Brodogradnja Volume 76 Number 1 (2025) 76103

University of Zagreb Faculty of Mechanical Engineering and Naval Architecture

journal homepage: www.brodogradnja.fsb.hr

Brodogradnja

An International Journal of Naval Architecture and Ocean Engineering for Research and Development

A fuzzy logic and optimisation based approach for shipyard facility layout problem with consideration of risk, activity, and flow factors

Mustafa Kafali

Naval Architecture and Maritime Faculty, Izmir Katip Celebi University, Izmir, Turkiye

ARTICLE INFO

Keywords:
Shipyard
Preliminary facility layout
Fuzzy logic
Optimisation

ABSTRACT

One of the crucial factors of shipbuilding in terms of production efficiency is the arrangement of workstations. Since shipyard design involves the layout of many workstations, an initial setup is helpful for the shipyard designer. This paper proposes a new methodology for determining the relative locations of shipyard workstations. The novelties of this study are the use of the Simulated Annealing (SA) approach for determining shipyard workstation's relative locations, the use of fuzzy logic and metaheuristic optimisation together in the shipyard facility layout planning (FLP) domain, and the incorporation of safety concept into the shipyard FLP. The procedure for determining proximity rating involves both qualitative (activity) and quantitative (flow and risk) factors and employs fuzzy logic. The problem of determining the relative locations of workstations is treated as an optimisation problem. The proposed methodology successfully generated three distinct shipyard layouts. These include U, L, and I-shaped arrangements for profiled panel production, as well as an almost star-shaped branched arrangement for sub-block production. Results show that this approach offers beneficial alternative starting layouts for a shipyard designer.

1. Introduction

Shipbuilding includes the construction of large and complex structures. These structures are generally custom-ordered and produced to the customer's specifications [1]. After a lengthy construction period, a high-priced and tailored product must be accomplished until the agreed-upon deadline [2]. Since gaining an edge over shipyards is crucial in today's competitive shipbuilding market [3] such a complicated production environment requires a good facility layout. It involves choosing the optimal arrangement of physical facilities to enhance resource utilization in manufacturing processes. The layout of the facility affects numerous facets of the company's success [4]. It is essential for achieving efficient production flow, minimizing overall manufacturing costs, and maximizing output while minimizing effort on the production floor [5, 6]. Bottlenecks, blockage, and inefficient space usage can be brought on by inefficient layouts, which can then result in work pileups and idle or overloaded workstations. It can also lead to workplace problems, make operations and people management more challenging, and lead to anxious and uncomfortable employees [7].

* Corresponding author.

E-mail address: mustafakafali@outlook.com

http://dx.doi.org/10.21278/brod76103

Received 26 August; Received in revised form 28 October 2024; Accepted 28 October 2024;
Available online 31 October 2024
ISSN 0007-215X; eISSN 1845-5859

The construction of a convenient shipyard is the very first milestone in shipbuilding industry. The design of a shipyard layout is the first step in the construction of a shipyard [8]. Most shipyard layouts are based on professional experiences [2]. Since many factors affect the distribution of workstations, it is a multi-faceted problem. Flow, activity, and risk factors are considered in this study. Detailed explanations on these factors are given in the methodology section.

The research questions guiding this study are as follows:

1. How can proximity ratings of workstations be determined using a combination of qualitative and quantitative factors, and how can fuzzy logic be employed to assess these ratings?
2. How can the shipyard FLP be formulated as an optimisation problem considering the determined proximity ratings of workstations?
3. How does incorporating safety considerations into the layout design impact the shipyard facility layout?

In line with the research questions, this study contributes to the existing literature by proposing a novel framework that incorporates both proximity ratings and relative workstation positions, while integrating safety considerations into the shipyard layout design. The primary aim of this study is not to develop a final facility layout but rather to determine the relative locations of workstations as a starting point for a shipyard designer.

This paper investigates the shipyard facility layout problem, offering a comprehensive overview of the proposed framework and its application using real shipyard data. The following section reviews the literature, encompassing current methods and studies related to facility layout design in shipbuilding field. Furthermore, the motivation and the novel contributions of this study are stated within the same section. The subsequent section introduces the methodology and outlines the steps involved in determining the proximity ratings and formulating the optimization model. After that, validation of the proposed model, discussion of the results, and sensitivity analysis are given. Finally, the conclusions section summarizes the key findings and concludes the study by offering insights into potential areas for further research.

2. Literature review

Facility layout problem is a topic that has been extensively researched in the literature. There are many different industrial areas such as metal-mechanical sector [9], HVAC (Heating, Ventilation, and Air Conditioning) field [10], construction [11], manufacturing industry [12]. However, there is a limited amount of research available on the facility layout problem of shipyards. Table 1 gives the list of the studies on the shipyard FLP.

Table 1 Overview of shipyard FLP studies

Reference	Year	Methodology	Shipyard Layout Design Phase
[2]	2009	Systematic layout planning, system engineering and simulation	Basic
[13]	2009	Systematic layout planning, analytical hierarchy process	Preliminary
[14]	2013	A commercial software specific heuristic algorithm	Preliminary
[15]	2017	Genetic algorithm and stochastic growth algorithm	Basic
[16]	2020	Fuzzy similarity index and fuzzy goal programming	Basic
[17]	2021	Genetic algorithm	Preliminary
[18]	2022	Systematic layout planning and graph-theoretical approach	Basic
[19]	2023	Genetic algorithm, stochastic growth algorithm, ELECTRE, local search	Basic

In Table 1, the phase of each study is categorized either based on the authors' descriptions within their article or using the definitions provided by [14]. The studies cover both the preliminary and basic phases of shipyard FLP, with methodologies ranging from systematic layout planning to advanced algorithms like genetic algorithms and fuzzy goal programming. While some studies, such as [13], [14], and [17], focus on the preliminary design phase, others -including [2], [15], [18], [19], and [16]- address the basic design phase. This suggests that studies have primarily concentrated on foundational layout structures rather than detailed design. However, the detailed design phase, which demands an in-depth consideration of each facility of the whole shipyard, remains a challenge to fully encapsulate in a single study due to the complexity and scope of shipyard FLP. Addressing this phase requires a highly tailored approach for each facility, making it difficult to cover the intricacies of detailed design comprehensively within one single paper.

Looking at the current studies the examination of topology and geometry optimization has primarily been conducted in the works of [15], [17], and [19]. These studies have focused on optimizing both the spatial arrangement and the physical dimensions of shipyard facilities. The literature highlights several important factors that influence shipyard layout design. Singh and Ingole [20] mentioned that the material handling cost is one of the primary determinants of the ideal layout in every manufacturing field. It can be stated that material handling costs are closely related to material flow. When designing a shipyard's layout, according to [14] flow, relation, and cost should all be considered. Shin et al. [2] takes into account flow, activity and space. Matulja et al. [13] establish a methodology based on the flow of material, activity, and space. Choi et al. [15] examine flow, shape of the workstation, space, adjacency, and alignment. Türk et al. [17] focus on flow, geometry, adjacency, and alignment. Tamer et al. [18] address activity relationships, flow, geometry, and adjacency. Junior et al. [19] also emphasize flow, geometry, adjacency, and alignment. Dixit et al. [16] consider flow and activity relationships. Kudelska et al. [4] utilize data on flow and connections between workstations, indicating that these connections are relevant to production process technologies. Consequently, it can be deduced that this aspect also pertains to activity.

The layout of a shipyard is influenced by both qualitative and quantitative factors, as highlighted above. When designing a shipyard layout, various factors -including material flow, activity relationships, geometry, adjacency, alignment, and connections between workstations- play a crucial role. It can be considered that adjacency and alignment are constraints related to activity. Since the primary objective of this study is to determine the relative positioning of workstations within a two-dimensional space, geometric considerations are excluded from the scope of this investigation. The inclusion of safety as a factor in the shipyard FLP is a distinctive contribution of this study. Shipbuilding involves various activities and working conditions that present significant risks, including working at heights, moving heavy objects, and the potential for fire and explosions [21]. These hazards can lead to serious work accidents, resulting in injuries and fatalities. Additionally, most of the damage results in a loss of work in the shipyard [22]. Therefore, research shows that such accidents not only pose risks to worker safety but also disrupt production processes, leading to reduced productivity and increased operational costs. By including safety as a risk factor in shipyard facility layout design, this study will provide a safer working environment for employees by enabling more informed decisions about workstation layout and the overall design of the shipyard. This integration is also important in preventing accidents and reducing risks, thereby improving employee well-being and promoting a safety culture within the organization.

This study proposes a methodology that incorporates the analytic hierarchy process (AHP), fuzzy logic, and the simulated annealing (SA) algorithm. AHP possesses the ability to handle the hierarchical structure of criteria, allowing for systematic evaluation of both qualitative and quantitative factors in facility layout. This method has been widely used in similar fields and provides a robust framework for decision-making, especially when subjective judgments are required. The SA algorithm is commonly used due to its effectiveness in solving complex optimization problems, particularly in the field of FLP. As noted in [23], when the number of workstations increases, meta-heuristic algorithms such as SA are essential for finding approximate solutions. SA is one of the most frequently used algorithms in FLP literature [15, 19]. However, despite its widespread application in other domains, there is no study that specifically utilizes SA for shipyard FLP. Thus, this study aims to apply SA to the shipbuilding industry, evaluating its ability to deliver near-optimal solutions in this context. The algorithm’s strength lies in its capacity to escape local optima, which is especially important in complex layout problems like shipyard FLP. Fuzzy set theory is commonly used to address the inherent uncertainty in several fields such as robot selection [24], logistics [25], social media [26], offshore wind industry [27] as well as in shipyard layout planning. As mentioned in [16], it is a methodology that helps uncover and leverage the tacit knowledge of shipbuilding expertise, which is critical in this field.

Since layout design often involves imprecise data and qualitative criteria that are difficult to quantify, fuzzy logic becomes a natural choice for managing these uncertainties effectively.

This study is motivated by the limited number of proposed algorithms specifically targeting the shipyard FLP. The SA algorithm has been widely used in FLP problems across other industries. However, despite its success in other fields, SA has not been applied specifically to the shipyard FLP. To fill this gap, the current study leverages SA to determine the relative locations of workstations in a two-dimensional space, overcoming the challenges posed by the large number of workstations and the complexity of shipyard operations. The combination of fuzzy logic with metaheuristic optimization provides an efficient decision-making framework that successfully integrates shipbuilding experts' subjective insights with the computational efficiency of metaheuristic optimization. Most previous research has concentrated on material flow and activity relationships, ignoring the inherent risks in the shipyard environment. This study incorporates safety considerations in a quantitative way into the shipyard FLP field, which is an important but underrepresented factor in previous shipyard FLP literature. In this context, this study has three novelties that enhance the understanding and application of shipyard FLP:

- The utilization of the SA algorithm to find near-optimal shipyard facilities arrangement,
- The use of fuzzy logic and metaheuristic optimisation together in the shipyard FLP domain,
- The inclusion of safety concept as a quantitative risk factor into the shipyard FLP.

3. Shipyard preliminary layout generation methodology

Shipyard FLP plays a crucial role in enhancing production efficiency, reducing costs, and ensuring safety. Despite its importance, it remains a challenging problem due to the variety of factors that must be considered. Given the limited number of proposed algorithms specifically for the shipbuilding industry, there is still significant potential for improvement. While many existing studies focus on factors associated with material flow and activity relationships, considering safety as a quantitative risk factor is uncommon. This research addresses that gap by integrating safety considerations into the layout planning process.

Although fuzzy logic and metaheuristic optimization are frequently used in facility layout problems in other industries, their combined application in shipyard layout planning is relatively rare. This study introduces a new model aimed at simplifying the preliminary design phase of shipyards by determining the relative positions of workstations. The model consists of three main stages as shown in Figure 1. Table 2 provides concise explanations of the steps involved in the proposed model for shipyard preliminary FLP. In this study, the proposed model was applied using real-world data from a shipyard found in the literature. The case study involves sixteen workstations, listed in Table 3.

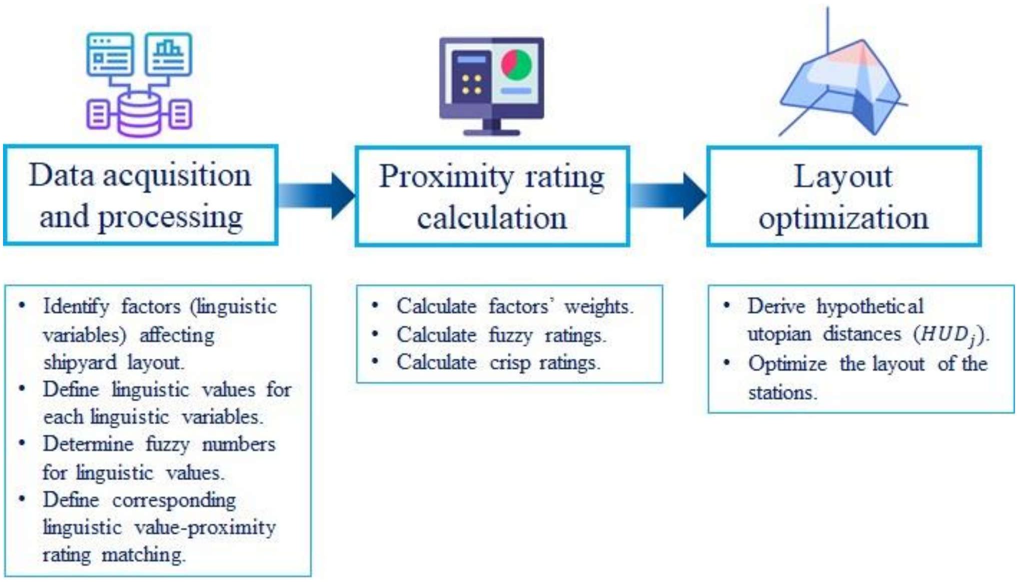

Fig. 1 Overview of the stages and steps involved in the proposed model

Table 2 Summary of steps in the proposed model for shipyard preliminary FLP

Stages	**Steps**	**Explanation**
1. Data acquisition and processing	1.1. Identification of factors	The factors influencing the layout of a shipyard are described. These factors are also linguistic variables.
	1.2. Definition of linguistic values	Each linguistic variable is associated with specific linguistic values.
	1.3. Determination of fuzzy numbers	After the linguistic variables and related values have been designated, fuzzy numbers for each linguistic value are specified.
	1.4. Matching of linguistic values and proximity ratings	To connect linguistic values with proximity ratings, a "linguistic value-proximity rating" correspondence is established.
2. Proximity rating calculation	2.1 Calculation of factors' weights	The weights of the factors are determined using the AHP via pairwise comparison matrix.
	2.2. Calculation of fuzzy ratings	To address the inherent uncertainty in shipyard FLP, fuzzy ratings are utilized through fuzzy logic.
	2.3. Calculation of crisp ratings	The fuzzy ratings are defuzzified to transform fuzzy scores into crisp numbers.
3. Layout optimization	3.1. Derivation of hypothetical utopian distances	The hypothetical utopian distances between interrelated workstations are generated based on crisp ratings.
	3.2. Optimization of the layout	The relative positions of workstations are established for the preliminary layout design of the shipyard.

Table 3 List of workstations (WS) with corresponding codes used in the model

WS Code	**WS Name**	**WS Code**	**WS Name**
St1	Edge cutting	St9	Grinding
St2	Edge cleaning and sequencing	St10	Profile piece part preparation
St3	Panel production	St11	Profile bending
St4	Panel cutting	St12	Plate piece part preparation
St5	Stiffener mounting	St13	Minor and sub assembly fabrication
St6	Stiffener welding	St14	Jig
St7	Web mounting	St15	Plate bending (Press)
St8	Web welding	St16	Unit assembly

3.1 Data acquisition and processing

In this stage, necessary data is collected and processed. First, the factors influencing the shipyard layout are identified, followed by defining appropriate linguistic variables and their values (i.e., term sets).

3.1.1 Stage 1 Step 1: Identify factors affecting shipyard layout

A shipyard layout should have an attribute that accomplish the shipyard's goal at the lowest possible expense and with the highest possible efficiency and quality [16]. The design of a shipyard is shaped by various qualitative and quantitative factors, as emphasized in the existing literature. Following the discussions in the literature review section, the key factors influencing the shipyard layout have been identified as flow, activity, and risk. Flow and activity data were sourced from [28], where flow indicates the number of conveyances rather than piece quantity. Risk data were obtained from [22], using risk priority numbers (RPNs) based on workstation failures to calculate risk values. One method for determining the risk factor for a relationship is to sum the RPNs of each workstation [29]. Data for risk, flow, and activity factors are shown in Table 4.

Table 4 Risk, flow, and activity data for relationships between shipyard workstations [22, 28, 29]

Relation	Risk	Flow	Activity	Relation	Risk	Flow	Activity	Relation	Risk	Flow	Activity
St1-St2	146	427	A	St7-St12	520	37	I	St12-St13	961	623	A
St2-St3	204	427	A	St7-St13	979	890	E	St12-St14	834	51	O
St3-St4	247	83	A	St8-St9	106	80	A	St12-St15	338	9	O
St4-St5	226	83	A	St9-St16	521	87	E	St12-St16	730	120	O
St5-St6	140	83	A	St10-St11	258	122	E	St13-St14	1293	192	O
St5-St10	338	136	I	St10-St13	920	131	O	St14-St15	670	65	I
St6-St7	281	76	A	St10-St16	689	5	O	St14-St16	1062	26	I
St7-St8	333	80	A	St11-St14	631	61	O	St15-St16	566	24	O

3.1.2 Stage 1 Step 2: Define linguistic values for each linguistic variable

The factors described in the first step are also linguistic variables, and each must have assigned linguistic values. Flow and Risk share the same values: VH (very high), H (high), M (medium), L (low), and VL (very low). For the activity factor, linguistic values from [28] are applied: A (absolute closeness) means two workstations must be close, while E, I, O, U, and X represent varying levels of importance, from "especially important" to "undesirable" closeness.

3.1.3 Stage 1 Step 3: Determine fuzzy numbers for linguistic values variable

This step aims defining membership functions of corresponding linguistic values by considering crisp values. The membership function of each linguistic value should be specified to represent the characteristic of factor. As a result, the fuzzy numbers for each linguistic variable are defined as shown in Figure 2.

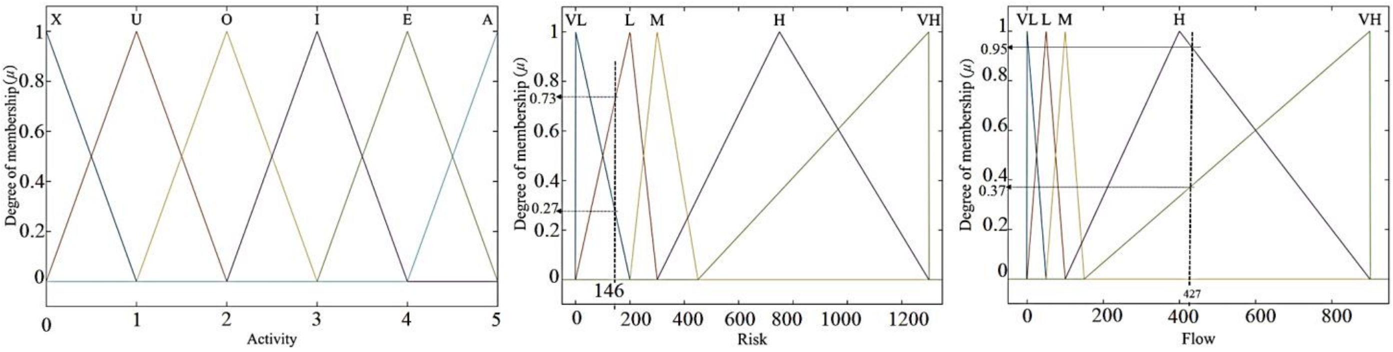

Fig. 2 Fuzzy numbers and their associated membership functions utilized in the data acquisition and processing stage

3.1.4 Stage 1 Step 4: Define corresponding linguistic value-proximity rating matching

The activity factor uses linguistic terms as proximity ratings, but flow and risk do not directly relate to proximity ratings. To address this, their linguistic terms are converted into proximity ratings, as shown in Table 5. For flow, "Very Low" doesn't imply an undesirable relationship, so the matching starts from "Unimportant (U)." For risk, "Very High" indicates an undesirable relationship, so the matching starts from "Undesirable (X)."

Table 5 Mapping of linguistic values to proximity ratings for flow and risk factors

Flow	VH	H	M	L	VL
	A	E	I	O	U
Risk	VL	L	M	H	VH
	E	I	O	U	X

Let say, $\widetilde{MF}_{j,r}^{(Ri)}$ and $\widetilde{MF}_{j,f}^{(Fl)}$ stand for fuzzy sets (i.e., membership functions) that the current risk and flow belong to, respectively. Then, the equivalent fuzzy sets (linguistic values) which are, $\widetilde{MFE}_{j,r}^{(Ri)}$ and $\widetilde{MFE}_{j,f}^{(Fl)}$ are calculated as follows:

$$\begin{aligned}
&if\ \widetilde{MF}_{j,r}^{(Ri)} = \text{VL then } \widetilde{MFE}_{j,r}^{(Ri)} = \text{E} \\
&if\ \widetilde{MF}_{j,r}^{(Ri)} = \text{L then } \widetilde{MFE}_{j,r}^{(Ri)} = \text{I} \\
&\ldots \\
&if\ \widetilde{MF}_{j,f}^{(Fl)} = \text{VH then } \widetilde{MFE}_{j,f}^{(Fl)} = \text{A} \\
&if\ \widetilde{MF}_{j,f}^{(Fl)} = \text{H then } \widetilde{MFE}_{j,f}^{(Fl)} = \text{E} \\
&\ldots
\end{aligned} \quad (1)$$

where j is the index of the relationship and $j = 1,2,\ldots,J$. r and f are the intersection indices of the current risk and flow value; Ri and Fl symbolize risk and flow, respectively. Intersection index represents the number of fuzzy sets that the current risk or flow value intersects. As shown in Figure 2, flow value 427 intersects both the H and VH fuzzy sets. As a result, where f can have a value of 1 and 2.

3.2 Proximity rating calculation

In this stage, first, weights of the factors are computed by using AHP developed by Saaty [30]. After that, fuzzy proximity ratings are computed. Then, defuzzification is applied.

3.2.1 Stage 2 Step 1: Calculate factors' weights values

In order the calculate weights, a survey is carried out. Table 6 presents the survey results. Experts' opinions can be aggregated by geometric mean method [31]. It is assumed that all experts have equal importance, so Eq. (2) is used for synthesizing the experts' judgements:

$$a_{nm} = \left(\prod_{k=1}^{K} a_{nm}^{k}\right)^{1/K} \quad (2)$$

where a_{nm}^{k} is the k^{th} expert's judgement; K is the total number of experts; n and m are the factor indices. Other summary details of the AHP can be found in [32]. The factor weights are calculated as $w^{(Ri)} = 0.77$, $w^{(Fl)} = 0.15$, $w^{(Ac)} = 0.08$ by using AHP arithmetic [29].

Table 6 Expert evaluations of factor significance used to calculate the weights of risk, flow, and activity factors

	Flow over Risk	Flow over Activity	Risk over Activity
Expert 1	1/9	1	6
Expert 2	1/9	1	9
Expert 3	1/5	3	6
Expert 4	1/5	3	7
Expert 5	1/7	3	9
Expert 6	1/7	3	9

3.2.2 Stage 2 Step 2: Calculate fuzzy ratings

To calculate fuzzy proximity ratings Eq. (3) is used:

$$\begin{aligned}
\widetilde{TR}_j = &\left(w^{(Ri)} \otimes \left(\sum_{r=1}^{R} \widetilde{MFE}_{j,r}^{(Ri)} \otimes \bar{\mu}_{j,r}^{(Ri)}\right)\right) \oplus \left(w^{(Fl)} \otimes \left(\sum_{f=1}^{F} \widetilde{MFE}_{j,f}^{(Fl)} \otimes \bar{\mu}_{j,f}^{(Fl)}\right)\right) \\
&\oplus \left(w^{(Ac)} \otimes \left(\sum_{a=1}^{A} \widetilde{MF}_{j,a}^{(Ac)} \otimes \bar{\mu}_{j,a}^{(Ac)}\right)\right), \quad j = 1,2,\ldots,J
\end{aligned} \quad (3)$$

Eq. (3) multiplies the membership degree by the equivalent membership function. In Eq. (3), $\widetilde{TR}_j$ is the total fuzzy rating for j^{th} relationship; J is the total number of relationships; $w^{(Ri)}, w^{(Fl)}$ and $, w^{(Ac)}$ are the crisp weights of the risk, flow and activity factors, respectively; $\widetilde{MFE}_{j,r}^{(Ri)}$ and $\widetilde{MFE}_{j,f}^{(Fl)}$ are the equivalent fuzzy sets for risk and flow, respectively which are determined in the Stage 1, Step 4. $\widetilde{MF}_{j,a}^{(Ac)}$ stand for fuzzy sets that the current activity value belongs to; $r = 1,2, \dots, R$, $f = 1, 2, \dots F$ and $a = 1, 2, \dots, A$ are the membership function intersection index; R, F and A are the number of fuzzy sets that the current risk, flow and activity value intersects; $\bar{\mu}_{j,r}^{(Ri)}$, $\bar{\mu}_{j,f}^{(Fl)}$ and $\bar{\mu}_{j,a}^{(Ac)}$ are the normalized membership degrees of the current risk, flow and activity values, respectively.

The risk and flow factors have asymmetric fuzzy sets, as illustrated in Figure 2. If the sum of the membership degrees is not equal to 1, the membership degrees should be normalized. Eq. (4) is employed in the normalizing process, where x stands for r or f, and X stands for R or F:

$$\bar{\mu}_{j,x}^{(y)} = \frac{\mu_{j,x}^{(y)}}{\sum_{i=1}^{X} \mu_{j,i}^{(y)}} \quad , \qquad j = 1,2, \dots, J; \ \forall y \in \{Ri, Fl\} \tag{4}$$

For example, the fuzzy rating for the first relation ($j = 1$), which is between St1 and St2, is calculated as follows. First of all $\widetilde{MF}_{1,r}^{(Ri)}$, $\widetilde{MFE}_{1,r}^{(Ri)}$, $\widetilde{MF}_{1,f}^{(Fl)}$, $\widetilde{MFE}_{1,f}^{(Fl)}$, $\widetilde{MF}_{1,a}^{(Ac)}$, $\bar{\mu}_{1,r}^{(Ri)}$, $\bar{\mu}_{1,f}^{(Fl)}$, $\bar{\mu}_{1,a}^{(Ac)}$, R, F and A are determined. Table 4 displays the risk value for this connection to be 146, the flow value to be 427, and the activity value to be A. Depending on risk value: R=2; $\bar{\mu}_{1,1}^{(Ri)} = 0.27$; $\bar{\mu}_{1,2}^{(Ri)} = 0.73$; $\widetilde{MF}_{1,1}^{(Ri)} = VL$; $\widetilde{MF}_{1,2}^{(Ri)} = L$; $\widetilde{MFE}_{1,1}^{(Ri)} = E$; $\widetilde{MFE}_{1,2}^{(Ri)} = I$ (see Table 1 and Figure 2). Depending on flow value: F=2; $\mu_{1,1}^{(Fl)} = 0.95$; $\mu_{1,2}^{(Fl)} = 0.37$; $\widetilde{MF}_{1,1}^{(Fl)} = H$; $\widetilde{MF}_{1,2}^{(Fl)} = VH$; $\widetilde{MFE}_{1,1}^{(Fl)} = E$; $\widetilde{MFE}_{1,2}^{(Fl)} = A$ (see Table 1 and Figure 2). As can be observed, the total of the membership degrees depending on flow value is not equal to 1. Consequently, they ought to be normalized using Eq. (4) as follows:

$$\bar{\mu}_{1,1}^{(Fl)} = \frac{\mu_{1,1}^{(Fl)}}{\sum_{i=1}^{2} \mu_{1,i}^{(Fl)}} = 0.72; \ \bar{\mu}_{1,2}^{(Fl)} = \frac{\mu_{1,2}^{(Fl)}}{\sum_{i=1}^{2} \mu_{1,i}^{(Fl)}} = 0.28 \tag{5}$$

Activity value is used directly as shown in Table 4. Following all these computations, the first relationship's fuzzy rating ($\widetilde{TR}_1$) is calculated as:

$$\begin{aligned}
\widetilde{TR}_1 = & \left(w^{(Ri)} \otimes \left(\sum_{r=1}^{2} \widetilde{MFE}_{1,r}^{(Ri)} \otimes \bar{\mu}_{1,r}^{(Ri)} \right) \right) \oplus \left(w^{(Fl)} \otimes \left(\sum_{f=1}^{2} \widetilde{MFE}_{1,f}^{(Fl)} \otimes \bar{\mu}_{1,f}^{(Fl)} \right) \right) \\
& \oplus \left(w^{(Ac)} \otimes \left(\sum_{a=1}^{1} \widetilde{MF}_{1,a}^{(Ac)} \otimes \bar{\mu}_{1,a}^{(Ac)} \right) \right) \\
& = 0.77 \otimes \left(\left(\widetilde{MFE}_{1,1}^{(Ri)} \otimes \bar{\mu}_{1,1}^{(Ri)} \right) \oplus \left(\widetilde{MFE}_{1,2}^{(Ri)} \otimes \bar{\mu}_{1,2}^{(Ri)} \right) \right) \\
& \oplus 0.15 \otimes \left(\left(\widetilde{MFE}_{1,1}^{(Fl)} \otimes \bar{\mu}_{1,1}^{(Fl)} \right) \oplus \left(\widetilde{MFE}_{1,2}^{(Fl)} \otimes \bar{\mu}_{1,2}^{(Fl)} \right) \right) \\
& \oplus 0.08 \otimes \left(\widetilde{MF}_{1,1}^{(Ac)} \otimes \bar{\mu}_{1,1}^{(Ac)} \right) \\
& = 0.77 \otimes \left((E \otimes 0.27) \oplus (I \otimes 0.73) \right) \\
& \oplus 0.15 \otimes \left((E \otimes 0.72) \oplus (A \otimes 0.28) \right) \oplus 0.08 \otimes (A \otimes 1) \\
& = 0.77 \otimes \left(\left((3,4,5) \otimes 0.27 \right) \oplus \left((2,3,4) \otimes 0.73 \right) \right) \\
& \oplus 0.15 \otimes \left(\left((3,4,5) \otimes 0.72 \right) \oplus \left((4,5,5) \otimes 0.28 \right) \right) \\
& \oplus 0.08 \otimes \left((4,5,5) \otimes 1 \right) = (2.56, 3.56, 4.44)
\end{aligned} \tag{6}$$

The values for each fuzzy rating are displayed in Table 7.

Table 7 Fuzzy and crisp ratings of workstation pairs

Relation	Fuzzy rating	Crisp rating	Relation	Fuzzy rating	Crisp rating	Relation	Fuzzy rating	Crisp rating
St1-St2	(2.56,3.56,4.44)	3.52	St7-St12	(0.27,1.16,2.16)	1.20	St12-St13	(0.85,1.47,2.31)	1.54
St2-St3	(2.32,3.32,4.20)	3.28	St7-St13	(0.84,1.44,2.29)	1.52	St12-St14	(0.23,0.97,1.97)	1.05
St3-St4	(1.75,2.75,3.67)	2.72	St8-St9	(2.46,3.46,4.38)	3.44	St12-St15	(0.80,1.80,2.80)	1.80
St4-St5	(1.91,2.91,3.83)	2.88	St9-St16	(0.50,1.39,2.39)	1.43	St12-St16	(0.40,1.20,2.20)	1.26
St5-St6	(2.34,3.34,4.26)	3.31	St10-St11	(1.65,2.65,3.65)	2.65	St13-St14	(0.55,0.79,1.77)	1.04
St5-St10	(1.20,2.20,3.20)	2.20	St10-St13	(0.41,1.07,2.07)	1.18	St14-St15	(0.36,1.17,2.17)	1.23
St6-St7	(1.46,2.46,3.38)	2.44	St10-St16	(0.10,0.91,1.91)	0.97	St14-St16	(0.24,0.76,1.76)	0.92
St7-St8	(1.26,2.26,3.18)	2.24	St11-St14	(0.26,1.09,2.09)	1.15	St15-St16	(0.15,1.01,2.01)	1.06

3.2.3 Stage 2 Step 3: Calculate crisp ratings

To convert fuzzy scores to crisp values, the centroid method is used:

$$TR_j = \frac{TR_{j,l} + TR_{j,m} + TR_{j,u}}{3} \tag{7}$$

where, TR_j is the crisp rating of the j^{th} relation; $TR_{j,l}$, $TR_{j,m}$ and $TR_{j,u}$ are the lower, middle and upper values of the triangular fuzzy rating, respectively. The calculation for the first relationship is shown in Eq. 8 with all crisp values listed in Table 6:

$$TR_1 = \frac{TR_{1,l} + TR_{1,m} + TR_{1,u}}{3} = \frac{2.56 + 3.56 + 4.44}{3} = 3.52 \tag{8}$$

3.3 Layout optimization

The relative positions of the workstations are determined through the use of the SA algorithm.

3.3.1 Stage 3 Step 1: Derive hypothetical utopian distances

To carry out optimization procedure the crisp ratings are used. The higher the score, the closer the stations should be. Hypothetical utopian distance (HUD_j) refers to a theoretical measure representing the ideal distance between two workstations in shipyard. To derive HUD_j, the crisp rating scores are first normalized using the linear normalization method (Eq. 9). Where $\overline{TR}_j$ is the normalized rating score of the j^{th} relation; TR^{max} is the highest crisp rating score across all relationships. The first two relationships are given below as an illustration of how normalized ratings were determined:

$$\overline{TR}_j = \frac{TR_j}{TR^{max}} \quad , \quad j = 1,2, \ldots, J$$
$$\overline{TR}_1 = \frac{TR_1}{TR^{max}} = \frac{3.52}{3.52} = 1; \quad \overline{TR}_2 = \frac{TR_2}{TR^{max}} = \frac{3.28}{3.52} = 0.932 \tag{9}$$

Table 8 provides all the normalized ratings. To establish a logical link between workstations distances, the normalized rating scores are inverted, and HUD_j are calculated (Eq. 10). A lower HUD_j value indicates that the stations should be closer together. For the first two relationships HUD_j are computed as shown below:

$$HUD_j = \frac{1}{\overline{TR}_j}$$
$$HUD_1 = \frac{1}{\overline{TR}_1} = \frac{1}{1} = 1; HUD_2 = \frac{1}{\overline{TR}_2} = \frac{1}{0.932} = 1.073 \tag{10}$$

Table 8 Normalized crisp ratings and HUD_js

Relation	Normalized crisp rating	HUD_j	Relation	Normalized crisp rating	HUD_j	Relation	Normalized crisp rating	HUD_j
St1-St2	1.000	1.000	St7-St12	0.340	2.940	St12-St13	0.438	2.281
St2-St3	0.932	1.073	St7-St13	0.433	2.311	St12-St14	0.300	3.337
St3-St4	0.773	1.294	St8-St9	0.976	1.024	St12-St15	0.511	1.957
St4-St5	0.819	1.221	St9-St16	0.405	2.467	St12-St16	0.359	2.786
St5-St6	0.941	1.062	St10-St11	0.753	1.328	St13-St14	0.295	3.388
St5-St10	0.624	1.602	St10-St13	0.336	2.973	St14-St15	0.350	2.856
St6-St7	0.693	1.444	St10-St16	0.275	3.632	St14-St16	0.261	3.836
St7-St8	0.636	1.573	St11-St14	0.326	3.066	St15-St16	0.300	3.334

3.3.2 Stage 3 Step 2: Optimize the layout of the stations

The SA algorithm is used for the purpose of determining the workstations' relative positions. SA is presented by [33, 34]. For the development of this method, which uses a probabilistic search technique, the annealing procedure used in metalworking served as inspiration. The SA technique denotes a heuristic mechanism that conducts a random search, considering certain neighbour solutions that improve the objective function as well as some of those that do not, to prevent staying on the local optimum [35]. Eq. (11) is used to calculate the probability of acceptance:

$$P(\Delta E, T) = e^{-\frac{\Delta E}{T}} \tag{11}$$

where $\Delta E = f(s') - f(s)$; $f(s')$ is the computed value of the objective function based on the neighbouring solution; $f(s)$ is current value of the objective function; T is the temperature parameter [36]. A random number generated between 0 and 1 is contrasted with the acceptance probability. The neighbouring solution that does not enhance the objective function is approved if $P(\Delta E, T)$ is higher than the randomly generated value [37]. In the early stages of the search, when temperatures are greater, worsening solutions are more likely to be approved [36].

The difference between HUD_j and the generated location in each iteration forms the basis for developing the optimization model as a minimization problem. The sum of the differences is minimized to achieve a feasible workstation arrangement. Accordingly, the objective function is defined as follows:

$$Min\ f = \sqrt{\sum_{j=1}^{J} \left(HUD_j - D_j\right)^2} \tag{12}$$

where, D_j displays distances between workstations and it changes in each iteration of the search procedure. The coordinates of the workstations in two dimensions are used to compute D_j. Initial solution is constructed using a set of random coordinates at first. The neighbour solutions (i.e., neighbour coordinates) are determined in subsequent iterations. The optimization model offers a sample workstation layout as a starting point for the design. Since the SA algorithm uses a stochastic search, each run produces a different layout. A shipyard designer can choose any of these layouts as a starting point.

4. Results

4.1 Validation of the model

To validate the proposed preliminary shipyard layout generation model, a comparative analysis was conducted using data from [16]. In [16] authors design an ideal shipyard layout, providing a detailed reference for station placements. This ideal layout is used as a benchmark for assessing the effectiveness of the proposed model. The developed model does not aim to determine exact locations for stations; rather, it generates a preliminary layout that can serve as a starting point for further refinement. Using the data provided by [16], the optimization model is run to calculate the preliminary positions of the shipyard workstations. The output layouts generated by the developed model, represented in Figures 3a, 3b, and 3c, show workstation placements that are similar to those presented in [16] ideal layout (Figure 3d).

Although the model does not intend to calculate precise station locations, it is observed that the general positioning of workstations aligns closely with the ideal layout from [16]. This demonstrates that the model is capable of providing a viable initial design that approximates an optimal arrangement. Such consistency between the output of the preliminary shipyard layout model and the ideal layout supports the validity of the proposed approach, indicating that it can be effectively used in the early stages of shipyard design. The deviation in St 16's placement is due to the model focusing on preliminary design rather than determining exact locations. The model provides a starting point for the overall layout, so minor deviations like this are expected and do not significantly affect the general arrangement.

Fig. 3 Comparison of preliminary layout results from the proposed model (3a, 3b, 3c) with the ideal layout by [16] (3d)

4.2 Discussions

In discussing the outcomes of this study, it is valuable to acknowledge areas where further refinement is possible. While the proposed approach provides a structured foundation for optimizing shipyard layouts, a few constraints inherently affect its applicability and results. Recognizing these limitations not only highlights the boundaries of the current work but also reveals potential pathways for further research and enhancement. With these considerations in mind, the following points outline key limitations observed in this study. First, the findings are influenced by subjective factor weightings based on expert judgments, which may vary across cases and between specialists. The coming subsection (i.e., sensitivity analysis) addresses this issue. Second, the generated layout designs are preliminary and provide only an initial framework without determining the exact final locations for workstations, serving as a foundation for further refinement in detailed planning stages. Third, the risk calculations rely on RPN, which are based on failure data specific to individual workstations, thereby limiting the scope of the risk assessment. Expanding the risk analysis to include broader factors beyond workstation-specific failures could offer a more comprehensive approach. Lastly, while the factors used in this study were selected based on an extensive literature review, future applications could adapt or expand these factors according to specific shipyard needs. Different facilities may have unique priorities or operational requirements, which could necessitate the inclusion of additional factors to better suit each particular case.

Survey findings reveals that the risk, flow, and activity weights are, respectively, 0.77, 0.15, and 0.08. As can be observed, the risk factor's weight is very high. This is a remarkable result. According to the experts that were consulted, this shows how great the importance of the risk associated with the shipyard layout issue is. It should be noted at this point that these weights are subject to change. Therefore, the survey should be conducted with a case-based approach. On the other hand, determining the value of risk is difficult. The method employed to determine the risk value must take into consideration the shipyard characteristics.

The connections between workstations are illustrated in Figure 4. Nodes represent the workstations, while lines show that there is a relationship. Due to the complex relations start after the fifth workstation, a layout design cannot be simply constructed.

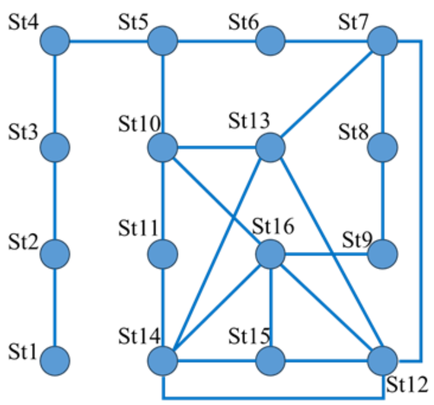

Fig. 4 Visualization of the links between workstations

If we look at the specifics of how the workstations relate to one another, the pieces cut in St1 first go to St2, then to St3, and then they are combined here. Following this procedure, the intermediate product is treated at workstations St4 and St5, respectively. After the parts from St10 have been attached to the panels at the St5 workstation, full welding is completed at the St6 workstation. The intermediate product, whose production process is finished at workstation St6, is combined with the components from workstations St13 and St12 at workstation St7. Following this procedure, full welding and grinding are done at St8 and St9 workstations, respectively. At the St14 workstation, components for curved blocks are produced. Because of this, the curved block components from workstations St11, St15, St13, and St12 are united here. The parts from St12 and St10 are assembled at the St13 workstation to construct minor and sub-assemblies. The pieces that need to be bent from the parts that were cut at St10 and St12 move to St11 and St15 workstations, respectively. The block is formed at the St16 workstation by uniting the elements from the St9, St10, St12, St14, and St15 workstations.

Considering the number of material transport, the busiest station is St13, which has four connections (Figure 4-5). A substantial number of large and small parts from St10 and St12 are merged here, and the resulting intermediate products are distributed from there to the St7 and St14.

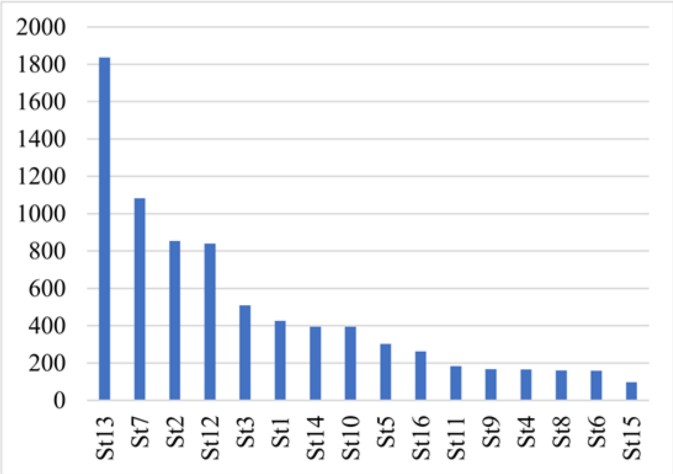

Fig. 5 Workstation ranking in terms of the total number of material transport

Table 8 provides activity relations based on workstations. The ranking shown in Figure 6 is generated by digitizing the activity ratings using the scale employed by [13]. As a result, the workstation with the highest activity relationship score was identified as St7. It is remarkable that St7, which is connected to four workstations, ranks first in this segment even though St12, St14, and St16 are connected to five workstations. This is since this workstation's activity relationships are crucial, whereas those of the others are more moderate.

Table 8 Activity relation ratings by workstations

WS	Activity ratings	WS	Activity ratings	WS	Activity ratings	WS	Activity ratings
St1	A	St5	A, A, I	St9	A, E	St13	A, O, O, E
St2	A, A	St6	A, A	St10	I, E, O, O	St14	O, O, O, I, I
St3	A, A	St7	A, A, I, E	St11	O, E	St15	O, I, O
St4	A, A	St8	A, A	St12	I, A, O, O, O	St16	E, O, O, I, O

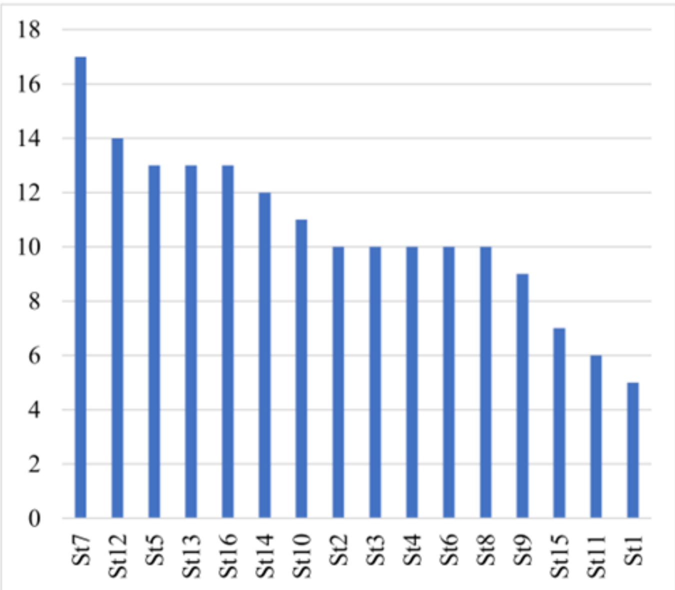

Fig. 6 Workstation ranking in terms of the total activity ratings

St14, St13, St16, and St12 are located in the first four rows, respectively, when the risk values of the workstations are taken into account (Figure 7).

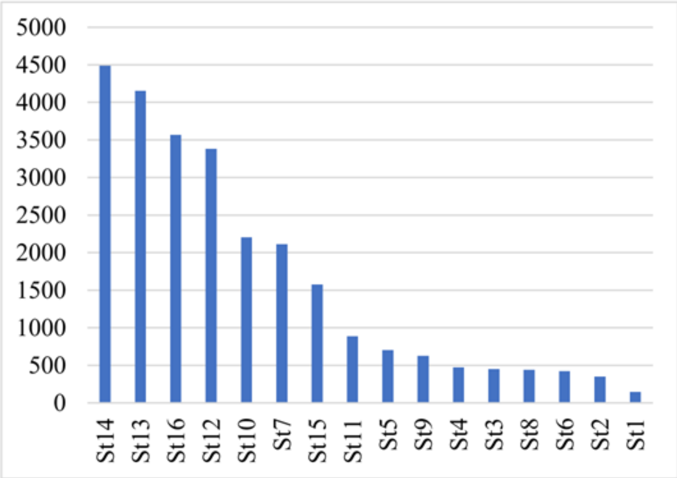

Fig. 7 Workstation ranking in terms of the total risk values

For all three factors, St13 and St12 stations are in the top five, whereas St8 station is in the bottom five. Figure 8 depicts three exemplary workstation arrangements obtained at the conclusion of the optimization runs.

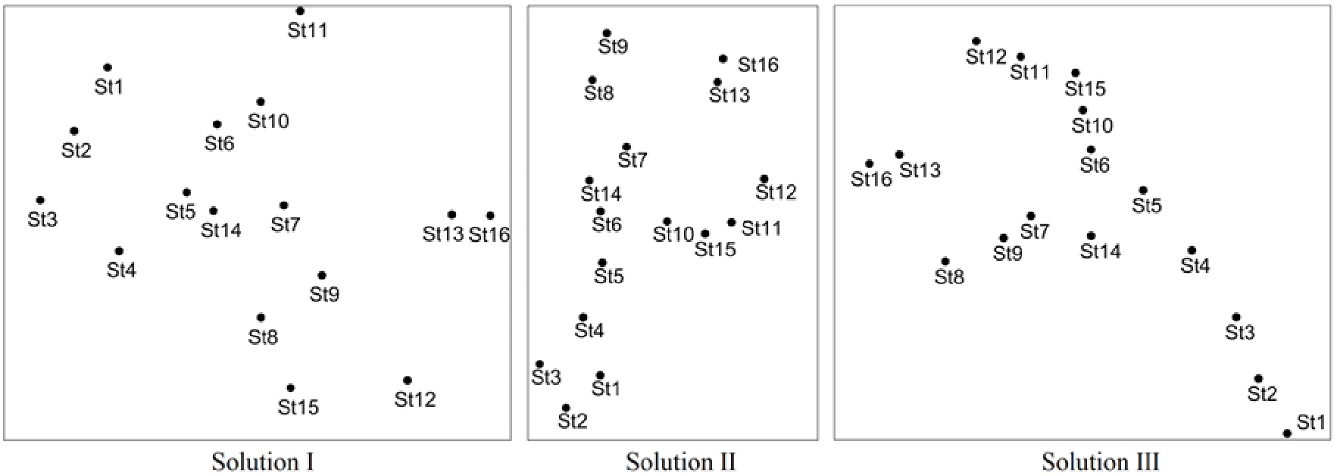

Fig. 8 Relative positions of the shipyard workstations

When Figure 4 and 8 are examined together, it is seen that St1, St2, St3, St4, St5 and St6 are all placed in the same region in all solutions. These workstations are already serially linked, as shown in Figure 4. Workstations St7, St8, and St9 are situated near to one another. It is worth noting that in all three layouts, St12 is placed on the edge rather than in the centre. The explanation for this could be that there are no arrivals from other workstations, only material movement from it to others.

When the generated arrangements are looked at as a whole, some workstations are situated adjacent to one another even if they are unconnected (e.g. St13 and St16). As a result, it can be claimed that the algorithm acted freely while positioning these two stations and brought them close to one another because of their connections to other stations. Profiled panels are produced in the workstation sequence St1, St2, St3, St4, St5, St6 and St10. When Figure 8 is inspected, they are arranged in the first solution in the form of a "U", in the second solution in the form of a "L", and in the third solution in the form of a "I". Sub-blocks are constructed in the workstation sequence St6, St7, St8, St12, and St13. Of these, St6, St12 and St13 send parts to St7. Therefore, a star-shaped branched layout emerges around St7. The main body of the sub-blocks is produced at St6, St7, and St8, which are all placed in a "I" form in the three solutions.

It should be noted that the factors used here could vary depending on the shipyard. In a similar fashion, even if a survey was conducted with some professionals, the weights of the factors are determined in a subjective manner. This implies that distinct expert groups may designate different factors with varying degrees of importance. Along with all these issues, each shipyard has its own special requirements and priorities, just like any other industrial facility.

In this study, the focus was placed on the steel production process of ship block construction, with outfitting, painting and other components excluded from the analysis. When examining the optimal topology identified by [17], it is evident that workstations such as pre-treatment, fabrication, panel line, part assembly, sub-assembly, and block assembly are positioned similarly to the results obtained in this study. The workstations defined by [17] can be represented by groupings of the workstations defined here. In [2], the shipyard layout is designed based on production capability planning and includes several stations not considered in this study. However, when focusing solely on the relevant workstations, similar workstations are positioned in close proximity to each other, reflecting comparable patterns. Additionally, the block steel production stations locations in the proposed layout by [18] align well with the preliminary layout configurations obtained in this study. As this study primarily addresses only the steel production process of ship block construction, the inclusion of additional workstations, such as those for painting and outfitting, presents a promising area for future model development.

4.3 Sensitivity analysis

In practice, decision-makers often have varying priorities based on their unique objectives and the importance they assign to different factors. For instance, some may prioritize risk, while others might focus more on flow or activity. This variation in priorities can lead to different outcomes depending on the weight given to each criterion. To assess how changes in these weights influence the results, a sensitivity analysis is performed. By adjusting the weights of factors and observing the resulting changes in HUD values, we can understand how sensitive the outcomes are to factor weights. In addition to the survey results, three alternative scenarios were developed, as illustrated in Table 9. The sensitivity analysis calculation results are plotted in Figure 9, illustrating how different weight combinations for flow, risk, and activity impact the HUD between workstations in the shipyard. By comparing the survey result, risk-dominant, flow-dominant, and activity-dominant scenarios, we can observe how adjustments to the weight distribution lead to changes in the HUD values, which are used in the optimization process. These variations highlight the impact of different criteria on determining preliminary workstation arrangements.

Table 9 Summary of scenarios, including survey results and three alternative weight combinations

Factors	Weights (Survey result)	Weights (Risk dominant)	Weights (Flow dominant)	Weights (Activity dominant)
Flow	0,15	0,25	0,5	0,25
Risk	0,77	0,5	0,25	0,25
Activity	0,08	0,25	0,25	0,5

According to the survey results, risk is already the dominant factor with a weight of 0.77, which is reflected in the higher HUD values observed in the blue line. This indicates that prioritizing risk leads to larger distances between workstations, as seen across many of the station pairs. In scenarios where risk continues to dominate (dashed orange line with circles), the HUD values remain relatively high, emphasizing the correlation between high-risk weights and greater workstation distances. Conversely, the lowest HUD values are generally observed when activity becomes the dominant factor (dotted yellow line with stars), suggesting that placing more emphasis on activity results in closer spacing between workstations, which could imply greater efficiency in terms of physical layout. Interestingly, the analysis shows that for about half of the workstation pairs, changes in the weighting have little impact on the HUD values. This indicates that for these pairs, the distances between workstations are not highly sensitive to the criteria weights, providing some stability in the layout. However, for the other half, significant changes in HUD values are observed when weights are adjusted, suggesting that these pairs are more sensitive to the weight distribution of flow, risk, and activity.

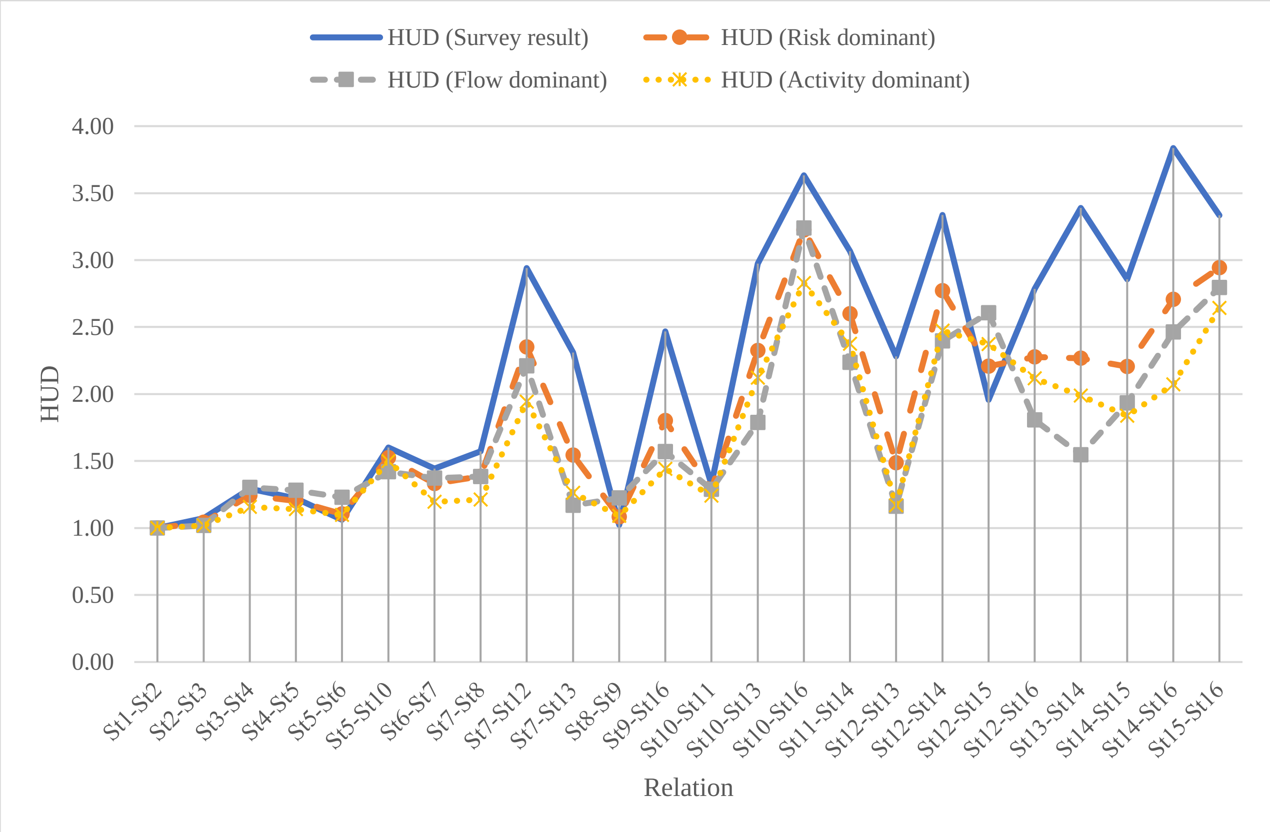

Fig. 9 Sensitivity analysis results showing the effect of different weight combinations for flow, risk, and activity on the HUD between workstations

5. Conclusions

The arrangement of workstations plays a crucial role in production efficiency, making effective shipyard layout planning essential. Since shipyard design involves the organization of multiple workstations, an initial setup provides valuable guidance for designers. This study introduces a novel methodology for determining the relative locations of shipyard workstations in the preliminary phase of layout design. The proposed approach generates practical preliminary workstation layouts based on expert opinions and a range of factors, including flow, risk, and activity. Since there are complicated interactions between workstations half of the workstations considered have at least three connections. By integrating AHP, fuzzy logic, and the SA algorithm, the method produced multiple viable layouts, such as U, L, and I-shaped configurations for profiled panel production, and a star-shaped layout for sub-block production, offering useful alternatives for shipyard designers. St1, St2, St3, St4, St5, and St6 may all be in the same area.

Sensitivity analysis demonstrates that factor weightings impact workstation arrangement. In the case study presented because the importance of the risk factor is assessed to be quite high according to expert judgments, the safety phenomenon has a significant impact on the layout. The novel aspects of this study include the application of the SA algorithm for optimizing shipyard facility layouts, the combined use of fuzzy logic with metaheuristic optimization in the shipyard FLP domain, and the incorporation of safety as a quantitative risk factor into shipyard FLP. Despite these promising results, the study has certain limitations. The findings are influenced by subjective factor weightings based on expert judgments, which may vary between cases and specialists. Future research could explore alternative weighting methods to minimize subjectivity. Additionally, the layout designs are preliminary, and the methodology does not provide final exact locations for stations. Future study could focus on developing a more detailed optimization model that determines precise workstation placements. Expanding the scope to include other risk factors related to workstation activities could also lead to a more comprehensive and refined design process.

REFERENCES

[1] Gungor, A., Unsan, Y., Barlas, B., 2023. A novel approach for planning of shipbuilding processes. *Brodogradnja*, 74(4), 17-39. https://doi.org/10.21278/brod74402

[2] Shin, J. G., Song, Y. J., Lee, D. K., Woo, J. H., 2009. A concept and framework for a shipyard layout design based on simulation. *Journal of Ship Production*, 25(03), 126-135. https://doi.org/10.5957/jsp.2009.25.3.126

[3] Rubeša, R., Hadjina, M., Matulja, T., Bolf, D., 2023. The shipyard technological level evaluation methodology. *Brodogradnja*, 74(3), 91-106. https://doi.org/10.21278/brod74305

[4] Kudelska, I., Stachowiak, A., Pawłowska, M., 2018. The framework of IT tool supporting layout redesign in a selected industrial company. *Advances in Intelligent Systems and Computing*, 835, 360-369. https://doi.org/10.1007/978-3-319-97490-3_35

[5] Deshpande, V., Patil, N. D., Baviskar, V., Gandhi, J., 2016. Plant layout optimization using CRAFT and ALDEP methodology. Productivity Journal by National Productivity Council 57(1), 32-42.

[6] Scalia, G., Micale, R., Enea, M., 2019. Facility layout problem: Bibliometric and benchmarking analysis. *International Journal of Industrial Engineering Computations*, 10(4), 453-472. https://doi.org/10.5267/j.ijiec.2019.5.001

[7] Pérez-Gosende, P., Mula, J., Díaz-Madroñero, M., 2021. Facility layout planning. An extended literature review. *International Journal of Production Research*, 59(12), 3777-3816. https://doi.org/10.1080/00207543.2021.1897176

[8] Lee, S. J., Woo, J. H., Shin, J. G., 2014. New business opportunity: Green field project with new technology. *International Journal of Naval Architecture and Ocean Engineering*, 6(2), 471-483. https://doi.org/10.2478/IJNAOE-2013-0193

[9] Pérez-Gosende, P, Mula, J, Díaz-Madroñero, M., 2023. A bottom-up multi-objective optimisation approach to dynamic facility layout planning. *International Journal of Production Research*, 62(3), 626-643. https://doi.org/10.1080/00207543.2023.2168308

[10] Guo, W., Jiang, P., Yang, M., 2023. Unequal area facility layout problem-solving: a real case study on an air-conditioner production shop floor. *International Journal of Production Research*, 61(5), 1479-1496. https://doi.org/10.1080/00207543.2022.2037778

[11] Yang, Z., Lu, W., 2023. Facility layout design for modular construction manufacturing: A comparison based on simulation and optimization. *Automation in Construction*, 147, 104713. https://doi.org/10.1016/j.autcon.2022.104713

[12] Kumar, R., Singh, S. P., 2019. Cellular facility layout problem: a case of tower manufacturing industry. *Management of Environmental Quality: An International Journal*, 30(6), 1345-1360. https://doi.org/10.1108/MEQ-04-2018-0076

[13] Matulja, T., Fafandjel, N., Zamarin, A., 2009. Methodology for shipyard production areas optimal layout design. *Brodogradnja*, 60(4), 369-377.

[14] Song, Y. J., Woo J. H., 2013. New shipyard layout design for the preliminary phase & case study for the green field project. *International Journal of Naval Architecture and Ocean Engineering*, 5(1), 132-146. https://doi.org/10.3744/JNAOE.2013.5.1.132

[15] Choi, M., Kim, S. H., Chung, H., 2017. Optimal shipyard facility layout planning based on a genetic algorithm and stochastic growth algorithm. *Ships and Offshore Structures*, 12(4), 486-494. https://doi.org/10.1080/17445302.2016.1176294

[16] Dixit, V., Verma, P., Raj, P., 2020. Leveraging tacit knowledge for shipyard facility layout selection using fuzzy set theory. *Expert Systems with Applications*, 158, 113423. https://doi.org/10.1016/j.eswa.2020.113423

[17] Türk, A., Gürgen, S., Ozkok, M., Altın, İ., 2021. A comprehensive investigation into the performance of genetic algorithm for effective shipyard topological layout. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 236(3), 726-740. https://doi.org/10.1177/14750902211062057

[18] Tamer, S., Barlas, B., Gunbeyaz, S. A., Kurt, R. E., Eren, Ş., 2022. Adjacency-Based Facility Layout Optimization for Shipyards: A Case Study. *Journal of Ship Production and Design*, 39(01), 25-31. https://doi.org/10.5957/JSPD.05210013

[19] Junior, W. A., Azzolini, F. G. P., Mundim, L. R., Porto, A. J. V., Amani, H. J. S., 2023. Shipyard facility layout optimization through the implementation of a sequential structure of algorithms. *Heliyon*, 9(6), e16714. https://doi.org/10.1016/j.heliyon.2023.e16714

[20] Singh, D., Ingole, S., 2019. Multi-objective facility layout problems using BBO, NSBBO and NSGA-II metaheuristic algorithms. *International Journal of Industrial Engineering Computations*, 10(2), 239-262. https://doi.org/10.5267/j.ijiec.2018.6.006

[21] Efe, B., 2019. Analysis of operational safety risks in shipbuilding using failure mode and effect analysis approach. *Ocean Engineering*, 187, 106214. https://doi.org/10.1016/j.oceaneng.2019.106214

[22] Ozkok, M., 2014. Risk Assessment in Ship Hull Structure Production Using FMEA. *Journal of Marine Science and Technology*, 22(2), 173-185.

[23] Zolfi, K., Jouzdani, J., 2023. A mathematical model and a simulated annealing algorithm for unequal multi-floor dynamic facility layout problem based on flexible Bay structure with elevator consideration. *Journal of Facilities Management*, 21(3), 352-386. https://doi.org/10.1108/JFM-09-2021-0102

[24] Imran, R., Ullah, K., Ali, Z., Akram, M., 2024. A multi-criteria group decision-making approach for robot selection using interval-valued intuitionistic fuzzy information and Aczel-Alsina Bonferroni means. *Spectrum of Decision Making and Applications*, 1(1), 1-32.

[25] Kannan, J., Jayakumar, V., Pethaperumal, M., 2025. Advanced fuzzy-based decision-making: the linear diophantine fuzzy CODAS method for logistic specialist selection. *Spectrum of Operational Research*, 2(1), 41-60. https://doi.org/10.31181/sor2120259

[26] Hussain, A., Ullah, K., 2024. An intelligent decision support system for spherical Fuzzy Sugeno-Weber aggregation operators and real-life applications. *Spectrum of Mechanical Engineering and Operational Research*, 1(1), 177-188. https://doi.org/10.31181/smeor11202415

[27] Erkurtulmus, S. A., Pesman, E., 2024. GIS-based floating offshore wind turbine installation site selection using fuzzy analytic hierarchy process in northeast Aegean Sea. Brodogradnja, 75(2), 1-21. https://doi.org/10.21278/brod75204

[28] Kafali, M, Ozkok, M., 2012. Development of the shipyard's initial layout (In Turkish). *10th Shipbuilding and Marine Technology Technical Congress*, Istanbul, Turkiye.

[29] Kafali, M., Ozkok, M., 2021. A method for determining facility layout in shipbuilding (In Turkish). *2nd International Congress on Ship and Marine Technology*, Istanbul, Turkiye.

[30] Saaty, T. L., 1980. The Analytical Hierarchy Process: Planning, Priority Setting, Resource Allocation. *McGraw-Hill*, New York.

[31] Krejčí, J., Stoklasa, J., 2018. Aggregation in the analytic hierarchy process: Why weighted geometric mean should be used instead of weighted arithmetic mean. *Expert Systems with Applications*, 114, 97-106. https://doi.org/10.1016/j.eswa.2018.06.060

[32] Ma, Q., Wang, Z., Zhou, T., Liu, Z., 2024. Robust optimization method of emergency resource allocation for risk management in inland waterways. *Brodogradnja*, 75(1), 1-22. https://doi.org/10.21278/brod75103

[33] Kirkpatrick, S, Gelatt, CD, Vecchi, MP, 1983. Optimization by simulated annealing. *Science*, 220(4598), 671-680. https://doi.org/10.1126/science.220.4598.671

[34] Černý, V., 1985. Thermodynamical approach to the traveling salesman problem: An efficient simulation algorithm. *Journal of Optimization Theory and Applications*, 45(1), 41-51. https://doi.org/10.1007/BF00940812

[35] Yang, X. S., 2010. Engineering Optimization: An Introduction with Metaheuristic Applications. John Wiley & Sons, Hoboken, New Jersey.

[36] Talbi, E. G., 2009. Metaheuristics: from design to implementation. *John Wiley & Sons*, Hoboken, New Jersey. https://doi.org/10.1002/9780470496916

[37] Poe, W. A., Mokhatab, S., 2017. Modelling, control, and optimization of natural gas processing plants. *Gulf Professional Publishing*, UK. https://doi.org/10.1016/B978-0-12-802961-9.00001-2