five mentioned groups. Some frameworks, such as a balanced scorecard, include four perspectives: customer, financial, internal and innovation and learning perspective (Kaplan and Norton 1992), and it has been applied broadly in many sectors, including in shipbuilding sector (Gavalas et al. 2022). The other framework is Tree Bottom Line which includes people, the economy and the environment, which in some cases, it has been applied to risk analysis of the ship recycling industry (Ozturkoglu et al. 2019). However, these models cannot accommodate the five purposed criteria groups as the former focus on the business while the latter focus on sustainability, people and economy.

Value Engineering (VE) is a systematic methodology aiming to enhance the value or quality while reducing cost (Dell'Isola 1997; SAVE International 2007). It also includes multi-disciplinary cross experts included in the process. The VE concept can be integrated with other methodologies, such as the integration of VE with gray multi-criteria decision-making (Dahooie et al. 2020), Quality Function Deployment (QFD) (Ishak et al. 2020), sustainability for construction projects (Gunarathne et al. 2022), and the design for assembly concept for product development (Setti et al. 2021). VE also can be integrated with risk assessment and implemented in the manufacturing industry. The integrated VE with risk assessment concept is currently implemented in the automotive industry through the combination of Function Analysis System Technique (FAST) and Failure Mode and Effect Analysis (FMEA) from Anđelić et al. (2020) and construction project management from Masengesho et al. (2021). However, Baihaqi et al. (2021) analyse that the integrated VENRA concept is limited to theoretical and qualitative measurement and has not been applied in the marine industry.

With the knowledge of integrated VENRA, the five groups of criteria proposed for shipyard performance can be included using the VENRA criteria framework. In addition, as explained before, the VE's multi-dimensional field experts in process assessment remove each expert's limitations in each dimension and allow cross-dimensional enhancement.

2.3. Fuzzy DEMATEL and WET

The VENRA framework consists of multi-dimension groups, criteria and sub-criteria. It needs a methodology to analyse the criteria interrelationship and the weight of criteria for shipyard performance. There are many MCDM methodologies to asses multiple complex criteria; however, the fuzzy DEMATEL is chosen as it can assess the criteria cause–effect relation and the weight of criteria ranking.

The DEMATEL method is an MCDM tool that can deal with complex and comprehensive decision-making problems and efficiently determines the attribute cause–effect relationship and importance (Gabus and Fontela 1973; Fontela and Gabus 1976). To eliminate subjectivity, DEMATEL can be integrated with FST, as proposed by Zadeh (1965), integrated into fuzzy DEMATEL, eliminating the numerical way of assessing the attributes in the original method and using a more natural linguistic approach.

The fuzzy DEMATEL method has been used to analyse problems in assessing causal factors in operational hazards during gas-freeing in cure oil tankers (Akyuz and Celik 2015). It also has been used in the break-in two ship accident analysis (Kuzu 2021), enclosed space accidents/incidents factors on shipboard analysis (Soner 2021) and ship recycling safety management (Ozturkoglu et al. 2019). In addition, Gayathri et al. (2022) use fuzzy DEMATEL for port performance measurement in combination with The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Gavalas et al. (2022) use fuzzy DEMATEL integrated with an Analytic Network Process (ANP) and Multi-Objective Optimization On the basis of Ratio Analysis (MOORA) for assessing shipbuilding performance indicators through a balanced scorecard model. However, the higher number of criteria included, the judgement process needs more time and burdens the experts. In this case, the integration of fuzzy DEMATEL with other method is needed to assess the criteria and sub-criteria within VENRA framework more effectively.

WET is a simple, straightforward, and robust method for determining attribute weights, despite the existence of numerous straightforward weighting methods, including simple additive weighting (SAW), the Likert scale, eigenvector, and entropy. According to WET, the moderator (or manager) begins by ranking ordering attributes, assigning relative attribute importance on a scale of 0–100. The criteria perceived as most important are assigned a weight of 100, and all other criteria of relative importance are assigned a weight comparable to that (Turan et al. 2004; Ölçer and Odabaşi 2005; Ölçer et al. 2006; Ölçer and Majumder 2006).

Andrawus et al. (2009) used WET to determine weight criteria for decommissioning options on oil and gas platforms, while Al-Ghuribi et al. (2016) used it to evaluate financial and non-financial criteria of decommissioning options for offshore installations and well abandonment. This method was also applied to assess attribute weight for ship design producibility evaluation (Turan et al. 2004) and ro-ro vessel subdivision arrangement (Ölçer et al. 2006), as well as addressing the manoeuvring system selection problem (Ölçer and Odabaşi 2005). It also has been used in a proposed optimal-ballasting methodology case-based system for flooding crises onboard ships (Ölçer and Majumder 2006). However, no one has attempted to combine fuzzy DEMATEL with WET in the marine sector.

This paper attempts to fill the gaps identified in the existing literature and research by proposing a holistic, systematic and multi-dimensional framework using an integrated VENRA approach as a performance measurement tool in the shipyard industry. The integration of fuzzy DEMATEL and WET approaches is proposed in this paper as it can assess the cause–effect and weight of criteria and sub-criteria more effectively. Instead of using a standard 0–4 scale in the original DEMATEL method, the broader scale range proposed by Chen and Hwang (1992) is used, transformed and adapted for the fuzzy DEMATEL scale as it can accommodate experts' judgement on a broader range from the lowest to the highest. To the best of the authors' knowledge, this combined method has not been developed and applied in the marine industry, especially for measuring shipyard performance.

3. Development of the VENRA framework

This study addresses a systematic approach to enhance shipyard performance using a multi-discipline perspective through the developed VENRA framework. Developing frameworks and conceptual designs are more valuable, efficient, and effective than robust and rigorous models. Figure 1 shows the overall framework of the VENRA model for the shipyard's performance measurement.

It starts with developing integrated VENRA concepts and knowledge that are adopted and used to design the criteria. It conducted a thorough literature review of VE and its integration, including risk assessment concepts and knowledge to develop the criteria framework. The next step is to review the existing literature on performance measurement, competitiveness, selection, productivity, and benchmarking in the shipyard, shipbuilding, ship repair, or ship modification to identify the relevant criteria for VENRA. Semi-structured interviews with marine industry experts were also performed to obtain feedback and additional criteria.

The collected criteria are classified into value and risk criteria using VENRA knowledge and concepts, in which value includes quality, cost, and time. In contrast, risk includes the harmful activities associated with safety and the environment in shipyards. The criteria are developed into five primary dimensions, called the VENRA group. The output performance of shipyards concerning technical capacity and capability, business performance, proximity to external performance, and the capacity to manage safety and environmental impact influence the grouping into these five dimensions.

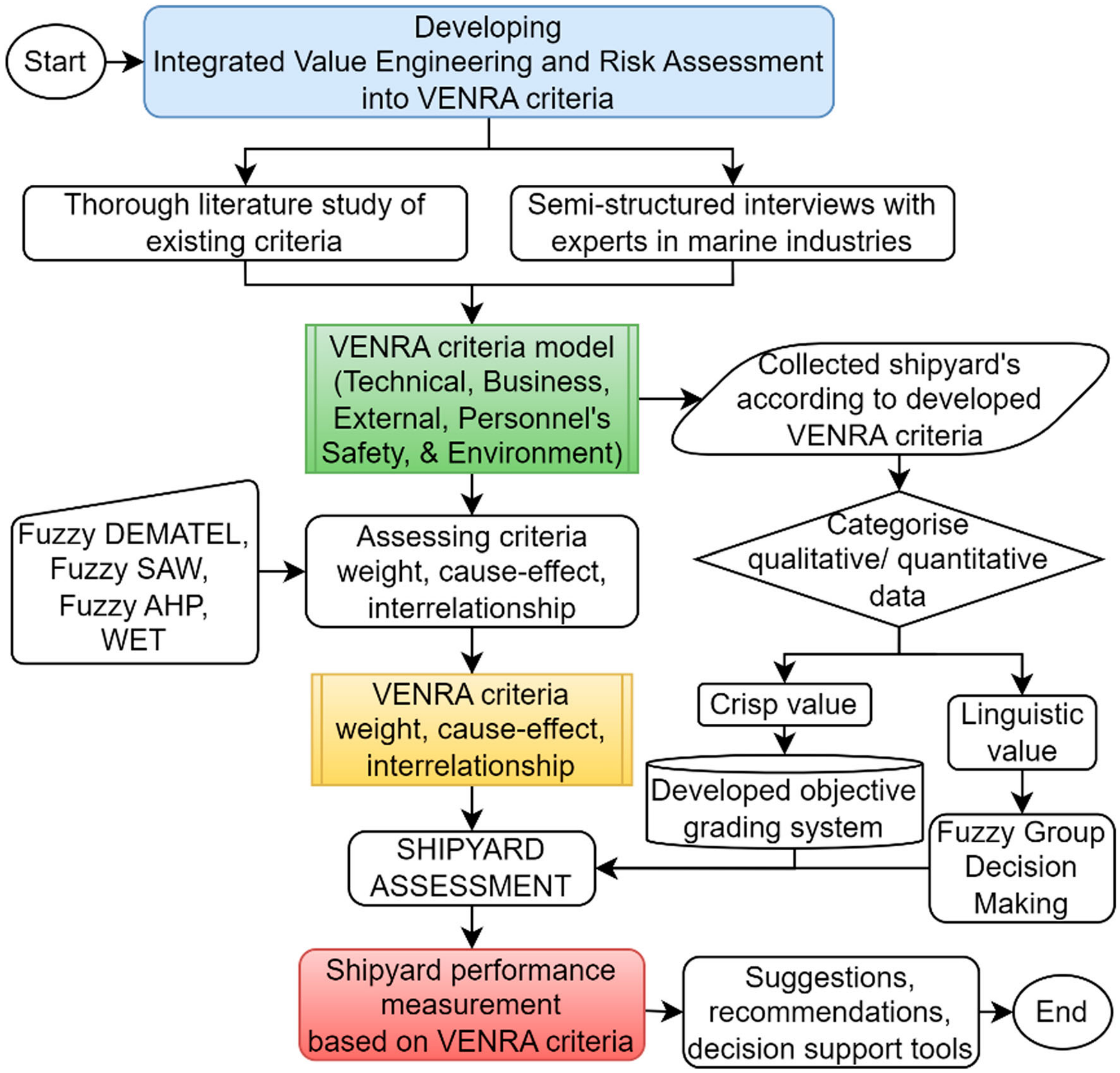

Figure 1. Novel VENRA design framework for shipyard performance measurement (This figure is available in colour online).

The next step is to evaluate each criterion's weight, cause–effect relationship, and interrelationship to identify the most important criteria, the group of cause–effect criteria, as well as the relationship between the criteria. Many methods are available, including fuzzy DEMATEL, ANP, Analytic Hierarchy Process (AHP), and simple weighting methods like SAW or WET. AHP and ANP can be used to assess the criteria weight, broadly used and has consistency analysis. Likewise, SAW and WET can also determine the criteria weight; however, these tools cannot analyse the cause–effect relationship between attributes. The integrated fuzzy DEMATEL-WET is proposed as a combined tool as it can effectively identify cause-and-effect and determine criteria and subcriteria importance rankings.

In the final step, once the criteria assessment has been conducted, the shipyard's data are collected according to the VENRA criteria framework. The shipyard's data are classified into qualitative and quantitative categories and assessed using fuzzy multi-attribute group decision-making (FMAGDM) (Ölçer and Odabaşi 2005) for linguistic data and through a developed objective grading system for crisp data values. Assessed criteria and the shipyard's assessment score are combined to identify the lowest score for the shipyard's performance according to VENRA criteria and are included in the most critical criteria group.

3.1. VENRA criteria framework

As stated, the VENRA criteria framework was initiated through the knowledge and concept of integrated VENRA, which has values and risks. As collected and evaluated before, the suggested criteria were split into five main groups, as shown in Figure 2. Each group further includes a list of main criteria and sub-criteria.

The Technical group includes criteria and sub-criteria affecting the technical performance effectiveness and the manufactured product's impact. It comprises six main criteria with codes T1 to T6. The Business group mainly contributes to managing the shipyard business to achieve more efficient business and economics. It is broken down into eight main criteria with codes B1 to B8. The next is the External group, which has three main criteria with codes E1 to E3, which concern the external proximity with other parties or resources. Personnel's Safety and Environment groups are developed into six and five criteria with code S1 to S6 and En1 to En5, respectively. Each criteria's name of the VENRA framework for the shipyard's performance with their codes is presented in Figure 2. All these groups and criteria are considered and proposed as performance measurement criteria for the shipyard's assessment to achieve the best value (reducing cost and time while maintaining quality) while also lowering

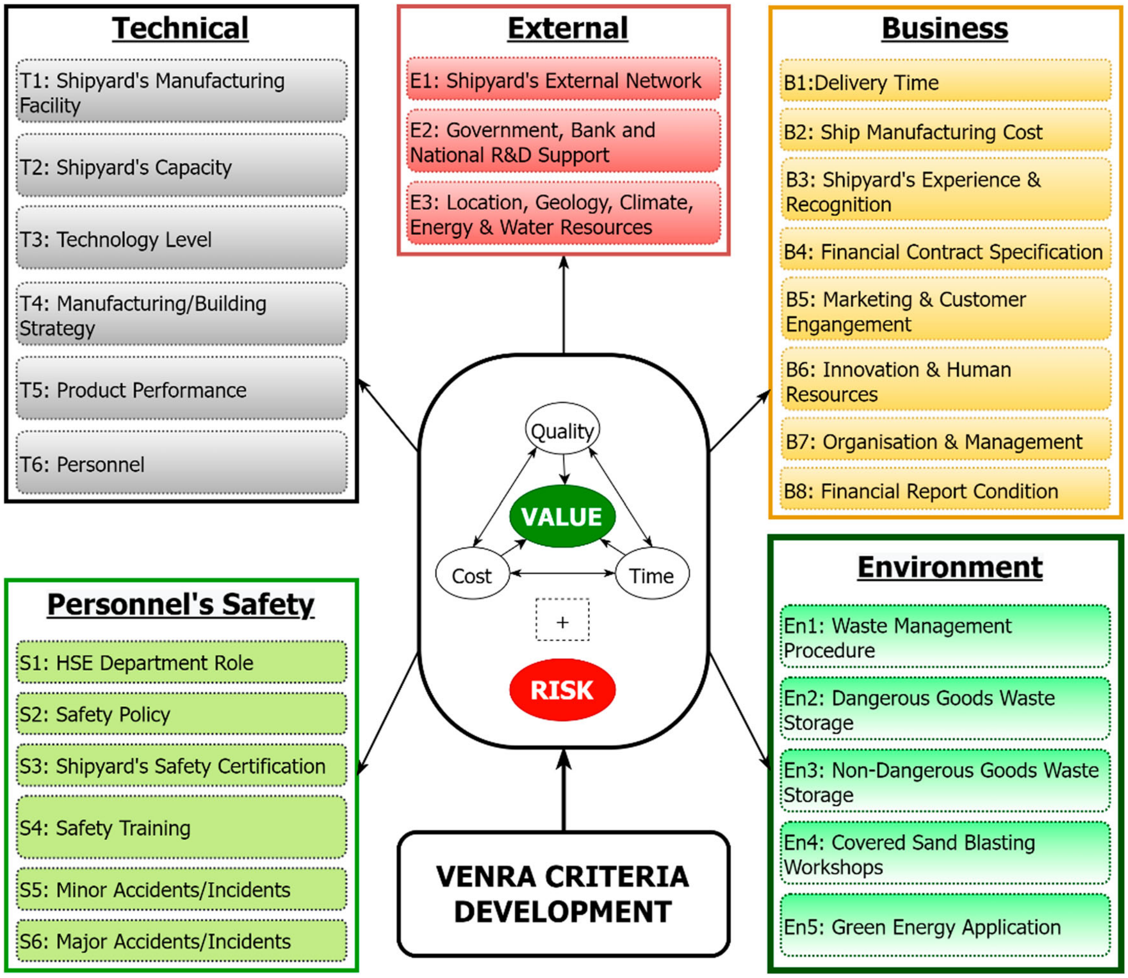

Figure 2. The VENRA criteria development for shipyard performance (This figure is available in colour online).

the risk impact on the shipyard's personnel safety and the environment.

Due to the extended number and detailed description of criteria and sub-criteria in the VENRA framework and considering the limited space on the paper, the Technical Group of VENRA is described in more detail, with 34 sub-criteria, as shown in Table 1. The remaining groups will be presented in a subsequent publication.

3.2. Methodology

3.2.1. Fuzzy DEMATEL

The VENRA-based criteria require a method to determine each criterion's weight, cause-and-effect relationship, and interrelationship. With this concern, a fuzzy DEMATEL method is used to achieve the objective, as it can determine the weight of criteria and the cause-and-effect relationships within criteria. The commonly employed scale in fuzzy DEMATEL ranges from zero to four, which is relatively standard and cannot accommodate the broader scale for expert judgement. As shown in Table 2, the scale developed by Chen and Hwang (1992) is adopted and modified for use in the fuzzy DEMATEL scale.

The fuzzy DEMATEL method consists of steps 1–7, explained in the following paragraph.

Step 1: Obtain a n x n fuzzy direct-relation matrix $\tilde{A}$ from experts, based on pairwise comparisons of the criteria. Its elements $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ represent the degree to which criterion j is affected by criterion i. In this paper, the expert's degree of level is considered based on the formal education background, industrial experience and academic-working experience, which is graded and weighted according to Table 3.

Assume the degree of importance of expert E_k $(k = 1, 2, \ldots, M)$ is we_k. In this case, each expert's relative importance is considered. First, the experts' background profile data is collected, graded and weighted according to their level of education, practical experience, and academic working experience, as presented in Table 3, and each score is as re_k, is obtained. Finally, the degree of the expert's importance we_k is defined as follows:

$$we_k = \frac{re_k}{\sum_{k=1}^{M} re_k} \tag{1}$$

Thus, the obtained $n \times n$ fuzzy direct-relation matrix aggregated experts, for the first step, become:

$$a_{ij} = \sum_{k}^{1 \le k \le M} we_k \, (a_{ij}^l, \ a_{ij}^m, \ a_{ij}^u) \tag{2}$$

Step 2: Determine the normalised fuzzy direct-relation matrix $\tilde{X}$ using Equation (3).

$$\tilde{X} = s \times \tilde{A} \tag{3}$$

where $s = \dfrac{1}{\max 1 \le i \le n \sum_j^n U_{ij}}$.

Table 1. Technical sub-criteria of VENRA.

Criteria code	Sub-criteria code	Sub-criteria	Description
T1	T1.1	Layout, material flow and environment	Shipyard's layout, material flow and environmental condition
	T1.2	Covered warehouse for storage	Percentage degree of the covered warehouse for storage
	T1.3	Covered workshops for steel processing	Percentage degree of covered workshops for fabrication, sub-assembly, and assembly
	T1.4	Fabrication machinery	Types, quantity and conditions of cutting bending/forming machinery owned by the shipyard
	T1.5	Welding machines	Types (e.g. SMAW, GMAW, FCAW), quantity and condition of welding machines owned by the shipyard
	T1.6	Transporter for block transport	Type (e.g. low loader, truck), quantity, capacity and condition of block transporter owned by the shipyards
	T1.7	Launching/docking	Type and quantity of docking facility owned by the shipyard (e.g. airbag system, graving, slipway, floating dock)
	T1.8	Design and engineering office services	The capability and capacity of internal design and engineering office services (e.g. ship design engineering & construction, producing production drawings)
	T1.9	Internal consultant service	The capability and capacity of internal consultant experts service to handle exceptional cases (e.g. construction assembly failure, capsized ship during launching, engine installation failure)
T2	T2.1	Total shipyard facilities area	Including design office, warehouse, production facility, buffer area, building birth, and docking area in square metre
	T2.2	Erection area/physical dock size	Length and breadth of erection area/dock size (maximum ship size in GT/DWT, which can be built in erection/dock area)
	T2.3	Maximum crane capacity	Crane max capacity (in tons) for ship block erection owned by the shipyard
	T2.4	Quay length	Total quay length (metres) for deck equipment installation or floating repair
	T2.5	Steel throughput capacity	Steel processing capacity: fabricated steel or welded panel-assembled construction per period (ton/day, ton/week, ton/month, ton/year)
T3	T3.1	Integration of CAD/CAM systems in design and production engineering	The application level of CAD/CAM systems for design, construction and production
	T3.2	Steel stockyard and treatment	Automation and integration level in raw material preparation (straightening, blasting, and painting)
	T3.3	Marking, cutting, and forming	Automation and integration level of marking, cutting and forming/bending material from production drawing
	T3.4	Flat-panel and sub-assembly	Level of technology and degree of automation for joining piece parts into flat panels and sub-assembly fitting up, tack-welding, complete welding technique, the accuracy of dimensions and forms, and the fairing (accuracy re-shape) technology
	T3.5	Assembly	Level of technology and degree of automation for joining panels into more giant blocks: fitting up, tack-welding, complete welding technique, the accuracy of dimensions and forms, and the fairing (accuracy re-shape) technology
	T3.6	Erection	Level of technology and degree of automation for erecting blocks in building birth: fitting up and levelling, tack-welding, complete welding technique, the accuracy of dimensions and forms, and the fairing (accuracy re-shape) technology
T4	T4.1	Construction method	The block division size and strategy plan to construct the main hull body (panel, partial block, or ring block)
	T4.2	Pre-outfitting	Degree of pre-outfitting level in hull construction (on-unit, on-block, onboard)
	T4.3	Modules	Degree of using modules (e.g. accommodation room, kitchen, bathroom, furniture)
	T4.4	Make or buy strategy	Percentage of make or buy in acquiring parts, panels, or ship components (piping, windows, electrical, HVAC-Heating, ventilation, and air conditioning)
T5	T5.1	Ship type-complexity	Ship type specialisation to building, repair or modification (e.g. cruise ship, container, LNG carrier, offshore support vessel)
	T5.2	Material-processed capability	Type of material that can be processed satisfactorily by shipyards (e.g. carbon steel, stainless steel, duplex, aluminium, fibreglass, wood)
	T5.3	Customer satisfaction	Owner's satisfaction notes about the products' output quality
	T5.4	Class Society and the regulation satisfaction	Satisfaction of the Class Society and the regulation in terms of standard quality ISO, IMO, quality of the material, machinery used, and environment
T6	T6.1	Availability of management/senior staff	The role, responsibility, communication, and correspondence of management staff (design engineer, admins, finance personnel, managers, board of directors, the CEO) in project deliverables
	T6.2	Availability of qualified workforce	Percentage degree of qualified and certified workers (e.g. project engineers, labour: fitters, welders, electricians, mechanics, NDT)
	T6.3	Worker's average age	The worker's age average, including in the design office and the field/workshop
	T6.4	Diversity, equity and inclusion	The ratio of male & female workers
	T6.5	Personnel education level/certification	Education background (HND, HNC, B.Eng. MEng. PhD) of shipyard personnel (in the design office and field/workshops), e.g. B. Eng. naval engineering, PhD marine engineering, M. Eng. hull structure engineering.
	T6.6	Personnel with high skill	The availability of specialists in shipyards, e.g. boiler specialists, hull structure experts, welding engineers, coating specialists

CAD/CAM: Computer-Aided Design/Computer-Aided Manufacture; SMAW: Shielded Metal Arc Welding, GMAW: Gas Metal Arc Welding, FCAW: Flux-cored Arc Welding; DWT: Deadweight Ton; LNG: Liquid Natural Gas; ISO: International Organization for Standardization; NDT: Non-destructive Test; HND: Higher National Diplomas; HNC: Higher National Certificates.

Table 2. Linguistic terms for fuzzy DEMATEL evaluation.

Abbreviation	Linguistic term	Triangular Fuzzy number Low (l)	Medium (m)	Upper (u)
N	0. None	0	0	0.1
VL	1. Very Low	0	0.1	0.2
L	2. Low	0.1	0.3	0.5
FL	3. Fairly Low	0.3	0.4	0.5
ML	4. More or less low	0.4	0.45	0.5
M	5. Medium	0.3	0.5	0.7
MG	6. More or less good	0.5	0.55	0.6
FG	7. Fairly Good	0.5	0.6	0.7
G	8. Good	0.5	0.7	0.9
VG	9. Very Good	0.8	0.9	1
E	10. Excellent	0.9	1	1

Table 3. Expert-level scoring model.

Formal education (15%)		Industrial practical experience in year (70%)		Academic working experience in years (15%)	
Category	Score	Range category	Score	Range category	Score
High school	25%	≤5	40%	<5	35%
Diploma (Pre-University)	35%	6–10	60%	5–10	50%
Bachelor's degree	60%	11–15	85%	11–15	75%
Master's degree	85%	16–20	90%	16–20	90%
Doctoral/PhD	100%	≥21	100%	≥21	100%

Step 3: Define three crisp matrices based on $\tilde{X}$, where $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$.

$$X_l = \begin{bmatrix} 0 & l_{12} & \dots & l_{1n} \\ l_{21} & 0 & \dots & l_{2n} \\ \vdots & & & \vdots \\ l_{n1} & l_{n2} & \dots & 0 \end{bmatrix}, X_m = \begin{bmatrix} 0 & m_{12} & \dots & m_{1n} \\ m_{21} & 0 & \dots & m_{2n} \\ \vdots & & & \vdots \\ m_{n1} & m_{n2} & \dots & 0 \end{bmatrix},$$

$$X_u = \begin{bmatrix} 0 & u_{12} & \dots & u_{1n} \\ u_{21} & 0 & \dots & u_{2n} \\ \vdots & & & \vdots \\ u_{n1} & u_{n2} & \dots & 0 \end{bmatrix},$$

Step 4: Obtain the fuzzy total-relation matrix $\tilde{T}$ using equations (4) to (7).

$$\tilde{T} = \tilde{X}(I - \tilde{X})^{-1} \tag{4}$$

$$\text{Matrix } [l'_{ij}] = X_l(I - X_l)^{-1} \tag{5}$$

$$\text{Matrix } [m'_{ij}] = X_m(I - X_m)^{-1} \tag{6}$$

$$\text{Matrix } [u'_{ij}] = X_u(I - X_u)^{-1} \tag{7}$$

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \dots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \dots & \tilde{t}_{2n} \\ \vdots & & & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \dots & \tilde{t}_{nn} \end{bmatrix}$$ where, $\tilde{t}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij,})$ and I is the identity matrix. Identity matrix I is square matrix with ones on the main diagonal and zeros elsewhere.

Step 5: Defuzzify $\tilde{T}$ using the centre of area (COA) to determine the best non-fuzzy performance (BNP) using Equation (8) and determining the total influence matrix for each set of criteria considered.

$$BNP_{ij} = \frac{u_{ij} - l_{ij} + m_{ij} - l_{ij}}{3} + l_{ij} \tag{8}$$

Step 6: Determine the cause–effect relationship and criteria weight. First, compute the row sum (R_i) and the total influence matrix's column sum (C_j). (R_i-C_j) values determine the cause or effect factors; a positive value means factor i is grouped as a causal factor, while if the value is negative, factor i is impacted by other factors or grouped as affected factors. (R_i+C_j) values provide the degree to which factor i affects or is affected by j, which can be normalised and present the criteria's weight.

Step 7: Construct cause–effect relation diagrams and criteria weight. The diagram is plotted based on (R_i+C_j) values as the axis and (R_i-C_j) values as the ordinate.

Table 4. The WET scale used to grade sub-criteria.

No	Linguistic term	Score range
1	Critical	91–100
2	Extremely important	81–90
3	Very important	71–80
4	Important	61–70
5	Moderately important	31–60
6	Less important	16–30
7	Unimportant	0–15

3.2.2. Weighted evaluation technique

In the proposed approach, WET is used to determine the sub-criteria weights. Although it is a conventional method, WET is a straightforward and advantageous weighting technique. The author moderated the investigation as he has an educational background and knowledge of the shipbuilding and shipyard industries and has previous experience in shipyard assessment. This paper also complements the scale with the linguistic term to more naturally accommodate the experts' linguistics.

First, the moderator rank ordering of sub-criteria, assigning relative sub-criteria importance on a scale of 0–100 and linguistic WET grading score as in Table 4. The score weighting is conducted on sub-criteria for each main criterion, e.g. the shipyard's manufacturing facility (T1) has nine sub-criteria, which are weighted using WET and normalised according to the T1 criteria. The next step is to validate the ranking by conducting semi-structured interviews with relevant experts with experience in the shipyard industry, shipping companies, or relevant academicians with shipbuilding or shipyard backgrounds.

3.2.3. Integrated fuzzy DEMATEL-WET

The fuzzy DEMATEL and WET methods are combined to evaluate the shipyard performance measurement according to the VENRA criteria framework to gain more effective criteria and sub-criteria cause–effect and weight ranking results. Below is the description of the main steps in the combined method, presented as a flowchart in Figure 3.

The above VENRA framework is demonstrated in the case of an Indonesian shipyard to prove its applicability and effectiveness, as presented in the following section.

4. Case study and results

4.1. Shipyard case study and data analysis

This shipyard, established 12 years ago, offers a mix of new construction and repair services for steel and aluminium vessels. Located in Indonesia, it has a steel capacity throughput of around

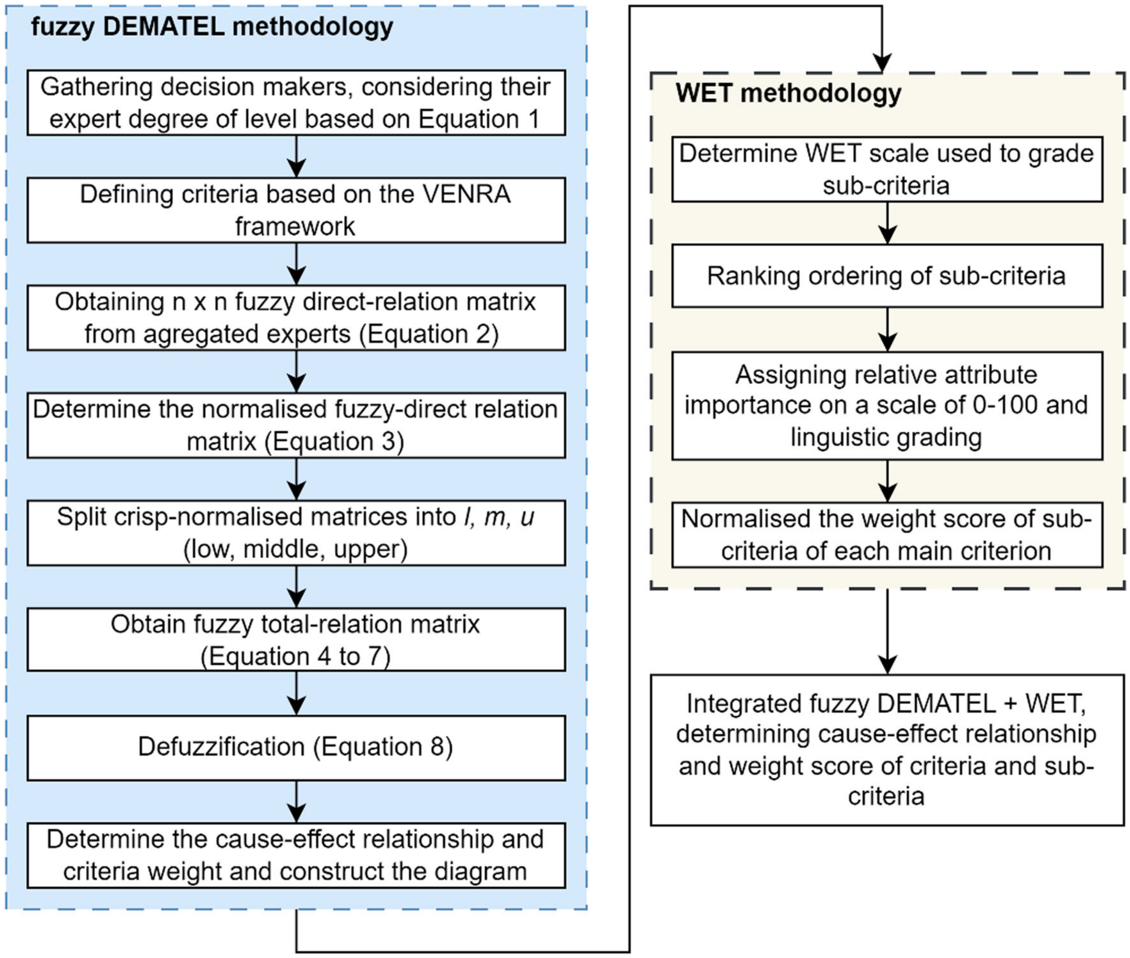

Figure 3. Integrated fuzzy DEMATEL-WET methodology (This figure is available in colour online).

3120 tons/year for steelwork and around 48 tons/year for aluminium. The management has a great vision to improve the technology by investing in drawing production software and nesting optimisation software for the steel-cutting process using CNC. It has experience building government-contracted ships for Indonesia's sea toll ship programme, such as general cargo and container ships. This shipyard also has experience building offshore support vessels and passenger boats. Not only a new building, but this shipyard can also handle docking services, ship repairs, and maintenance for vessels up to 2,000 GT.

Table 5. Grading system example of Welding Machines (T1.5) sub-criterion on Shipyard's Manufacturing Facility (T1) criteria.

Verbal score	Assessment	Grade score
Very poor	Have a few manual welding (e.g. SMAW-Shielded metal arc welding), mainly using back weld welding	0–10
Poor	Have some manual welding & few semi-automated welding (only FCAW: Flux-cored arc welding or SAW-Submerged arc welding, or GMAW-Gas metal arc welding) but still not using side welding	11–30
Adequate	Have quite a manual welding and more than one semi-automated welding using (FCAW & GMAW) but still use back weld welding	31–60
Good	Have adequate manual welding, semi-automatic welding, and use one-side welding	61–80
Excellent	Use robotic welding using electro-gas or electro-slag welding and also have FCAW, SMAW, SAW, and GMAW	81–100

A direct survey and semi-structured interviews with the shipyard's expert representatives were conducted to collect data on the shipyard. It also included other supporting resources such as company profiles, online resources, open publications, or internal technical report studies. The qualitative or quantitative data were summarised and scored using a developed grading system that accepts verbal score assessment (low, medium, high) or grading evaluation that can be converted into a ranged score. The range scored is then classified and adjusted by the investigator to gain the exact predicted values, considering both assessments (verbal score from interviews and assessed data). An example of the developed grading system is shown in Table 5, which presents the verbal score, assessment, and grade score for the welding machines (T1.5) sub-criteria, part of the shipyard's manufacturing facility (T1) criteria. The assessed data score is validated by sending the data to the shipyard's representatives' experts after it has been summarised and graded based on its qualitative or quantitative values. Validated data is then inputted into the VENRA criteria to obtain the results needed to measure the shipyard's performance.

Table 6 summarises collected shipyard data based on the Technical Group of the VENRA framework criteria, which have been graded using the developed grading system, as shown in Table 5.

4.2. Cause–effect and criteria prioritising

This study involved seven experts in providing their expert judgement in assessing the criteria. The tabulated expert list and

Table 6. Shipyard's data, the code and score results.

Criteria code	Code	Shipyard's data collected	Score (0–100)
T1	T1.1	The layout is fair enough, with the assembly area needs soil hardening	50
	T1.2	<50% are covered. Plates, stiffeners, and pipes are placed outside. Important materials such as the main engine, electrical, and systems parts are saved in the coverage building	40
	T1.3	<50% are covered. Has covered fabrication workshop, but not for sub-assembly and assembly	40
	T1.4	2 CNC automatic cutting and bending for plate, pipe, and profile. But no for 3D curvature forming (hot or cold)	55
	T1.5	5 Manual & 15 semi-automatic welding machine	70
	T1.6	No dedicated transporter for block transport (use mobile crane)	40
	T1.7	Cradle and airbag for new & repair activities	30
	T1.8	Capable of producing production drawings. No department in preliminary design development	40
	T1.9	Not available. Hire external resources if needed	0
T2	T2.1	32 K m^2 in total; 8 K m^2 for closed and semi-closed workshop area	30
	T2.2	Have a land-based open erection area (4 × @70 m × 12 m), approximately 4× @1200 GT	35
	T2.3	Mobile crane 100 ton, in 70% condition (limitation in radius, inclination, and angle)	35
	T2.4	Less than 200 m, with low depth (approximately 3–4 metres)	10
	T2.5	± 3120 tons/year for steelwork and ±48 tons/year for aluminium	18
T3	T3.1	Having modelling software for production output & optimise nesting software for CNC code for the nesting process. Both output files have to be manually inserted into the cutting machine	45
	T3.2	Have no integrated steel stockyard treatment, using manual labour for blasting & painting.	10
	T3.3	Using CNC cutting (input from software output drawing), manual marking process, forming partially using a bending machine (the 3D curvature use manual working)	45
	T3.4	Manual sub-assembly process, manual welding using SMAW mostly	15
	T3.5	Manual Assembly method using a mobile crane in the open area, joining process using manual welding (SMAW) mostly	15
	T3.6	Manual erection method using a mobile crane in the open area, joining process using manual welding (SMAW) mostly	15
T4	T4.1	Conventional method joining piece part into panel and block	15
	T4.2	A small part in pre-outfitting, such as installing part of ducting, inlet and outlet of piping system in the hull, possibly less than 5%	10
	T4.3	No using modular at all	0
	T4.4	Less than 5% in value are produced/assembled by a third party (Shipyards tend to conduct a making strategy mostly)	10
T5	T5.1	Tugboat, AHTS (Anchor Handling Tug System), general cargo, patrol boat & special passenger boat.	45
	T5.2	Carbon steel & aluminium mostly	50
	T5.3	A possibly satisfied customer with some complains	45
	T5.4	Accepted by local and IACS societies: BKI (Indonesia Bureau Classification), ABS (American Bureau of Shipping), and BV (Bureau Veritas) with some notes for improvement	50
T6	T6.1	Have a management/senior staff and office workers with good/excellent correspondence and communication through the system (in-house system, integrated system information)	85
	T6.2	Labour workers (welders, fitters, crane operators) are certified, which is approximately more than 50%	60
	T6.3	Considered as a young group of workers (less than 35 years old)	85
	T6.4	95–99% male	10
	T6.5	9% Primary School, 11% Junior High school, 14% Senior high school, 25% D3 (HND), 36% bachelor's degree, 5% master's degree	40
	T6.6	Not available. Hire external resources	0

CAD/CAM: Computer-Aided Design/Computer-Aided Manufacture; SMAW: Shielded Metal Arc Welding, GMAW: Gas Metal Arc Welding, FCAW: Flux-cored Arc Welding; DWT: Deadweight Ton; LNG: Liquid Natural Gas; ISO: International Organization for Standardization; NDT: Non-destructive Test; HND: Higher National Diplomas; HNC: Higher National Certificates.

profile considered the experience, academic experience and practical experience. The details of the expert's profiles are shown in Table 7. Expert 1 is a senior technical and development director in a shipyard. Experts 2, 4, and 5 are lecturers in naval architecture and shipbuilding engineering with experience in ship production technology. Expert 3 is a commander with experience in ship maintenance and is very familiar with the shipyard activities and facilities, while Expert 6 is a project manager/coordinator within a shipyard and is responsible for managing the shipyard activities and resources. Expert 7 has relevant experience as a marine consultant in monitoring and supervising the production of a ship within a shipyard.

Table 7. Experts list background and profile.

No	Ed.	Exp.	Acad.	Grade Level	Job sector	Job's position
1	MSc	17	10	Senior	Shipyard	Technical and development director
2	MSc	3	8	Middle	Academia	Lecturer staff
3	MSc	13	5	Middle	Ship maintenance	Commander
4	MSc	6	8	Middle	Academia	Lecture staff
5	MSc	6	8	Middle	Academia	Lecture staff
6	MSc	6	4	Middle	Shipyard	Project manager/ coordinator
7	BEng	3	2	Early	Marine consultancy	Marketing staff

Ed.: Education background, Exp.: Industrial practical experience, Acad.: Academic working experience.

Table 8 provides an example of step 1 in fuzzy DEMATEL, showing the linguistic fuzzy direct relation matrix of Expert 1.

Table 9 presents the fuzzy aggregation of the direct relation matrix from seven experts, considering their expert degree level as the result of Equation (2). The calculation was conducted using MS Excel software.

Table 10 shows the normalised fuzzy direct relation matrix based on Equation (3), which is separated into low (l), medium (m) and upper (u) scores in the applied triangular fuzzy number.

The fuzzy total relation matrix, as in step 4, is then calculated based on Equation (4), which is divided into the low score (Equation 5), medium score (Equation 6), and upper score (Equation 7), and the results are presented in Table 11.

The crisp value from the fuzzy number of the matrix $\tilde{T}$ is then de-fuzzified as in step 5 based on equation (8) to find the crisp values, and the results are shown in Table 12.

Calculate the row sum (R_i) and column sum (C_j) based on the crisp value of the total relation matrix T as in step 6. $R_i - C_j$ values

Table 8. Linguistic fuzzy direct-relation matrix $\tilde{A}$ of Expert 1, in the first step of fuzzy DEMATEL.

	T1	T2	T3	T4	T5	T6
T1	N	E	E	G	VG	L
T2	VG	N	L	G	M	FG
T3	VG	E	N	VG	G	FG
T4	L	FG	L	N	VG	ML
T5	VL	VL	VL	ML	N	ML
T6	VG	FL	M	VG	VG	N

classify the cause or effect, with positive values classifying the cause and negative values classifying the effect. Meanwhile, the $R_i + C_j$ values represent the importance level of the criteria, with higher values indicating more significant importance. The tabulated results of these analyses, including the normalised weight, cause–effect criteria and weight ranking, are presented in Table 13.

Figure 4 depicts a cause-and-effect diagram created using $R_i + C_j$ values as the axis and $R_i - C_j$ values as the ordinate (plot using Matlab software). It shows the plotted six criteria for the Technical Group of VENRA in the diagram as presented according to the criteria's name and code. The higher values of $R_i + C_j$ mean the criteria have a greater level of importance. Positive $R_i - C_j$ values indicate that it is the cause criteria; the higher the score, the more significant the impact on the other criteria. The negative $R_i - C_j$ values indicate that it is the effect criteria; the lower the score, the more influential the impact on the other causal criteria.

'Shipyard's manufacturing facility' (T1), 'manufacturing/building strategy' (T4), and 'technology level' (T3) are the top three most important factors, respectively, followed by 'shipyard capacity' (T2). 'Product performance' (T5) and 'personnel' (T6) are the least important ones. However, the scores ranging between 15.1% to 17.6% are relatively similar. On the other hand, T6, T3, T1 and T2 are classified as the cause criteria, with T6 and T3 as the most influential factors. At the same time, T4 and T5 are grouped in effect criteria, with T5 as the most impacted factor.

Figure 5 presents the bar chart as the shipyard's assessment score and the line chart as technical criteria weight in percentage, ordered from highest to lowest criteria ranking. The shipyard has a high score in T6 and T5 in its performance but a low score for T4, T3, and T2, respectively. T6, T5 and T1 have medium scores in shipyard assessment, between 45%−55%, while T2 and T3 have a lower score, around 25%, and the least is T4, which scored less than 10%.

Figure 6 shows the shipyard's assessment score according to the sub-criteria ranking in technical group criteria presented as bar charts and line charts.

This shipyard scores well enough for the 'welding machines' (T1.5) sub-criteria of 70%, followed by 'fabrication machinery' (T1.4) of 55%, in the 'manufacturing facility' (T1) criteria. In contrast, the shipyard's scores for sub-criteria T1.1, T1.2, T1.3, T1.6, T1.7, and T1.8 are relatively low to medium, ranging between 25%−50%. Since the shipyard does not have an internal consultant service, T1.9 scores zero. The T1 sub-criteria ranking scores are between 10% and 16%, led by 'launching/docking' (T1.7) and 'fabrication machinery' (T1.4) as the most prioritised sub-criteria. In contrast, T1.8 and T1.6 are the lowest groups, and T1.9 is the least important criterion.

The average score of the 'shipyard's capacity' (T2) sub-criteria is low, around 25%. The 'total shipyard's facilities area' (T2.1), 'erection area/physical size dock' (T2.2), and 'maximum crane capacity' (T2.3) score between 30-35%, whereas 'quay length' (T2.4) and 'steel throughput capacity' (T2.5) score 10% and 18%, respectively. The sub-criteria ranking score average is between 17% to 22%, and T2.2 and T2.5 are the most important sub-criteria in the shipyard's capacity.

The shipyard's 'technology level' (T3) average scores are low but have a significant score of 45% for 'integration of CAD/CAM system' (T3.1) and 'marking, cutting, and forming' (T3.3), classified as the most crucial sub-criteria ranking in T3. The 'flat-panel and sub-assembly' (T3.4), 'assembly' (T3.5), and 'erection' (T3.6) scores are low by 15% each, while 'steel stockyard and treatment' (T3.2) scores are the lowest and least important sub-criterion.

Concerning 'manufacturing/building strategy' (T4), this shipyard has a low score in the overall sub-criteria, ranging from 0 to 15%. The 'pre-outfitting' (T4.2) and 'construction methods' (T4.2) have scores of 10% and 15%, respectively. Since the shipyard has not used the module's strategy, the score for the 'modules' (4.3) sub-criterion is zero, and the 'make or buy strategy' (T4.4) scored 10%. Sub-criteria ranking has a similar weight between 25%−29% except for T4.4 at around 17%.

The 'product performance' (T5) sub-criteria score is between 45% to 50%, with an average of around 47%. All of the sub-criteria in T5 are considered vital since it weighs from 21% to 27%, led by

Table 9. The aggregated fuzzy direct-relation matrix from seven experts.

	T1			T2			T3			T4			T5			T6		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*M*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
T1	0.00	0.00	0.10	0.82	0.92	0.95	0.69	0.80	0.87	0.61	0.78	0.91	0.52	0.67	0.83	0.26	0.39	0.52
T2	0.72	0.83	0.90	0.00	0.00	0.10	0.49	0.64	0.78	0.63	0.76	0.84	0.48	0.64	0.79	0.35	0.45	0.56
T3	0.62	0.73	0.81	0.72	0.82	0.87	0.00	0.00	0.10	0.56	0.67	0.76	0.71	0.86	0.95	0.55	0.67	0.79
T4	0.50	0.64	0.76	0.44	0.55	0.64	0.46	0.60	0.71	0.00	0.00	0.10	0.74	0.88	0.97	0.51	0.60	0.68
T5	0.34	0.45	0.56	0.24	0.32	0.40	0.28	0.41	0.54	0.50	0.60	0.67	0.00	0.00	0.10	0.27	0.36	0.44
T6	0.43	0.57	0.71	0.45	0.55	0.66	0.38	0.51	0.63	0.67	0.79	0.89	0.65	0.76	0.85	0.00	0.00	0.10

Table 10. Normalised fuzzy direct-relation matrix $\tilde{X}$ in three crips matrices.

	T1			T2			T3			T4			T5			T6		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*M*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
T1	0.00	0.00	0.02	0.19	0.22	0.22	0.16	0.19	0.20	0.14	0.18	0.21	0.12	0.16	0.19	0.06	0.09	0.12
T2	0.17	0.19	0.21	0.00	0.00	0.02	0.11	0.15	0.18	0.15	0.18	0.20	0.11	0.15	0.18	0.08	0.11	0.13
T3	0.14	0.17	0.19	0.17	0.19	0.20	0.00	0.00	0.02	0.13	0.16	0.18	0.17	0.20	0.22	0.13	0.16	0.18
T4	0.12	0.15	0.18	0.10	0.13	0.15	0.11	0.14	0.17	0.00	0.00	0.02	0.17	0.20	0.23	0.12	0.14	0.16
T5	0.08	0.10	0.13	0.06	0.07	0.09	0.06	0.09	0.12	0.12	0.14	0.16	0.00	0.00	0.02	0.06	0.08	0.10
T6	0.10	0.13	0.17	0.10	0.13	0.16	0.09	0.12	0.15	0.16	0.18	0.21	0.15	0.18	0.20	0.00	0.00	0.02

Table 11. Fuzzy total relation matrix $\tilde{T}$ results.

Low						Medium						Upper					
T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6	T1	T2	T3	T4	T5	T6
0.188	0.352	0.304	0.331	0.321	0.200	0.420	0.590	0.549	0.611	0.620	0.415	1.254	1.354	1.349	1.501	1.586	1.127
0.318	0.175	0.257	0.320	0.299	0.206	0.557	0.386	0.498	0.581	0.585	0.405	1.360	1.139	1.286	1.435	1.520	1.093
0.321	0.341	0.173	0.334	0.369	0.262	0.575	0.581	0.400	0.606	0.665	0.473	1.413	1.354	1.212	1.495	1.627	1.189
0.266	0.256	0.242	0.184	0.341	0.230	0.506	0.481	0.474	0.414	0.610	0.420	1.287	1.205	1.227	1.237	1.498	1.074
0.180	0.161	0.157	0.225	0.127	0.143	0.356	0.327	0.331	0.410	0.306	0.286	0.954	0.880	0.911	1.035	0.986	0.787
0.251	0.252	0.222	0.315	0.320	0.122	0.487	0.475	0.451	0.563	0.583	0.293	1.278	1.208	1.211	1.393	1.477	0.955

Table 12. Crisp values of total-influence Matrix $\tilde{T}$.

	T1	T2	T3	T4	T5	T6
T1	0.620	0.765	0.734	0.814	0.842	0.581
T2	0.745	0.567	0.680	0.779	0.801	0.568
T3	0.770	0.759	0.595	0.812	0.887	0.641
T4	0.686	0.647	0.648	0.612	0.816	0.575
T5	0.497	0.456	0.467	0.557	0.473	0.405
T6	0.672	0.645	0.628	0.757	0.794	0.457

'ship type complexity' (T5.1) as the most crucial sub-criterion by 27%, followed by 'material-processed capability' (T5.2) at 25%.

The last is the 'personnel' (T6) sub-criteria; this shipyard scores slightly above 55% on average. The shipyard has a high score in 'availability of management/senior staff' (T6.1) and 'worker's average age' (T6.3), with a score of 85% each. The 'availability of qualified workforce' (T6.2), the most critical sub-criterion, scored 60%, while the 'personnel education/certification' (T6.5) scored 40%. The score of 'diversity, equity and inclusion' (T6.4) is deficient by 10%, and this sub-criterion is considered the most negligible factor before 'personnel with high skill' (T6.6) which is score zero.

5. Discussion

Concerning the fuzzy DEMATEL results, the causal factors are 'personnel' (T6) and 'technology level' (T3), followed by 'shipyard's manufacturing facility' (T1) and 'shipyard's capacity' (T2), respectively, according to the highest R_i-C_j values. At the same time, the top three criteria are T1, 'manufacturing/building strategy' (T4), and 'technology level' (T3). It revealed that T3 is classified as the most impacting factor for other criteria and the most important factor for shipyard performance based on expert preferences, as shown in Figure 4.

The case study results show that the shipyard assessment score has the lowest score on T4, followed by T3 and T2. With this regard, through the VENRA framework, a strategic step is proposed and suggested to improve the shipyard's performance through cause-and-effect and importance level criteria, considering these shipyard's assessed lowest score.

The 'technology level' (T3) criteria are suggested to be prioritised as they can impact the other criteria, second place in causal factor, having a similar value of R_i-C_j with 'personnel' (T6), and directly impact the shipyard's performance (top three in weight ranking) as shown in Figure 4. The more advanced technology in the shipyard will possibly automatically impact production speed, such as the advancement of CNC cutting machines or welding machines, directly affecting product manufacturing speed. In addition, the T3 has also influenced other criteria; the most impacted one is the product output, as in this case, 'product performance' (T5). The more advanced technology used in the shipyard will affect the accuracy and quality of the production. Since 'personnel' (T6) has the most significant impact on the other factors, it is suggested that the shipyards maintain the qualified workers' and senior workers' positions. The potential young group should be maintained, trained, and educated to enhance the personnel's knowledge and skills, particularly concerning the future challenges of the greener shipyard.

Regarding the top three criteria ranking, which has a similar weight score, and considering the assessment score result of the shipyard's case study, it is suggested to focus on 'manufacturing/building strategy' (T4) and 'technology level' (T3). As stated before, advancing the technology will directly improve the shipyard facility and building strategy based on the cause–effect diagram in Figure 4. The T3 also impact the facility criteria (T1) and building/manufacturing strategy (T4) factors from the DEMATEL cause–effect diagram. Once again, considering these reasons, it is recommended to focus on enhancing the criteria in T4 and T3, respectively. The summary of the main suggested strategic improvement for the shipyard in accordance with criteria analysis and the shipyard's assessment score is presented in Table 14. A more detailed condition and further strategical step for each criterion based on the shipyard's assessment data is discussed further in the following subsection.

5.1. Shipyard's manufacturing facility (T1)

Using a cradle and an airbag system facility for launching/docking (T1.7) facilities must be reconsidered. The airbag system is inexpensive and can be supplied by a third party. However, it necessitates a validated calculation that affects the ship's structure for safe launching and docking using an airbag system. Meanwhile, cradle operation and maintenance are costly due to the cradle's submerged part location in corroded seawater. The second group criteria in the facility, considered low but essential, is covered workshops (T1.2 and T1.2), especially for fabrication and sub-assembly. These criteria affect product quality and rework due to weather, wind, and dust. At least flat panel assembly can be done in the covered workshop for better production quality, less rework, and a better process, such as using a pre-outfitting strategy (T4.2), which requires a covered workshop. Another improvement is covering

Table 13. Row sum (R_i), column sum (C_j), normalised weight, cause/effect and weight rank.

Criteria	R_i	C_j	$R_i + C_j$	$R_i - C_j$	Normalised weight	Cause/effect	Weight rank
T1	4.357	3.989	8.346	0.368	0.176	Cause	1
T2	4.140	3.839	7.979	0.301	0.168	Cause	4
T3	4.463	3.752	8.215	0.712	0.173	Cause	3
T4	3.984	4.330	8.314	(0.346)	0.175	Effect	2
T5	2.854	4.613	7.467	(1.759)	0.157	Effect	5
T6	3.952	3.227	7.179	0.725	0.151	Cause	6

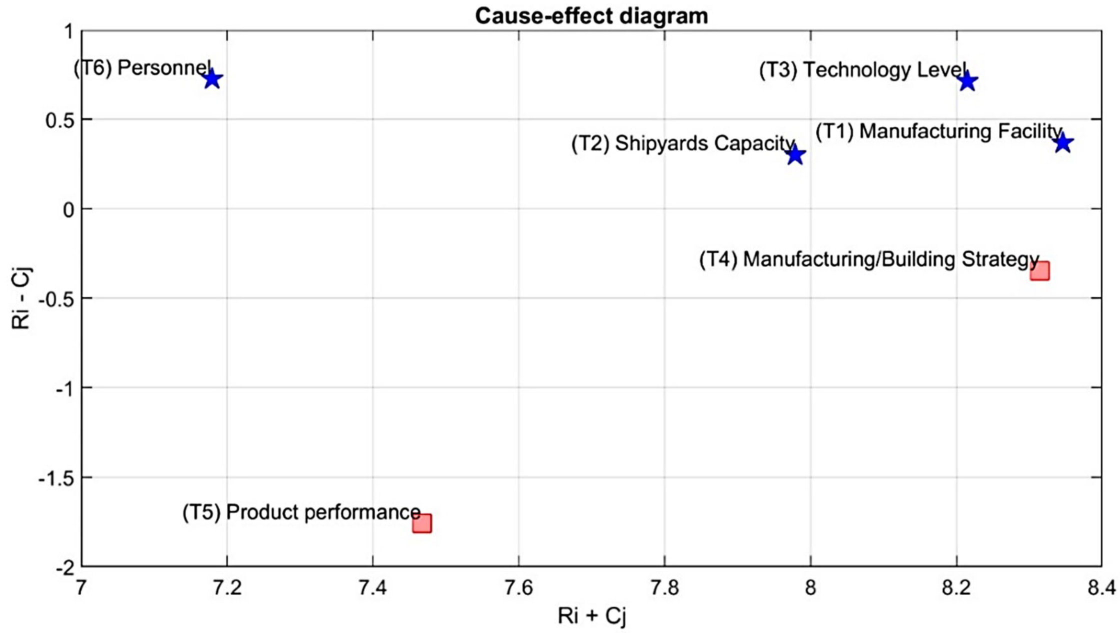

Figure 4. Cause-effect diagram of the total influence matrix (This figure is available in colour online).

the plate and profile outside to reduce the corrosion impact, plate thickness, and ship construction quality. For T1.1, the shipyard's land requires soil hardening since this affects manufacturing process output, mainly for block levelling.

For fabrication machinery (T1.4), the shipyard needs to improve the line heating machine to produce a complex 3D curve shape by investing in a hot forming machine or outsourcing it to a third party. The shipyard has a good facility for welding machines (T1.5), but a third party conducts the hull block construction and mainly uses manual welding. Using semi-automatic welding machines such as flux-cored arc welding (FCAW) and gas metal arc welding (GMAW) is recommended, especially for steel block construction, not only for aluminium ships. The shipyard has a design and engineering office (T1.8) capable of creating detailed production drawings, whereas a third party usually supplies preliminary design. This shipyard did not have a block transporter (T1.6), so they used a mobile crane to move the block during erection. The advisory service/internal consultant service (T1.9) sub-criterion is the least important because it can be outsourced and only applies in rare cases.

5.2. Manufacturing/building strategy (T4)

The pre-outfitting strategy (T4.2) is still low, as only minor partial ducting, an inlet or outlet for the piping system, is prepared in the outer hull. The piping system or ducts are installed after the 3D block is constructed or during the hull erection process. The method of hull construction (T4.1) is also affected by pre-outfitting, as it follows the pre-outfitting building strategy. After

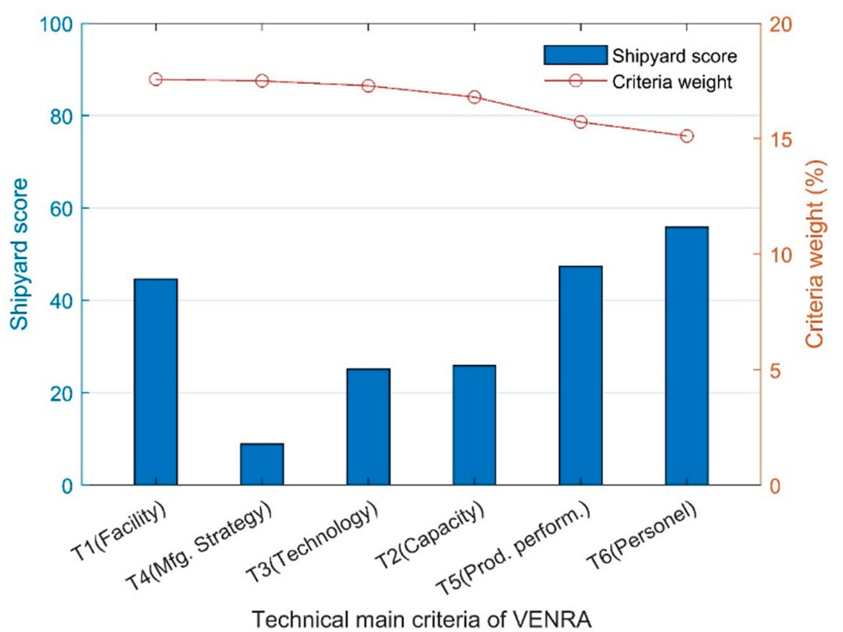

Figure 5. Shipyard assessed score within main criteria weight (This figure is available in colour online).

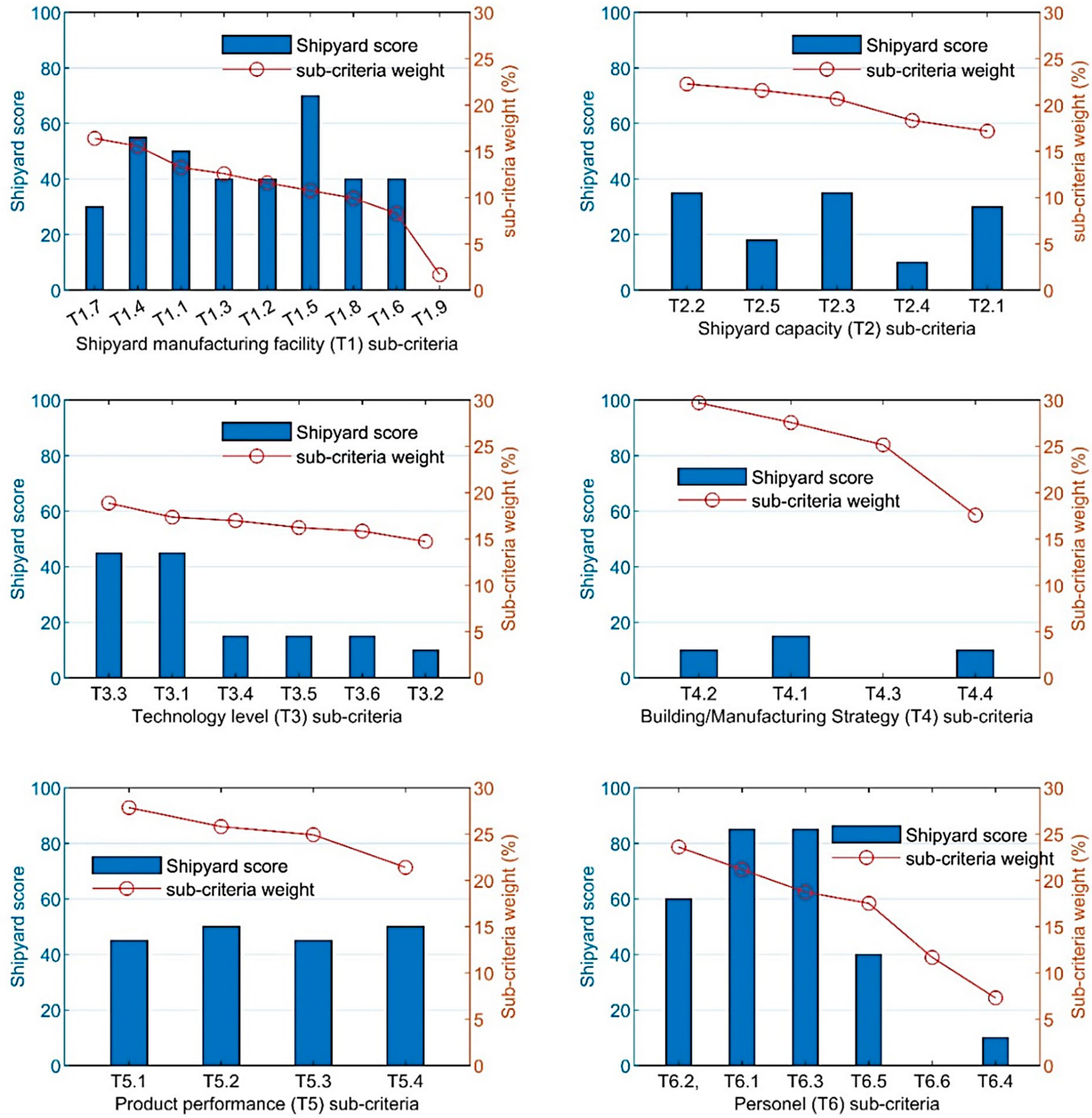

Figure 6. Shipyard assessed score within sub-criteria weight (This figure is available in colour online).

manufacturing the piece part, the shipyard hires subcontractors to construct the hull. The hull is divided into several ring blocks, and each subcontractor group is responsible for constructing its section of the block. The shipyard project coordinators supervise the subcontractors as they fabricate parts and assemble them into flat panels up to the exterior ring block. The hull 3D block/ring block is then built to form the hull. This shipyard has not implemented a modular building strategy (T4.3), such as the interior and accommodation deck. This shipyard rarely deals with a buying strategy (T4.4), sometimes making it easier for the shipyard to get the part ready and install it on the ship. It can also negatively impact the shipyard's cost budgeting and schedule.

5.3. Technology level (T3)

Shipyard's technology data score is classified as low, with an average score of around 25%. However, on technology for CAD/CAM and their integration (T3.1), this shipyard has a good start by implementing modelling software for production drawing and optimisation software for the nesting process and partially using semi-automatic cutting using integrated CNC cutting with CAD/CAM. Nevertheless, the welding technique is suggested using a semi-automatic one to improve productivity, welding accuracy and rework due to high distortion during welding. Regarding the marking, cutting and forming (T3.3) criterion, semi-automatic plasma cutting and side bender machines increase the piece part accuracy and shape quality. However, this shipyard still uses manual marking for the cut-piece part. The supporting CAD/CAM software for production and nesting optimisation reduced the plate waste in the cutting process. On the other hand, shipyards use manual labour line heating for more complex 3D hull shapes, utilising skilled workers' experience or getting the finished-fabricated 3D shapes from external resources from third parties.

The cut-piece part is fitted and joined to become panels or assembly parts conducted by sub-contractors under the shipyard's supervision. Mostly the sub-contractors use manual welding such

Table 14. Summarised suggested strategic improvement and implication for the shipyard's case study.

Code	Main criteria	Criteria analysis		Shipyard's assessment		Suggested strategic improvement	Implication
		Weight rank	Cause rank	Score	Rank		
T1	Shipyard's Manufacturing Facility (T1)	1	3	44.59	4	Improve airbag launching facility; investing covered workshop for flat panel assembly/ assembly; soil hardening	Safer docking/undocking process; improve workshop function for better production quality and improving pre-outfitting strategy percentage; better block levelling for assembly/erection
T4	Manufacturing/ Building Strategy (T4)	2	Effected criteria	8.86	1	Since the covered workshop is established, the pre-outfitting strategy and modular building can be improved	Increasing the percentage of manufacturing/ building strategy, reducing installation time for outfitting after erection/launching
T3	Technology Level (T3)	3	2	25.13	2	Advancement of CNC cutting or use of semi-automatic welding machine	Enhance production speed and improve production accuracy and quality; improve shipyard's facility and building strategy
T2	Shipyard's Capacity (T2)	4	4	25.89	3	Docking capacity is limited due to area and waterfront depth; However, increasing machine utilisation can increase the steel throughput capacity	Producing higher steel throughput means can produce steel construction for ships in a year
T5	Product Performance (T5)	5	Effected criteria	47.36	5	Since it is the effect criteria, it is highly impacted by technology levels, such as cutting and welding technology. By improving those both criteria, the shipyard can produce a better product at least or produce a more complex product beyond the current condition.	Possibility to gain more complex products or high-value products either for shipbuilding or repair
T6	Personnel (T6)	6	1	55.82	6	Maintaining qualified and senior workers; maintaining trained-educated potential young personnel knowledge and skills.	Facing future shipyard challenges such as a greener shipyard or future net zero-ship

as SMAW to perform the tack-weld fitting and intermittent welding or a full-penetration joining process, which is inexpensive but very low productive. Despite the low operational cost, using low technology in flat panel assembly in welding consumes more time due to low productivity, high rework, and high fairing process caused by high plate distortion. Semi-automatic welding can reduce the adverse impact of manual welding techniques that produce less heat, higher speed, and more accurate products. However, the shipyard mainly uses semi-automatic welding such as FCAW or GMAW for only aluminium hull ships produced in the covered workshop area but not for steel hull ships. These semi-automatic welding techniques need a protected covered area from wind, dust and rain outdoors as it impacts the welding quality. Thus, the mentioned suggestions can improve flat-panel and sub-assembly (T3.4) and assembly (T3.5). The case for the erection (T3.6) process has a similar level of technology with the sub-assembly and assembly process since it uses a similar welding technology.

The last rank factor is the steel stockyard and treatment (T3.2), which this shipyard applied using manual labour. Sometimes, the shipyard orders the ready plate, which is already straightened-blasted-painted, although it is costly. Nevertheless, within the shipyard, there is no integrated steel stockyard treatment.

5.4. Shipyard's capacity (T2)

The shipyard's capacity is limited due to docking capacity and waterfront depth level. However, given the maximum docking space capacity, steel throughput can still be increased. This shipyard, which has a land-based open erection area (T2.2) for approximately 4x 1200 GT, has a water depth restriction of 3–4 metres. Nonetheless, this shipyard can increase its steel throughput (T2.5) efficiency, currently 3120 tonnes per year, by increasing machine utilisation considering machine hour time load, which is still relatively low.

Due to the shipyard's section-by-section construction strategy, the 100-ton crane capacity (T2.3) with a 70-ton working safety load is more than sufficient for a joint assembly. The 70-ton mobile crane has benefits in flexibility but requires adequate space for mobility. The quay length (T2.4) contributes to the floating installation for shipbuilding and ship floating repair. Considering the shipyard's quay length, it is enough for shipbuilding activity but needs a longer one if more number of ships to be repaired increases. The total shipyard's facility area (T2.1) is considered a minor contributor to the performance, and this shipyard has a small erection area. A shipyard with extensive facilities area can have an advantage in producing more blocks or capacity. Especially nowadays, the shipyard sometimes does not use a fixed graving dock or uses land-based inclined landings for the docking/undocking processes.

5.5. Product performance (T5)

It is possible to improve the product's performance by enhancing its machinery facilities and technology, particularly for the welding process, which still employs manual steel welding. Technology advancements in welding may reduce defects that necessitate rework, enhancing product quality, customer satisfaction, and class society acceptance.

This shipyard can produce tugboats, anchor-handling tug system (AHTS) boats, general cargo, patrol boats, and unique passenger boats; classifying this shipyard has fair-medium capability level in handling more advanced ships. This fact follows the shipyard's material-processed capability since it can produce and repair steel and aluminium base material for the ship. Aluminium is more difficult to be fabricated and welded since it is heat-sensitive, requiring higher cutting and joining technology than carbon steel material. Considering this condition, the shipyard can handle more complex materials (T5.2) and has fair-good product performance (T5.1).

The shipyard's analysis, interview, and survey showed that it could satisfy customers (T5.3) with more complex ships due to its experience. This scenario assumes the shipyard has complaints, but most customers are satisfied. In addition, the shipyard has also built vessels supervised by BKI (Indonesia Bureau Classification), ABS (American Bureau of Shipping), and BV (Bureau Veritas) with some notes for improvements (T5.4).

5.6. Personnel (T6)

The investigator cannot count certified workers precisely, but considering the available data, it has conducted crane training, leading the certification process. In addition, in the welding or fitting process, the classification authority must verify welder certification skills before conducting the welding process. Concerning the vital role of these labours, it is assumed that more than half of the workforce is qualified (T6.2). In addition, the management/senior staff (T6.1) use an in-house information system to coordinate and communicate the project progress, activities, and issues, significantly representing senior and management staff's critical role in the personnel criteria.

The workforce's average age (T6.3) is around 35, classifying it as a group of young individuals. It is highly advantageous to the shipyard that younger employees can be more receptive and develop their general skills. On the other hand, the workforce's education level (T6.5) consists of 25% non-degree vocational level (similar to HND) and 36% bachelor's degree, scoring this criterion between low and medium. Higher education improves workers' systematic thinking and job performance. Still, the shipyard prefers vocational high school and non-degree vocational (HND) graduates over bachelor's degree holders because the shipyard believes that they have more practical than theoretical experience, especially on the production floor. High-skilled workers for exceptional cases (T6.6) are considered unnecessary since the shipyard can hire them from external resources. At the same time, the diversity, equality and inclusion (T6.4) criterion in this sector is still neglected, making both-sub-criteria the least important in personnel.

6. Conclusion

The novel VENRA framework has been developed as it is more holistic and systematic, integrating value (quality, cost, and time) and risk concepts into five group dimensions, filling the existing literature gaps. In this respect, the framework develops and introduces a performance measurement framework, including five groups: Technical, Business, External, Personnel Safety and Environment; of which the Technical Group is presented in more detail, including the six criteria and 34 sub-criteria. In terms of criteria assessment methodology, the integrated fuzzy DEMATEL-WET method is suggested due to its ability to effectively determine the cause–effect relationship and importance level for criteria and sub-criteria.

According to the shipyard's case study results, the shipyard's manufacturing facility (T1) and manufacturing/building strategy (T4) are the most critical performance factors, while personnel (T6) and technology level (T3) significantly influence other criteria. The framework can determine the cause–effect relationship among criteria to enhance and improve the shipyard's performance more effectively by identifying the lowest score of the assessed shipyard data within the prioritised criteria and sub-criteria.

Future research steps include presenting VENRA's remaining four groups of criteria (Business, External, Personnel Safety, and Environment) and sub-criteria and demonstrating the above in the case of the same shipyard. A similar process can be applied in the case of comparing the results to another shipyard's performance in Indonesia and Europe/the UK. Moreover, the criteria assessment process can be further developed using another MCDM method, such as AHP or simple additive weighting (SAW).

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CRediT authorship contribution

Imam Baihaqi: Conceptualisation, Methodology, Validation, investigation, writing-original draft. Iraklis Lazakis: Conceptualisation, Methodology, Validation, Supervision, writing-Review & Editing. Rafet Emek Kurt: Supervision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available.

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