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The impact of fatigue on shipyard welding workers' occupational health and safety and performance

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ABSTRACT

Welding processes are critical for shipbuilding operations in shipyards. Welders' performance is critical for the quality and speed of the welding; on the other hand, welding requires awkward and repetitive body postures for long durations, which has a negative impact on the Occupational Health and Safety (OHS) of the welding workers. This study, therefore, investigates the long-term impact of welding workload on the body for different age groups and experience levels, as well as the long-term impact on chronic fatigue and inter-shift recovery. In order to determine the impact, this study conducted a comprehensive data collection campaign in the shipyard through observation and questionnaires. Results indicate that the eyes, knee, neck and waist are the most discomforted body parts for investigated welding positions. The age of welders was an important parameter of the most affected body part.

Moreover, the short-term fatigue impact on welding performance was also investigated to identify the impact on productivity. The Discrete event simulation (Rockwell ARENA) demonstrated that efficiency loss from short-term daily fatigue is around 22,9% compared to the rested condition. The main contribution of this study was investigating fatigue impact on OHS and productivity for selected shipbuilding tasks. The findings of this study can be utilised for shipyard production capacity and resource planning and OHS improvements. The results can also be used further as a coefficient of performance in the production simulation analysis when studying shipyard efficiency. This is a valuable contribution to the literature on shipyard productivity.

1. Introduction

The construction of ships is a multifaceted process involving knowledge and skills from various engineering expertise, including naval architecture and ocean, marine, mechanical, and electrical engineering (Barlas and Izci, 2018). Numerous activities, procedures, and sub-processes, including inspection, sorting, storage priming, cutting shaping, forming and welding of the steel, are carried out in a structured manner. Following steel treatment, operations such as assembly, panel fabrication, block assembly, pre-outfitting, grand assembly, pipe routing, heating/ventilation, wiring, surface preparation, and painting are completed (Aycı and Barlas, 2016). The size of the manufactured product differentiates from any manufacturing industry; these processes above require a vast range of abilities, materials and tools, bringing a unique status and approach to the maritime industry compared to similar manufacturing industries (Mandal, 2017).

Welding is one of the most critical manufacturing methods for combining the parts of the ship due to the complex shape and structural challenges of ships and is predominantly a manual activity (Baek and Nam, 2021) and is given significant importance in shipyards. Welding is carried out by qualified welders and controlled by quality assurance engineers and classification societies (Turan et al., 2011). Welding is impacted by various parameters (such as current, voltage, speed etc.) influence weld quality (Mandal, 2017). Welding speed, the linear rate at which the arc moves along a weld joint, is one of the parameters influenced by human factors (Mandal, 2017).

Welders' performance is critical for the quality and speed of the welding. On the other hand, welders' performance is expected to vary during shifts within heavy industries such as shipbuilding. Moreover, welding often requires awkward postures for long durations, forceful exertion, excessive repetitive heavy work, static load, and stress and introduces many ergonomic challenges (AWS, 2018; Baek and Nam, 2021), which leads to tiredness and fatigue. This leads to occupational illnesses in the long run, as well as affects the quality of the work during

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a workday. Studies related to the welder's health showed eye problems, hearing loss, and musculoskeletal problems, particularly in the knees, neck and back (Amani et al., 2017). Furthermore, compared to the non-welding workers, a higher incidence of symptoms of musculoskeletal disorders in the cervical, dorsal, lumbar, wrists and hands were found among the welders (Lourenço and Luís, 2021). Since musculoskeletal disorders caused by these awkward postures (Salleh et al., 2021) are present quite often, several research has been conducted to measure the level of discomfort (Baek and Nam, 2021; Dinagaran et al., 2019; Fahzan bin Salleh et al., 2020; Falck et al., 2017; Falck et al., 2010; Keshavarz Panahi and Cho, 2016; Lowe et al., 2001; Suman et al., 2018). Panahi et al. (2021) also studied this critical issue to detect muscle fatigue and identify vulnerable muscles vulnerably (to musculoskeletal disorders) and proved that Recurrence Quantification Analysis (RQA) is an effective method for evaluation during tasks. In addition to occupational illnesses, poor welding performance may result in quality-related expenses and time overruns. Kobayashi et al. emphasised that the strength of manual arc welded products strongly depends on the skills of the welding operator (Kobayashi et al., 2001).

Therefore, this article focuses on the impact of fatigue (short and long-term) on production performance and workers' occupational health through a combination of field data collection, Discrete Event Simulation (DES), and Occupational Fatigue Exhaustion/Recovery (OFER) scale questionnaires. Section 2 of this article will introduce short and long-term fatigue, while section 3 introduces the methodology. The results have been demonstrated in section 4 and discussed in Section 5 of this manuscript.

The primary contribution of this study is the fatigue prediction models for selected shipbuilding tasks. This study is the first to combine occupational health and safety and the productivity impacts of (short/long) fatigue. The shipbuilding industry depends on manual labour, requires physical strength, and is widely conceived as a dangerous industry for the workers. Since it requires heavy physical activities that include awkward postures for long durations, excessive repetitive work, static load and stress, and so on, the welders' performance vary. Currently, there is no manual welding fatigue-related shipbuilding focused research in the literature. This novel study will pave the way for manual shipyard operation (welding and potentially torch cutting) productivity estimations, and more accurate planning and scheduling practises for the industry.

2. Fatigue

2.1. Short-term fatigue

Ninety percent of all industrial accidents are caused by human error (Reason, 1990; Yeow et al., 2014). Human error mechanisms should be understood better to achieve increased safety. One performance factor that influences human performance and often contributes to human error is fatigue, which is caused by repetitive activities and depletes an individual's resources (Winwood et al., 2005). Tiredness and lack of energy have been identified as fatigue, such as physical exertion, discomfort, lack of motivation, and sleepiness (Lindeberg et al., 2010). Different manifestations of fatigue include mental exhaustion, a lack of alertness, specific muscular fatigue, and general body exhaustion (Åhsberg and Gamberale, 1998). Furthermore, fatigue harms judgement, causes omission, insignificance to essentials, decreased efficiency and productivity, and higher error rates and quality issues. Fatigue affects performance from slight to catastrophic levels (Fera et al., 2020; Griffith and Mahadevan, 2011). Short-term worker fatigue can occur on a daily basis, especially when employees are required to work long hours, perform physically or mentally demanding tasks, or work irregular and overnight shifts.

Furthermore, the welding conditions can significantly impact operator health and production efficiency. Inappropriate posture caused by confined spaces such as ship blocks may cause static muscle efforts. This may result in acute localised muscle fatigue, reducing productivity and increasing operator-related health hazards (Boussenna et al., 1982; Ismaila et al., 2011).

Since fatigue has been a significant concern affecting welder performance, several research has been conducted to measure fatigue in the welding (Bláfoss et al., 2019; Kołodziej and Ligarski, 2017; Williamson et al., 2011; Yung et al., 2017). Ismaila et al. (2011) conducted a study on the ergonomics aspect of welding operations, and 70.8% of workers have to maintain the same posture all the time, which negates ergonomic guidelines for working posture. In study by Ismaila et al., 58.3% also reported that their arms are above the shoulder and away from the body during the tasks, which induces repetitive strain injuries (Ismaila et al., 2011). Overall, studies show that fatigue has a substantial impact on work performance, as well as that prolonged fatigue has an effect on occupational and ergonomics health. In this study, the DES technique has been applied to identify the impact of short-term fatigue on welding performance (function of welding speed and quality).

2.2. Long-term fatigue

According to UK's Health and Safety Executive UK (HSE), long-term fatigue is a state of tiredness or exhaustion that persists over an extended period and is not alleviated by rest or sleep (HSE, 2021). It is a common problem for workers in many industries and can be caused by many factors, including heavy workloads, long working hours, irregular work schedules, and poor sleep quality.

Long-term fatigue can significantly impact workers' health and well-being, increasing their risk of accidents, injuries, and occupational diseases. It can also affect their productivity, performance, and ability to make sound decisions and respond to changes in their environment (HSE, 2021). Besides the impact on work, fatigue also reduces workers' quality of life, and when it becomes chronic or excessive, fatigue can contribute to work-related disorders. Rest breaks help to relieve muscle fatigue and allow workers to regain their normal strength and capacity (Jaber et al., 2013).

Long-term fatigue is impacted by various factors, including workers' age, welding experience, socio-economic background, etc. Although multiple studies link the evolution of acute fatigue to chronic fatigue, the existing scales do not tend to differentiate the acute and chronic fatigue.

Work-related fatigue is a common complaint and concern in a work environment and is difficult to measure. Many studies focus on measuring work-related fatigue using subjective (surveys, scales) and objective (sensors and devices) methods. Although objective methods give more definitive information about fatigue, subjective methods are easier to apply and less disruptive. Some of these methods include but are not limited to the Occupational Fatigue Recovery Exhaustion (OFER) Scale (Winwood et al., 2005, 2006), the Swedish Occupational Symptoms of Fatigue (Åhsberg et al., 1997), the Fatigue Assessment Scale (Michielsen et al., 2003). These subjective methods have been applied in a wide range of industries, including manufacturing (Hernandez et al., 2015; Ihsan et al., 2020), the oil and gas industry (Mehta et al., 2017; Shortz et al., 2019), emergency services such as hospitals (Havlioğlu et al., 2020), firefighters (Giuliani et al., 2020), seafarers (Wadsworth et al., 2006), or even heavy goods vehicle driving (Longman et al., 2021). The OFER Scale has been validated and proven in different sectors, including heavy labour-dependant industries similar to shipbuilding. Therefore, the OFER Scale is selected in this research study to identify the workers' long term chronic and intershift recovery fatigue.

The OFER scale originally contained 15-item questionnaire, five for each section: chronic fatigue, acute fatigue, and intershift recovery fatigue. This study implements the chronic fatigue and inter-shift recovery fatigue aspects of the OFER scale regarding long-term fatigue for manual welding operations in the shipbuilding industry.

3. Materials and methods

The methodology for this study (Okumus et al., 2022) involved several steps, as demonstrated in Fig. 1. A team of researchers observed workers' performance at a shipyard and monitored their performance on a task (welding and unit assembly). First, welding speed was compared using field observations in the morning and afternoon for the same workers. To do that, twelve welders were observed for three days. Welding speed (for acceptable welding quality, unacceptable welds were eliminated from the study via expert opinion) was calculated using video recordings during the field study. In total 27, pairs of high-quality recordings were obtained. Then, welding samples were assessed by three expert naval architects with an average of 18 years of field experience. The experts scored each sample with the naked eye depending on visual surface defects, as shown in detail in Annex 5.

In this study, welding performance score (WPS) is defined as a function of acceptable quality welding speed score (WSS) and welding quality score (WQS). According to expert opinions, speed and quality are assumed to have equal importance; therefore, the WPS formula is acquired as in Equation (1).

$$WPS = \frac{WQS + WSS}{2} \qquad \text{Equation 1}$$

Annex 5 includes quality rating criteria and a list of potential surface defects. Each welding sample was scored between one and five. Therefore, welding quality scores are calculated as shown in Equation (2) where *EO* represents the corresponding expert opinion score.

$$WQS = \frac{(EO_1 + EO_2 + EO_3)/3}{5} \qquad \text{Equation 2}$$

On the other hand, to calculate WSS, data from the field was normalised for each sample using Equation (3) below.

$$WSS_{i,j} = \frac{Welding\ speed_{i,j}}{Max_{i,j}(Welding\ speed)} \forall i,j \qquad \text{Equation 3}$$

where, i: Welding workers (i = 1, 2, …, 12).

J: Observation days (j = 1, 2, 3).

Next, a hypothesis T-test was used to reveal if daily fatigue affects worker performance. A DES model was created using Rockwell Arena Simulation Software to model a basic ship block production and calculate the workforce difference due to daily fatigue. A typical ship block assembly (on which the welding data collection was made) was modelled, which involves 500 different parts that form the overall structure of the block (steps include preproduction, panel production, and block production). This revealed the short-term fatigue effects on shipyard productivity.

In addition to studying the effects of short-term fatigue, an OFER scale survey focused on inter-shift recovery and chronic fatigue was carried out among welding workers in the shipyard. In addition, a welding workload evaluation questionnaire was conducted to identify the ergonomics and the level of discomfort (three levels) on the twelve body parts. These surveys did not include sensitive personal data (name and address), and the results were evaluated anonymously. General information (socio-cultural, economic, and educational status) was collected in the study. At the end of the tasks mentioned above, employees responded with verbal expressions to determine the effect on employee fatigue.

Some characteristics of the welders who participated in this part of the research are as follows.

- All welders who participated in the study are subcontractor company employees, and the shipyard does not employ them directly.
- None of them has recently worked a night shift. They work from 8:00 a.m. to 4:30 p.m. in the daytime. The longest time they worked non-stop (without a break) during the day was 2 h, and they had a lunch break from 12 p.m. to 1 p.m.
- When asked how often they find it challenging to complete the job they are given, 75% of the participants stated that at least sometimes they find it difficult. This might lead to mental and physical stress for the workers from prolonged exposure to heavy tasks.

Lastly, following the welding workload questionnaire, workers' Discomfort Priority Numbers (DPN) were calculated for each body part (level of discomfort multiplied by the frequency). Overall, this methodology allowed for a comprehensive examination of the effects of both daily and long-term fatigue on welding performance and worker health.

4. Results

4.1. The effect of short-term fatigue on welding performance

The hypothesis *t*-test is used to investigate the effect of short-term fatigue (during a workday or shift) on welders' performances by observing the same workers in the mornings and afternoons. The observation was done as close to the beginning of their shifts as possible and close to the end of their changes for three days while welding the same materials in similar positions. Since the same workers were observed at different times, a paired-sample *t*-test was selected for the analysis.

- Hypothesis 0: Fatigue or tiredness during the day does not affect welders' performance in manual gas metal arc welding operations.
- Hypothesis 1: Fatigue or tiredness during the day affects welders' performance in manual gas metal arc welding operations.

The number of participants is twelve, with experience levels varying from 2 to 28 years. The average welder's experience is 11.5 years. And the average welder's age is 35.8 years old. Table 1 demonstrates the

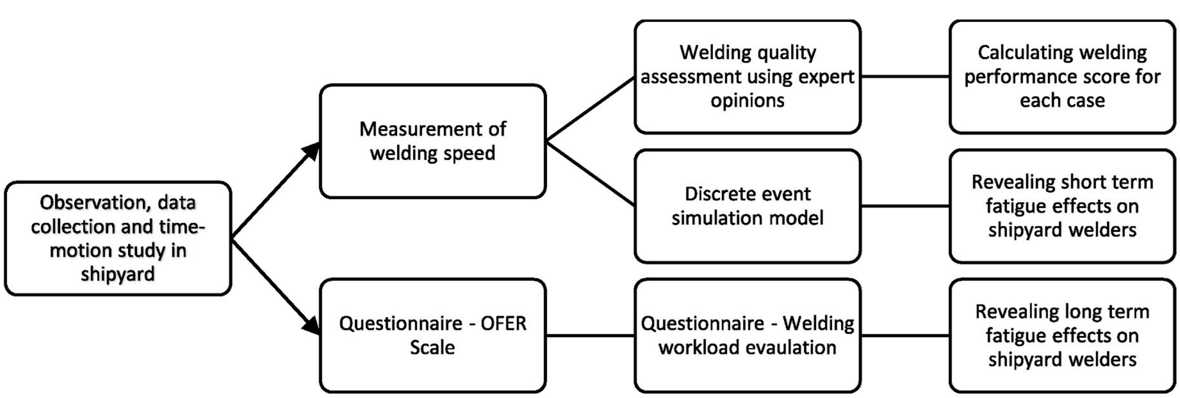

Fig. 1. Methodology followed in this manuscript.

Table 1
Paired samples test results from SPSS.

Paired Samples Statistics

		Mean	N	Std. Deviation	Std Error Mean
Pair 1	Morning performance_day1	.6850	10	.11297	.03572
	Afternoon performance_day1	.6080	10	.06563	.02075
Pair 2	Morning performance_day2	.6820	10	.07871	.01489
	Afternoon performance_day2	.5700	10	.12936	.04091
Pair 3	Morning performance_day3	.7114	7	.09227	.03488
	Afternoon performance_day3	.5743	7	.05593	.2114

Paired Samples Test

Paired differences

		Mean	Std. Dev	Std. Error Mean	95% confidence interval of the difference		t	df	Sig. 2-tailed)
					Lower	Upper			
Pair 1	Morning performance & afternoon performance_day1	.07700	.08460	.02675	.01648	.13752	2.878	9	.018
Pair 2	Morning performance & afternoon performance_day2	.11200	.11003	.03479	.03329	.19071	3.219	9	.011
Pair 3	Morning performance & afternoon performance_day3	.13714	.05057	.01911	.09038	.18391	7.175	6	<.001

paired samples test results for the collected data as part of this observation.

The statistical analysis indicates significant results for each pair ($p < 0.05$), which means the null hypothesis is rejected, and Hypothesis 1 is accepted. In other words, according to the paired samples T-test result, under 95% confidence, a statistically meaningful difference exists between the welder's performance in the morning and afternoon. The average performance of the workers is higher in the mornings than in the afternoon, as expected, due to fatigue that occurs during the working day. A DES model with Arena Simulation Software was built next to demonstrate the impact on the overall welding productivity in an example ship block manufacturing process.

4.2. Comparative study through ARENA DES

This stage aims to show the efficiency lost due to daily accumulated fatigue. Thus, the simulation will compare the welding performance of workers in the morning (between 8:30 a.m. and 9:30 a.m.), when short-term fatigue does not exist, and in the afternoon (between 3:00 p.m. and 4:00 p.m.) closer to the end of their shifts.

To assess the effect of short-term fatigue, the case study was built into two scenarios, as shown in Fig. 2. The simulation is based on a basic steel block production process that has three main welding stages.

a. Pre-production welding (W1) is where two single parts are welded together.
b. Panel production welding (W2) is where around 25 pre-production parts are combined together to form a panel.
c. Block production welding (W3) is where ten panels are welded together to form a steel block.

A representation of the above steps is illustrated in Fig. 3, just to give an idea. The most applied manual welding positions for these three steps are the same ones, namely the 2F horizontal and 3F vertical up positions shown in Fig. 4. Therefore, the scope of this study has been limited to the 2F and 3F positions.

Following the fieldwork, welding speed distributions for morning and afternoon observations were obtained. The distribution details, descriptives, and created simulation model are presented in Annex 4, while Table 2 below summarises the welding speed distributions and their corresponding square errors. The model reflects the production of blocks introduced in the methodology. The distribution provided in the table shows the welding speed in cm per minute.

To reflect a simple but realistic block production process, the authors considered the aforementioned steps and modelled a practical block production exercise. According to the model, first a total of 500 single parts enter the preproduction (W1) step, then 25 paired preproduction parts are welded together to form a panel (W2), and in the final step, 10 panels are welded together to form a steel ship block. Therefore, in the

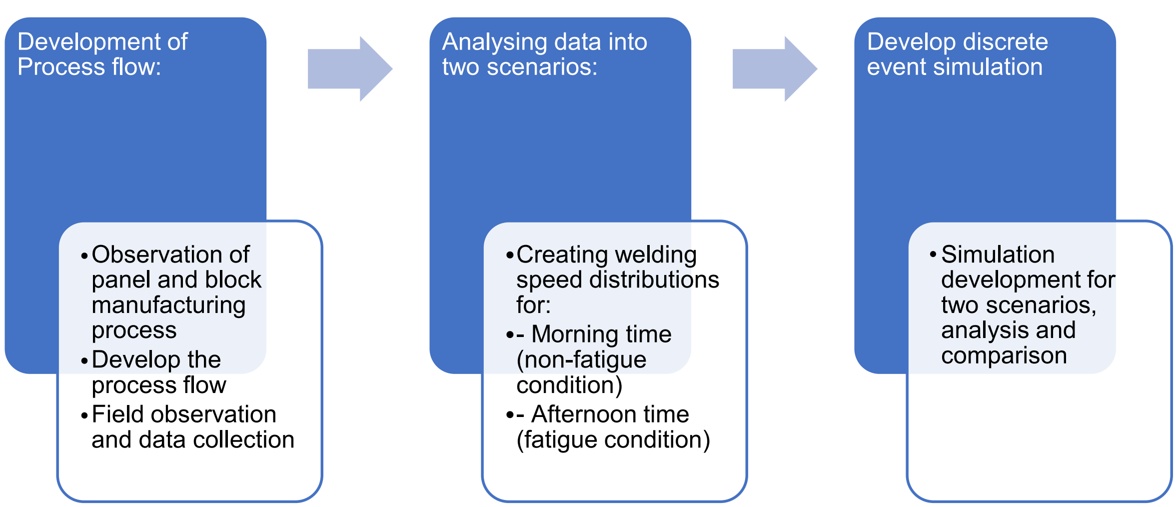

Fig. 2. Comparative analysis through Discrete Event Simulation.

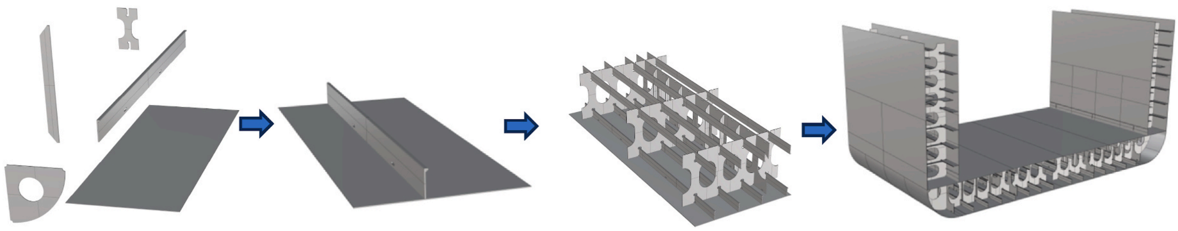

Fig. 3. Shipbuilding preproduction, panel production and block production stages.

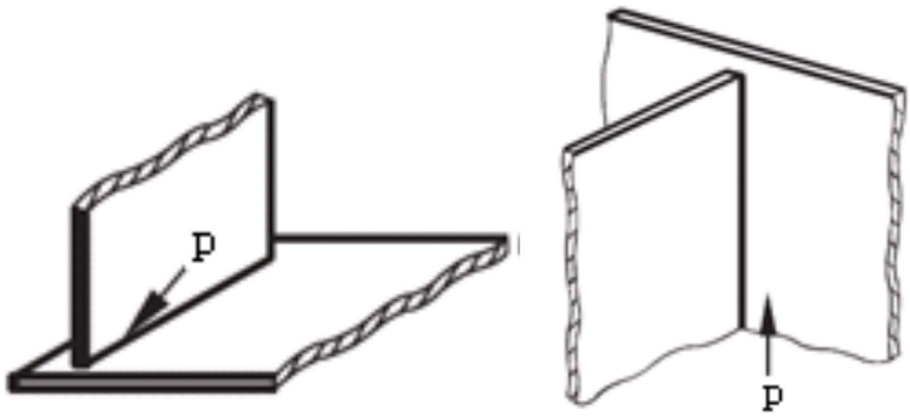

Fig. 4. 2F (PB) horizontal vertical and 3F (PF)vertical up welding positions (IACS, 2023).

Table 2
Scenarios to assess the effect of fatigue.

Scenario	Explanation	Distribution	Square error
1	Non-fatigue condition (Morning)	TRIA (20, 38, 56)	0.042933
2	Fatigue condition (Afternoon)	NORM (33.2, 9.61)	0.012198

model, W1 task is repeated 250 times, W2 task is repeated 10 times and W3 task is done once. The average welding lengths for a single repetition of each step are assumed to be 750 cm, 7500 cm, and 50000 cm for W1, W2, and W3, respectively.

Following that, the simulation model was run for 100 repetitions in the ARENA software to achieve production times for each scenario. Fig. 5 (a) demonstrates the average welding time per entity in minutes, and Fig. 5 (b) shows the total processing time to finalise the block production.

Welders affected by short-term fatigue require much longer working hours to produce the same output, as illustrated in Fig. 5. According to the simulation outputs, when welders suffer from daily fatigue, it results in a 22.9% productivity loss. Taking this performance difference into consideration in the business planning process may help shipyards make a more accurate man-hour calculation. In addition, considering that this difference will widen potential overtime shifts, this study will pave the way for future workforce optimisation studies in shipyard welding operations.

4.3. *Investigation of long-term fatigue*

For the long-term fatigue part of the research, this manuscript has focused on two different aspects.

- OFER Scale application,
- Identification of body parts affected by the repetitive nature of the welding job.

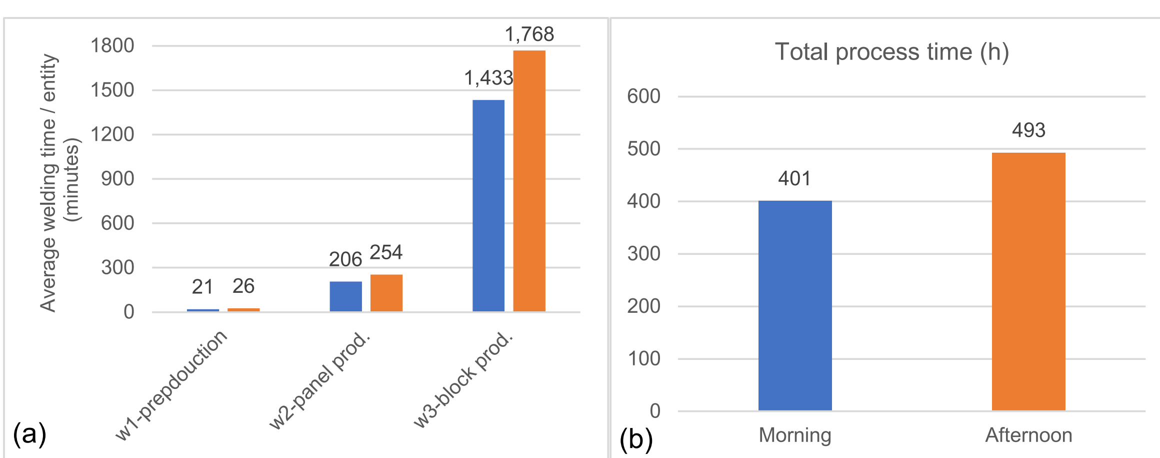

Fig. 5. Scenario 1 Vs scenario 2.

This section will investigate the relationships between workers' age, welding experience, and long-term fatigue. General information on ergonomics and long-term fatigue has been shared with the workers before they are invited to participate in the field OFER scale and ergonomics questionnaires. Chronic fatigue in the OFER scale is concerned with the exhaustion of a worker due to work-related effects. Self-reported uncertainty and despair in one's ability to maintain present work habits; decreased interest or participation, paired with physical manifestations of continuous tiredness, can be signs of chronic fatigue (Winwood et al., 2005). However, the inter-shift recovery aspect focuses on the recovery process between two shifts. It aims to reveal how well a worker can refresh before the next shift starts.

4.3.1. OFER scale application

Based on the literature review (Winwood et al., 2005), several questions were adopted to measure work-related fatigue and recovery. These questions focused on chronic fatigue (questions 1–5) and inter-shift recovery (questions 6–10) caused by the welding process. The list of questions can be seen in Annex 1. A seven-point Likert scale (i.e., 0–6) is used per the originally intended scale. And the participants' individual responses to those questions, along with their age, experience, and education level details are presented in Annex 3.

In the analysis, first the participants are divided into two age groups; younger and older welding workers -as shown in Table 3- and analysed accordingly. The chronic fatigue and inter-shift recovery results are given in Table 4.

Results in Table 4 show that older age is associated with high fatigue levels for welding workers in the shipbuilding industry, as half of the participants from the older group stated that they had experienced *high* fatigue levels. On top of that, one of six declared medium-high level fatigue. This is valid for both fatigue aspects examined in this study: chronic and inter-shift recovery fatigues. Only one-third of the older group affirmed either *low* or *low-medium* fatigue levels in both sections. On the other hand, although the *high* fatigue percentage is low for the younger group, there is a significant effect, as two-thirds of them stated that they had experienced *medium-high* chronic fatigue levels.

Table 4 demonstrates a positive trend associated with age and inter-shift recovery difficulties. Only one from the younger group stated high inter-shift recovery fatigue, while half of the older welders did.

Then the participants are divided into years of experience groups, as shown in Table 5, and analysed accordingly; the chronic fatigue and inter-shift recovery results are shown in Table 6.

Similar to the age distribution analysis, the result found that years of experience affect chronic fatigue levels. The trends show that the higher years of experience cause high fatigue levels, as 50% of participants from the oldest group stated that they had experienced high fatigue levels, followed by two fifths of the middle group and one-fifth of the least experienced group. In contrast, negative trends have been found for low- and medium-high levels. Four participants from the least experienced group stated that they had experienced low-medium or medium-high fatigue levels, followed by three participants from the middle group and one from the group with the highest experience.

Furthermore, various results have been found for inter-shift recovery, as shown in Table 6. Three-fifths of participants with 2–5 years of experience stated that they had felt low to low-medium fatigue level. They are followed by the over-24-years of experience group (50%) and the 8–17 year-experience group (20%). In contrast, four-fifths of participants from the 8–17 years of experience group stated that they have suffered from medium-high or high recovery fatigue levels, followed by over 24 years of experience and 8–17 years, at one over two and two-fifths, respectively.

Table 3
Age groups for assessing the OFER scale.

Group	Participant number
25–35 years	6
35–45 years	6

Tables 4 and 6 clearly indicate the increasing levels of fatigue with work experience and age for welders in the shipbuilding industry. This needs to be highlighted, as fatigue significantly contributes to accidents (Dawson et al., 2018). Therefore, HSE experts in the shipyards should be aware of and mitigate fatigue-related hazards and risks through measures such as balancing shifts, personal protective equipment, and regular training.

4.3.2. Welding workload evaluation

The number of body parts which can be bothered caused by repetitive tasks are the neck, shoulder, waist, upper arm, back, forearm, wrist, hip, knee, ankle, eyes, and ears (HSE, 2019). Various welding positions are also identified, as seen in Annex 2. At the end of this stage, the questionnaire was developed to assess fatigue caused by the welding process based on the methodology of (Baek and Nam, 2021). The processes monitored in this study consist of a 2F (horizontal) position and 3F (vertical) manual gas welding, AWS standards for welding position naming have been followed (AWS, 2018).

Furthermore, the analysis will focus on each body part's discomfort priority number (DPN), calculated as **DPN = Frequency x Level of discomfort**. Twelve welders participated in this survey, and discomfort levels for the body parts scored between 0 and 3, which results in the maximum DPN for any body part being 36, as given in Annex 2. The results of this analysis per body part are illustrated in Fig. 6.

For the 2F position, the analysis indicates that knee, ankle, waist, and upper arm fatigue have a higher risk than the 3F position for the analysed case. On the other hand, shoulder, back, forearm, and neck fatigue in the 3F position has a higher risk compared to the 2F welding position. The study also revealed that the eyes, knee, neck, and waist are the most discomforted body parts for both welding positions. The authors further investigated the impact according to the age groupings to understand the effect.

For 2F and 3F positions, the results indicate that the older group (35–45) has experienced more fatigue than the younger groups (25–35), as shown in Fig. 7 for the 2F position and Fig. 8 for the 3F welding position. In both positions, the eyes are the most affected body part. The second one depends on the welding position. For 2F, the knees are the second most affected body part, followed by the neck, waist, and ankles. The results look coherent, considering the crouching and sideways movement required during horizontal welding. Then again, for the 3F position, the second most affected body part is the neck, followed by the knee, ankle, ears, and shoulders. According to the welders' response, ears are affected the same for horizontal and vertical welding operations, but shoulders are affected significantly more in 3F compared to 2F.

To dive into age group details, for 25–35 years old, in the 2F position, the eyes and neck are the body part with the highest discomfort priority numbers. Similarly, the eyes are the most critical body part for the 3F welding position. In both positions, the welders also mentioned their knees and waists are notably affected. In brief, for the younger age group, the affected body parts and corresponding DPNs are quite similar in the horizontal and vertical positions investigated in this study, as shown in Fig. 9.

On the other hand, the older age group has substantially different results for the investigated horizontal and vertical welding positions, as depicted in Fig. 10. Even though the eyes are the most affected body part in both positions, in 2F, knees have the same DPN with eyes, closely followed by the waist and ankles. However, for the vertical position, the body parts coming after the eyes in descending order are the neck, shoulder, and ears. The welders also mentioned that their back gets affected by the 3F role in the welding process.

When Figs. 9 and 10 are examined together, it is clearly evident that, except in only a few cases, with the increasing age of the welders, the number of different body parts and DPN scores for each individual body

Table 4
OFER Scale – Chronic fatigue and inter-shift recovery results by age.

	CHRONIC FATIGUE LEVEL				INTERSHIFT RECOVERY FATIGUE LEVEL			
Age Year Groups	Low	Low-medium	Medium-high	High	Low	Low-medium	Medium-high	High
25–35 years	0	1	4	1	1	2	2	1
35–45 years	0	2	1	3	1	1	1	3
All participants	0	3	5	4	2	3	3	4

Table 5
Experience groups for assessing the OFER scale.

Group	Participant number
2–5 years	5
8–17 years	5
More than 24 years	2

part are rising.

For 2F, the DPN score of waist and ankles were moderate in the younger age group, but they grew substantially and made into the top three in the older age group. This means that waist and ankle-oriented disorders are potential results of working in horizontal welding positions for a long time. These body parts, along with high-rated other parts (i.e., eyes, knees), should be covered and protected by sufficient personal protective equipment (PPE) use. Surprisingly, the older age group have not rated the neck as a highly affected body part as the younger age group. This might be related to the higher expertise levels of older welders, as they might be paying more attention to their head position while welding horizontally.

For the vertical position 3F, the DPN scores of shoulders, ears and back have raised considerably when comparing the younger and older age groups. This might indicate that these body parts are potential long-term disorder locations for workers carrying out vertical welding. Therefore, appropriate measures should be taken, on top of always high DPN-scored body parts such as eyes and neck, using proper PPE all the working time.

5. Discussion and conclusion

This manuscript investigated shipyard welding activities to address an important knowledge gap in the industry: the effect of short-term fatigue, which occurs during a workday, and long-term fatigue amongst the workers who carry out manual gas welding operations in the shipbuilding industry.

The main contribution of this study was the investigation of fatigue impact on OHS and productivity for selected shipbuilding tasks. The human performance integration into a DES approach to estimate productivity was also achieved. This study also conducted a comprehensive data collection campaign in the shipyard through observation and questionnaires.

The approach was applied to two case studies to show the effect of fatigue in manual gas welding operations. As part of this study, hypothesis tests are first defined to examine short-term fatigue's effects. Then, statistical analyses are constructed according to the data gathered from the field, showing that daily fatigue significantly impacts the welders' performance. Therefore, the fatigued and rested scenarios were simulated separately using Rockwell Arena DES software to investigate this further. The simulation demonstrated that efficiency loss from short-term daily fatigue is around 22,9% compared to the rested condition. This can be utilised further as a coefficient of performance in the DES analysis when studying shipyard efficiency, which is a valuable contribution to the literature on shipyard productivity.

Long-term fatigue was also inspected as part of this study. Two separate questionnaires were employed; the OFER scale adapted from the literature and the welding workload on body parts questionnaire were designed for two different welding positions. The OFER scale covered the welders' chronic fatigue and inter-shift (between work periods) recovery difficulties. In contrast, the ergonomics questionnaire covered the body parts (such as the neck, upper arm, eyes etc.) affirmed to be affected due to working as a welder in the industry. The result shows that two different welding positions affect different body parts. For the 2F position, we observed that knee, ankle, waist, and upper arm fatigue have a higher risk than in the 3F place. On the other hand, shoulder, back, forearm, and neck fatigue in the 3F position has a higher risk than in the 2F. The age of welders was an important parameter; the older age group (35–45 years old) experienced more body part discomfort than the younger group.

Last, it can be concluded from the OFER scale result that age and years of experience influenced the chronic fatigue level and inter-shift recovery difficulties. Older age and higher experience (we assume it is also related to age) cause high fatigue. There is also a positive trend associated with age and inter-shift recovery difficulties. Last, we have found that the medium level of years' experience (8–17 years) is the most affected group to recover from inter-shift fatigue.

This study demonstrates that short and long-term fatigue significantly impacts productivity, occupational health, and safety. Shipyard

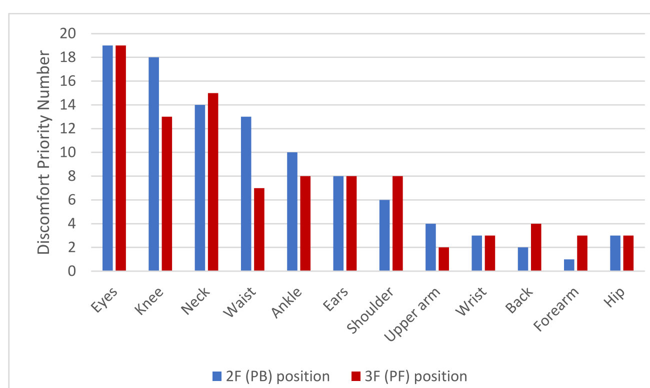

Fig. 6. Discomfort Priority Number for different body parts in 2F & 3F welding positions.

Table 6
OFER Scale – Chronic and Inter-shift recovery fatigue results by years of experience.

	CHRONIC FATIGUE LEVEL				INTERSHIFT RECOVERY FATIGUE LEVEL			
Experience Year Groups	Low	Low-medium	Medium-high	High	Low	Low-medium	Medium-high	High
2–5 years	0	1	3	1	1	2	1	1
8–17 years	0	1	2	2	0	1	2	2
More than 24 years	0	1	0	1	1	0	0	1
Grand Total	0	3	5	4	2	3	3	4

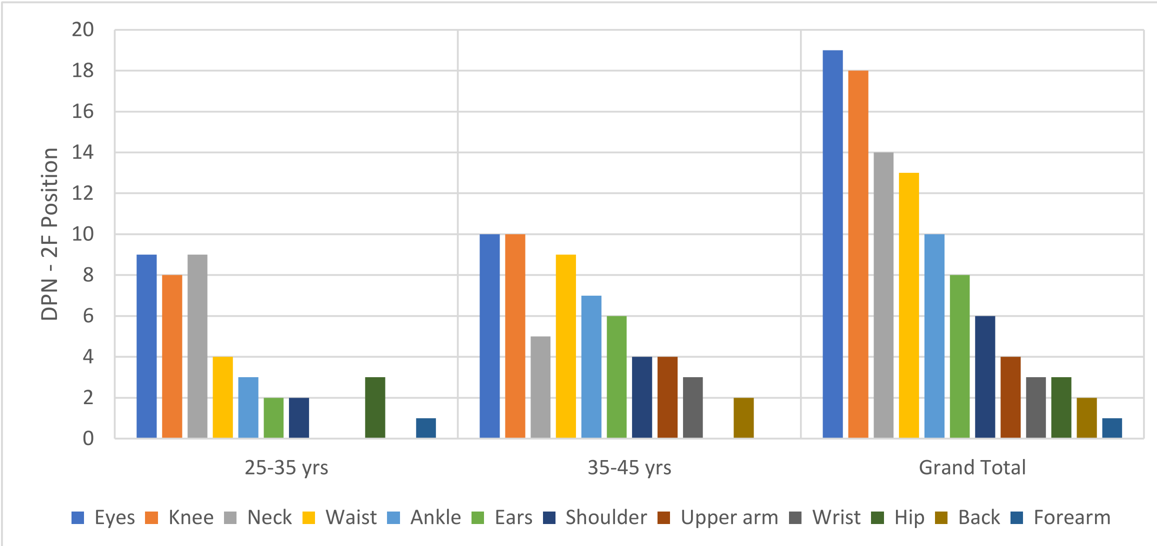

Fig. 7. DPN for Body Parts based on age groups for 2F position.

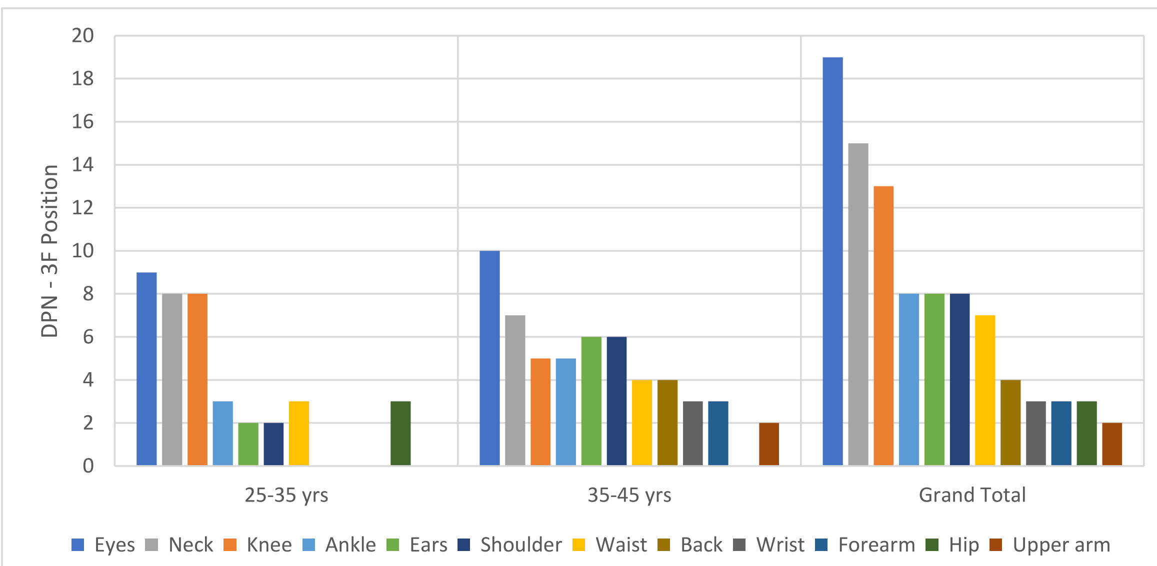

Fig. 8. DPN for Body Parts based on age groups for 3F position.

management teams should consider the results of these studies to improve their capacity and resource planning, including shift management and night shifts (mostly applies ship repair) and overtime. This study also provides valuable insight to HSE professionals regarding the effects of fatigue on the human body for welding operations in shipyards. This can lead to further investigations into measures for mitigation in the shipyards.

There are several limitations to be improved for future research. First, the sample size of welders was limited as welders with similar work tasks were allocated for them during the shipbuilding process. It should be noted that the welders were doing their daily tasks, and none of these tasks was determined or asked by the researchers. The second limitation can be considered as the subjectivity of the questionnaire, which can be addressed through a future study by utilising sensors to measure physical activity and fatigue (e.g. Li et al. (2019); Escobar-Linero et al. (2022); Ibrahim et al. (2023)).

Future studies may include applications to ship repair and ship recycling yards for some tasks (e.g., torch cutting), since the activities are similar. On the other hand, further activities can be included in these types of yards to investigate the impacts. Moreover, the geometry's complexity can be further investigated through the observation of complex block production. Furthermore, the correlation between short term and long term fatigue can be investigated with a larger participant group over longer periods of time. Also, the effect of environmental conditions such as humidity, temperature, and so on can be determined through further controlled experiments. Finally, a resource planning study should be conducted to balance the workload of the welders and identify the optimum scheduling of the workforce in the shipyards.

CRediT authorship contribution statement

D. Okumus: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **S. Fariya:** Visualization, Writing – original draft. **S. Tamer:** Conceptualization, Investigation. **S.A. Gunbeyaz:** Supervision, Funding acquisition, Writing – original draft, Writing – review & editing. **G.**

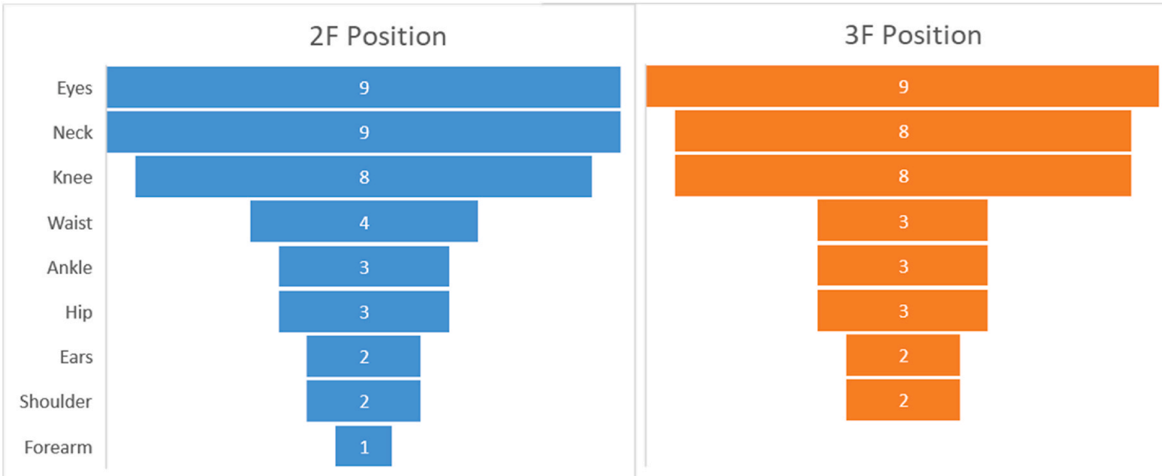

Fig. 9. Comparison of the affected body parts for the 25–35 years old group.

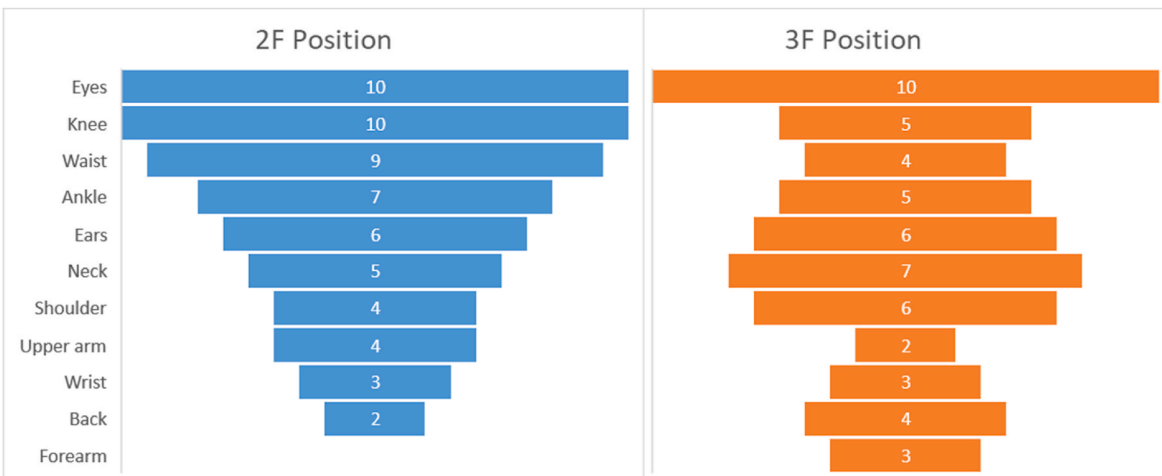

Fig. 10. Comparison of the affected body parts for the 35–45 years old group.

Yildiz: Investigation, Formal analysis. **R.E. Kurt:** Project administration, Data curation. **B. Barlas:** Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.oceaneng.2023.115296.

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