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RISK ASSESSMENT IN SHIP HULL STRUCTURE PRODUCTION USING FMEA

Murat Ozkok

Key words: shipyard, shipbuilding, hull structure, FMEA, risk analysis.

ABSTRACT

In the competitive environment, shipyards attempt to reduce failures in their production system in order to maintain their competitive power. Failures cause some damages such as injuries and deaths to the shipyard. Most of the damage causes work loss in the shipyard. To mitigate this damage, the most risky activities and work stations must be identified. For this, the risk levels of the failures must be calculated by applying the Failure Mode and Effects Analysis Method. In this study, the hull structure production process of a shipyard was considered. After collecting the failure statistical data of a shipyard, the failures were categorized and the probability and severity of the failures were determined. A comprehensive process analysis of the work stations was then performed, and the durations of the work activities were determined. Finally, risk priority numbers were calculated, and the most risky activities and work stations were identified.

I. INTRODUCTION

In the current global competitive environment, shipyards must examine their production processes in order to reduce failures. Failures cause injury, death, and work loss, which means money loss. Therefore, shipyards must recognize and reduce risks in their production system. To accomplish this procedure, comprehensive process analysis of the current situation must be performed and the reasons for the failures must be identified.

Numerous failures may occur in the production line of shipyards. The greatest risks in ship production are those categorized as conventional risks, namely risks connected to machine equipment, scaffolding, electricity use, and lifting of pieces and assembling groups. Other failures such as being crushed between objects, injured while lifting or carrying material, slipping, falling, bumping into stationary objects or moving objects, stepping on objects, being crushed under falling objects, touching hot surfaces, being electrocuted, fire breakouts, and explosions and burning, can occur.

A shipyard production system comprises numerous work stations that are involved in the hull structure production process. Several failures may occur at these stations. This study identified the work stations and activities that are most liable to failures. To achieve this aim, a shipyard in Turkey (located in the Tuzla Region of Istanbul) was used as an example for determining the most risky work stations and activities for hull ship production in this shipyard. The statistical data of previous failures at this shipyard were collected. The failures were categorized and the probabilities and severities of the failures were assessed. A process analysis of the work stations were performed, and the durations of the activities were calculated. Subsequently, the risk priority numbers (RPNs) of the failures were calculated by multiplying the probability, severity, and duration values. Finally, the RPNs of the failures were compared and the most risky activities and work stations were identified. Because no such comprehensive risk assessment of the ship hull production process has been reported in the literature, this paper may provide insight into the failures that occur during shipbuilding for shipbuilders. The reason for using this shipyard as an illustrative example in this study is because it has prevailing product-flow-type-layouts and has documented the accidents orderly. In addition, this paper presents a modified calculation of the RPNs by using duration rate.

Failure Mode and Effects Analysis (FMEA) is a risk assessment method. FMEA is a widely used engineering technique for defining, identifying, and eliminating known and potential failures, problems, and errors from systems, designs, processes, and services before they reach the customer [11]. A traditional FMEA quantifies risks according to three categories: severity, occurrence, and detection [4]. Severity represents the effect of the failure if failure occurs, occurrence is the probability of the failure actually occurring, and detection is the process controls of the system for preventing failure. Each category is rated on a scale from 1 to 10. They all mean: RPN = severity $\times$ occurrence $\times$ detection [8]. A high RPN represents a high risk.

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Numerous risk assessment studies are reported in the literature. Risk assessments are conducted in several fields, such as machinery information systems and selection of suppliers. He and Gu [5] evaluated the failures that affect steam-induced vibration by using FMEA. Shirouyehzad *et al*. [10] examined the failure factors, which led to successfully implementing enterprise resource planning, by using FMEA methods. Radvanska [9] performed risk assessment of abrasive water jet cutting technology from the viewpoint of operational personnel by using an FMEA method and calculated the risk number by multiplying occurrence × severity instead of severity × occurrence × detection. Lee *et al*. [6] performed risk assessment of Korean shipyards on design change, design manpower, and raw material supply and calculated the risk number as degree of loss × probability of occurrence. Duffey and van Dorp [3] evaluated the risk of a shipyard regarding labor and overhead costs by using Monte Carlo simulation software. Yao *et al*. [13] categorized shipyard failures based on production cost, technology risk, and production period instead of human-based effects. Bakacak [1] investigated and evaluated the risk for scaffolding accidents and ship repair accidents. Buksa *et al*. [2] attempted to improve shipyard pipeline processes, quantified RPNs by using FMEA, and recommended corrective actions for reducing RPNs.

II. SHIP HULL STRUCTURE PRODUCTION PROCESS

Ship production is an extremely complex job comprising numerous processes. A ship is manufactured by executing thousands of work activities and requires various types of work station. Each work station has a specific task for ship production. Table 1 shows the work stations and their specific function in hull structure production.

Table 1. The work stations in hull structure production.

Station no	Station name
I1	Edge cutting
I2	Edge cleaning and sequencing
I3	Panel production
I4	Panel cutting
I5	Stiffener mounting
I6	Stiffener welding
I7	Web mounting
I8	Web welding
I9	Grinding
I10	Profile piece part preparation
I11	Profile bending
I12	Plate piece part preparation
I13	Minor and sub assembly fabrication
I14	Jig
I15	Plate bending (Press)
I16	Unit assembly

The edge-cutting station (I1), for example, is used for the edge-cutting operation of ship hull plates, which constitute the panel structure. The edge-cut plates are transferred to the edge-cleaning and sequencing station (I2).

Some materials and slags may occur on the edge surfaces of the plates after edge cutting. By using a grinding machine, these materials and slags are removed from the edge surfaces of the plates. At Station I2, the plates are sequenced in accordance with the subsequent process. The plates are then sent to the panel production station (I3) where the hull plates are welded and the panel structure is produced.

At Station I4, the structured panel is subject to counter cutting according to its dimensions. After the panel is cut at Station I4, it proceeds to Station I5. The profiles are assembled on the panel by performing spot welding at Station I5. The profiles are then welded using tig welding at the stiffener welding station (I6). Minor and subassemblies are joined on the flat panel assembly by using spot welding at the web-mounting station (I7). The minor and subassemblies are welded onto the flat panel assembly by using tig welding at the web-welding station (I8).

The grinding station (I9) is the final station of the panel line. At this station, the grinding operations of the flat panel and major subassemblies are executed. The cutting operations of the profiles are performed at the profile piece part preparation station (I10) by using a plasma cutting machine. Standard-dimensioned profiles, which are sent to Station I10, are cut, and specific dimensioned profiles are fabricated. The bending operations of the profiles are performed using a frame bender machine at the profile bending station (I11). The bending profiles are mounted on curved panel structures. The plate piece part preparation station (I12) is the heart of the shipyard production system. At this station, the plates are subject to nest-cutting operation by using a nest-cutting plasma machine, and single plate piece parts are manufactured. Minor and subassemblies belonging to production stages C and D are fabricated at the minor and subassembly fabrication station (I13). Curved panel assemblies are produced at the jig station (I14). A jig structure consists of pin jigs that can be adjusted according to the slope surface of the curved panel. The curved panels are placed on the jig structure, and the curved profiles are welded onto the curved plates. At the plate bending station (I15), the bending operations of the plates, sent from the plate piece part preparation station (I12), are performed.

Thus, the flat plates are transformed to curved plates. The structures and parts produced at the previous work stations are sent to the unit assembly station (I16), and a block structure is formed by assembling the corresponding parts.

As mentioned, some work stations in ship production are combined to fabricate the hull structure of the ship. Each of these work stations are connected to one another. The material flows occur between the stations mentioned in Table 1. After the material is processed at a work station, the material is moved to another work station to be reprocessed. Thus, a flow

Table 2. Flow relations between the stations.

From	To
I1	I2
I2	I3
I3	I4
I4	I5
I5	I6
I6	I7
I7	I8
I8	I9
I9	I16
I10	I5, I11, I13, I16
I11	I14
I12	I7, I13, I14, I15, I16
I13	I7, I14
I14	I16
I15	I14, I16

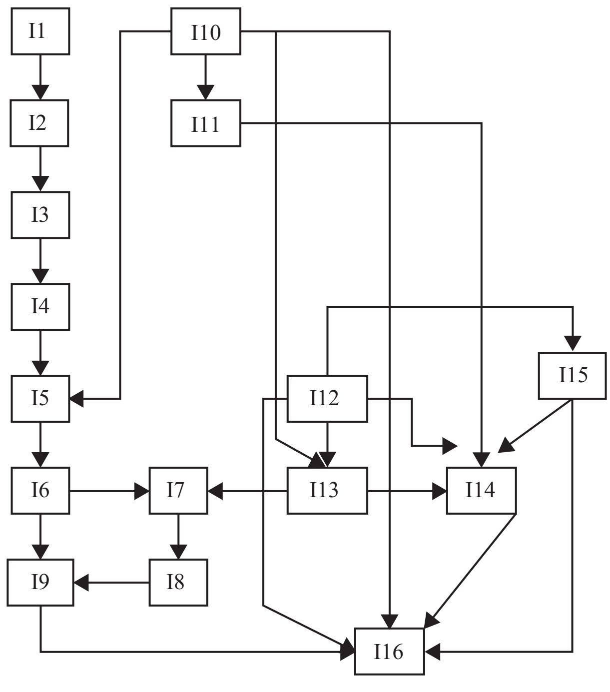

Fig. 1. Work flow in the shipyard production system.

relationship between all of the work stations occurs. Table 2 and Fig. 1 show the material relationships between the work stations.

Ship production is categorized in production stages, namely A, B, C, D, E, F, G, H, J and K. These categorizations enable production processes to be controlled easily. Production stages A and B represent the single section part and single plate part, respectively, as shown in Figs. 2 and 3. Both single section and single plate parts have specific dimensions and are fabricated when the standard-dimensioned profile and plate are cut at Stations I10 and I12.

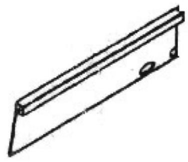

Fig. 2. Single section part (A).

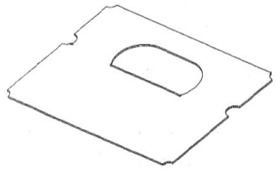

Fig. 3. Single plate part (B).

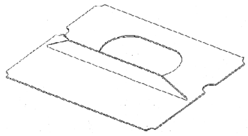

Fig. 4. Minor assembly (C).

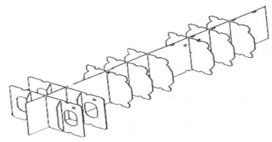

Fig. 5. Sub assembly (D).

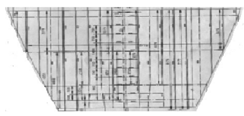

Fig. 6. Flat plate assembly (E).

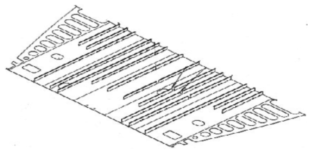

Fig. 7. Flat panel assembly (F).

As one single section part and one single plate part are assembled together, minor assembly (production stage C) is manufactured (Fig. 4). If two or more minor assemblies are fitted together, subassembly (production stage D) is constructed (Fig. 5). Both production stages are performed at Station I13.

The flat plates constitute the structures of the flat panel. When two or more flat plates are fitted, flat plate assembly (production stage E) is fabricated. If single section parts (production stage A) are fitted on the panel, the panel with profiles is created, which is called flat plane assembly (production stage F). As flat plate assembly (E) is performed at Station I3, flat panel assembly (F) is executed at Station I5. Figs. 6 and 7 show production stages E and F, respectively.

As minor and subassemblies (C and D production stages) are fitted on the flat panel assembly (F), major subassembly (production stage G) is manufactured. The major subassembly is fabricated at Station I7. Fig. 8 shows production stage G. The curved plate assembly structure (production stage H) is produced at Station I14 and consists of a curved panel, minor assemblies, and profiles, as shown in Fig. 9.

When the major subassembly leaves the panel line, it is moved to the block assembly area by using a crane. If the top of the major subassembly is covered by a panel, it is named a subunit assembly (production stage J). When the subunit assembly is upside down and the curved plate assembly (production stage H) is assembled on it, it is called a unit assembly. Both subunit assembly (J) and unit assembly (K) stages are performed at Station I16. Figs. 10 and 11 illustrate production stages J and K.

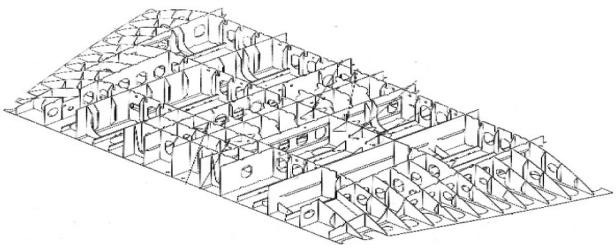

Fig. 8. Major sub assembly (G).

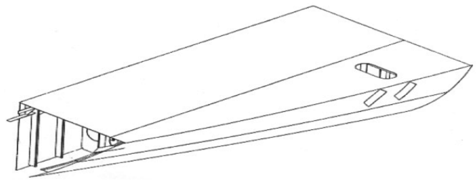

Fig. 9. Curved plane assembly (H).

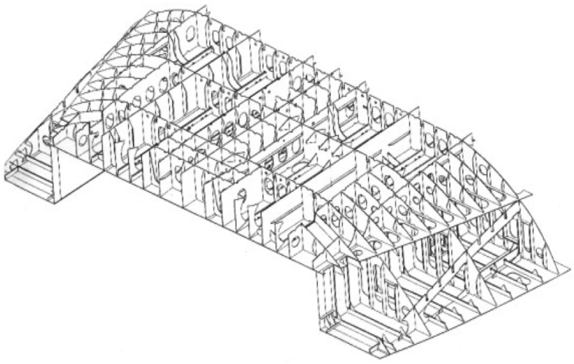

Fig. 10. Sub unit assembly (J).

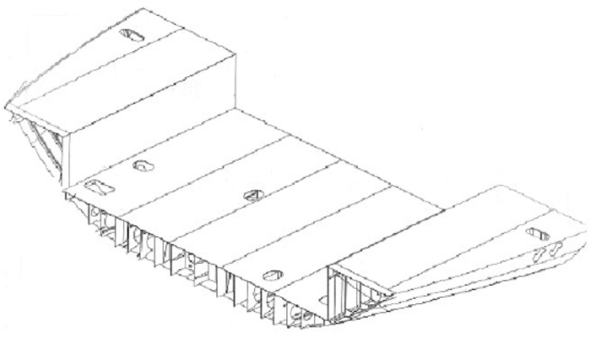

Fig. 11. Unit assembly (K).

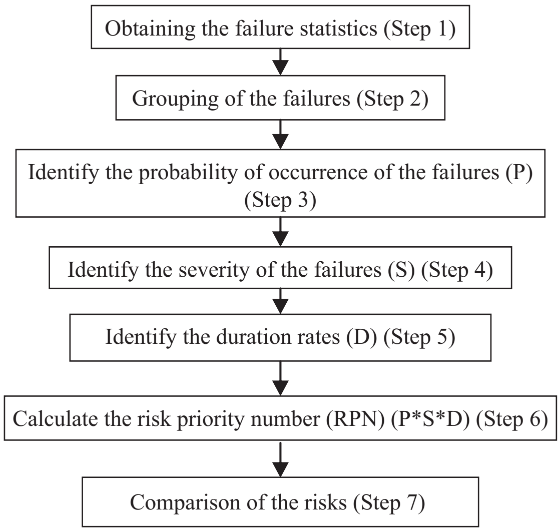

Fig. 12. The phases of the methodology.

III. METHODOLOGY

As described in Section I, FMEA quantifies the risks of the failures by means of RPNs. The RPN in traditional FMEA is calculated by multiplying severity (S) × occurrence (O) × detection (D). According to McCain [7], the FMEA process can be modified to satisfy some applications. Welborn [12] modified traditional FMEA and calculated the RPN by multiplying S × O × Frequency (F). Frequency represents a rating of how often the activity is performed. In this study, RPN is calculated as S × O × Duration (D). Duration represents the length of time of the activity. Because the duration of the activity plays a crucial role in determining the risk level, duration is used in RPN calculation. A long duration of the activity indicates a high risk of the activity. For instance, in a welding area, two men weld. The first man welds alone for 2 hours, and the second man welds alone for 4 hours. In this situation, the second man has a higher risk than the first man in this welding activity.

Fig. 12 presents the phases of the methodology of this study. The first phase is to achieve the failure statistics. In this phase, the previous failures of the shipyard were achieved. Risk assessment is effectively performed if more statistical data are available. After the previous failure statistics were collected, the failures were classified. The probabilities of the failures were then evaluated using the statistical data. Subsequently, the severities of the failures were determined. In the fifth step, the durations of the work activities were determined using process analysis of the work stations. In the sixth step, the RPNs were calculated. In Step 7, the calculated risk values of the work stations and activities were compared.

IV. CASE STUDY

1. Obtaining the Failure Statistics (Step 1)

A total of 181 failures, which occurred during 2009 and 2011, were investigated in the study. These failures were acquired from a shipyard in Turkey (located in the Tuzla Region of Istanbul). The shipyard has a capacity of consuming 20,000 tonnes of steel per year.

2. Grouping the Failures (Step 2)

The 181 failures were classified into eight categories:

Table 3. Failures due to grinding activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Burr penetration to eye while grinding materials	44	25
2	Injured while removing the grinding machine getting caught without shutting down	2	18
3	The worker wanted to help his co-worker but the grinding machine bumped his lip	1	0
4	Grinding stone broken and injured the worker's leg	1	5
TOTAL		48	48

Table 4. Failures due to welding activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Electric shock while the position of welding machine was changing, due to a broken earth cable	1	2
2	Burr penetration to eye while removing the welding slag	7	3
3	Be influenced with the welding emissions	2	2
4	Bumping the head while welding	1	6
TOTAL		11	13

Table 5. Failures due to cutting activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	While removing the scrap from the plate, wounded by cutting as result of bumping the foot against the plate	1	15
2	Crushing the finger between pipe and machine	1	20
3	Injuring the hand during the pipe cutting	1	5
4	Getting caught of the finger while cutting corner piece	1	7
TOTAL		4	47

grinding, welding, cutting, mounting, crane movement, worker's material handling, worker's movement, and worker's falling (Tables 3-10). Some slags and burr appeared after the cutting and welding activities. A grinding process was performed to remove the slags and burr from the plates and sections. During the grinding process, pieces of burr or slag might penetrate the eyes if appropriate protection is not used. Furthermore, grinding stone might cut a worker's hand when working. There are 48 failures associated with grinding. These failures caused the loss of 48 work days in 36 months (Table 3).

Welding is performed to fix materials permanently to each other and is a considerably crucial part of shipbuilding. Failures caused by welding included impression from the welding gas penetration of slags into the eyes and electric shock. Eleven failures associated with welding were recorded and caused a total loss of 13 work days in 36 months (Table 4).

In a shipyard, edge-cutting, nest-cutting, and profile-cutting activities are performed for fabricating single parts. When workers execute these activities, some injuries and damage may occur at any moment. Four failures associated with cutting activity were recorded and caused a total loss of 47 work days in 36 months (Table 5). During mounting of the parts, 34 failures occurred. Hand crushing-injuries and burr penetration frequently occurred and caused a loss of 250 work days in 36 months (Table 6).

Heavy materials are transported using cranes in shipyards. When cranes are used, some failures, such as dropping material or bumping into someone, may occur. Eighteen failures associated with crane movement occurred and caused a loss of 135 work days in 36 months (Table 7).

In the shipyard production system, light and heavy materials are used. In most situations, workers carry the light materials without using a crane. When the worker is carrying the materials, the materials may fall and the hands or ankles of the worker may be injured. Furthermore, the worker's back might be damaged by carrying the material. Nineteen failures caused by the material handling of workers occurred and caused a loss of 47 work days in 36 months (Table 8).

Work power is a substantial resource for a shipyard. During the production process, the workers often move at the job site, and consequently, some failures occur. For instance, when walking, a worker may hit his foot against the corner of materials on the floor, sprain his ankles, or fall. Twenty-five failures resulting from worker's movement occurred and caused a total loss of 150 work days in 36 months (Table 9).

Table 6. Failures due to mounting activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Hand caught while assembling	3	50
2	Injured by hitting hand with hammer	3	2
3	Wound by cutting while assembling	1	20
4	Material dropped on the worker's hand while trying to take the material	2	70
5	Breaking finger while assembling	1	30
6	Pipe bumped into hand while pipe dismantling	1	2
7	Pipe dropped to the finger during pipe assembly	2	13
8	Finger gotten caught during HVAC assembly	1	1
9	Finger gotten caught during pipe assembly	1	7
10	Finger gotten caught during pipe dismantling	1	15
11	Finger gotten caught between pipes	2	5
12	While screwing the bolt, wrench hit eyebrow	1	7
13	Eye penetrated by slag during assembling	1	0
14	Eye bumped by finger while screwing the bolt	1	2
15	Arm injured during cable assembly	1	9
16	Back injured while screwing the bolt	1	0
17	Burr penetration to eye during pipe assembly	6	2
18	Finger gotten caught while assembling	2	9
19	Hand gotten caught during pipe assembly	1	5
20	Head pumped by pipe during pipe assembly	1	0
21	Injured by hitting foot with hammer	1	1
TOTAL		34	250

Table 7. Failures due to crane's movement.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Material dropped while lifting by crane	5	57
2	Material slipped from crane and it bumped into the worker's shoulder	2	8
3	Finger gotten caught between crane platform and crane box	1	0
4	Pipe slipped and injured the worker while pipe storage	1	10
5	Plate bumped into worker's back while transporting	2	14
6	Pipe slipped and crushed the finger while pipe storage	1	0
7	Plate bumped into the worker's back while lifting by crane	2	6
8	Pipe slipped and cut the finger while storage of pipe	1	9
9	Finger gotten caught into the crane lock while binding the material to crane	1	0
10	Ladders slipped while transporting and broke worker's finger	1	29
11	Plate bumped into worker's hand while transporting by crane	1	2
TOTAL		18	135

The blocks of ships are remarkably large structures, and thus, scaffolds and ladders are required to paint hull structures. During this activity, the worker might fall or slip from scaffolds or ladders when ascending or descending. Twenty-two failures associated with falling occurred and caused a loss of 68 work days in 36 months (Table 10).

As shown in the aforementioned tables, the failures that occurred in the shipyard in 36 months (between 2009 and 2011) were categorized as grinding, welding, cutting, mounting, crane movement, worker's material handling, worker's movement, and worker's falling. A total of 181 failures occurred in the shipyard and caused a loss of 758 work days (Table 11).

3. Identify the Probability of the Failures (Step 3)

In this section, the probabilities of the occurrence of the failures were identified and ranked from 1 to 10; 10 represents the highest probability. The ratings were determined based on the number of failures that occurred per month.

Table 12 presents the ranks of the probability. For example, if any failure occurred between 0 and 0.1 times per month, the ranking of the probability would be regarded as 1. Similarly,

Table 8. Failures due to worker's material handling.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Material dropped onto the worker's hand while carrying it and crushing happened.	1	1
2	Material dropped onto the worker's shoulder	1	2
3	Pain from back happened during material transportation	1	2
4	Wounded by cutting from hand during offloading the scrap into the box	1	10
5	Worker slipped and injured during machine set-up	1	1
6	Material dropped onto the worker's ankle while carrying	1	2
7	Material dropped onto the worker's foot while carrying	3	4
8	Worker in the same place dropped the material onto his co-worker's foot	1	1
9	Worker in the same place dropped the material onto his co-worker's back	1	2
10	While emptying the scrap box, the material splattered and hit worker's eye-brow	1	1
11	Falling down while barrel stacking	1	0
12	Wrenching wrist while driving handcart	1	7
13	Hitting the foot to piece corner while carrying the material	1	3
14	Injured the wrist while carrying material	1	3
15	Injured the back while carrying material	2	3
16	Wounded by cutting the hand during scaffold dismantling	1	5
TOTAL		19	47

Table 9. Failures due to worker's movement.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Worker dropped the foot into opening	4	13
2	Worker slipped and fell down	7	76
3	Worker fell down since he put his foot on material on ground	5	37
4	Worker hit his head during break time	1	0
5	Worker wrenched his ankle and injured.	2	4
6	Worker hit his fibula to profile during working	1	0
7	Worker hit his head during tea break	1	0
8	Worker hit his foot to corner piece	1	2
9	Due to giddiness, the worker was injured since he hit his fibula to profile	1	5
10	Worker hit his fingers to corner piece and he was wounded by cutting.	1	10
11	Worker hit his shoulder to ladder and injured	1	3
TOTAL		25	150

Table 10. Failures due to worker's falling off.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Worker slipped and fell off from block	8	28
2	Worker fell off since the scaffold is not fixed sufficiently	3	4
3	Falling to bilge	1	2
4	Worker fell off due to insufficient lightening	3	3
5	While climbing ladder, the worker slipped and fell down.	2	1
6	Worker's foot was injured while going down from ladder	1	7
7	Worker wrenched his ankle while climbing ladder	1	0
8	Worker fell on bicycle from scaffold and wounded	1	9
9	Ladder slipped and the worker fell off	2	14
TOTAL		22	68

Table 11. The reason of the failure.

The reason of the failure	Number of failures	Workday loss (days)
Grinding	48	48
Welding	11	13
Cutting	4	47
Mounting	34	250
Crane movement	18	135
Worker material handling	19	47
Worker's movement	25	150
Worker falling off	22	68
TOTAL	181	758

Table 12. Ranking of the probability.

Number of occurrence (number/month)	Rank
0 – 0.1	1
0.2 – 0.3	2
0.4 – 0.5	3
0.6 – 0.7	4
0.8 – 0.9	5
1.0 – 1.1	6
1.2 – 1.3	7
1.4 – 1.5	8
1.6 – 1.7	9
1.7-	10

Table 13. Number of failures per month.

The reason of the failure	Number of failures	Time (month)	Number of failures per month
Grinding	48	36	1.3
Welding	11	36	0.3
Cutting	4	36	0.1
Mounting	34	36	0.9
Crane movement	18	36	0.5
Worker material handling	19	36	0.5
Worker's movement	25	36	0.7
Worker falling off	22	36	0.6

if any failure occurred between 1 and 1.1 times per month, the ranking of the probability would be regarded as 6. To calculate how often the failure occurred per month necessitated determining the number of failures that occurred. After the number of failures were obtained, determining how long these failures have been occurring was required.

Table 13 shows the number of failures per month. A total of 48 failures caused by grinding occurred in 36 months. Therefore, 1.3 failures associated with grinding occurred per month (48 failures/36 months).

Similarly, the number of failures associated with mounting per month was calculated as 0.9 (34 failures/36 months).

Table 14. The probability of the failures.

The reason of the failure	Probability (P)
Grinding	7
Welding	2
Cutting	1
Mounting	5
Crane movement	3
Worker material handling	3
Worker's movement	4
Worker falling off	4

Table 15. Ranking of the severity.

Average severity (severity/failure) (day)	Rank
0-1	1
1-2	2
2-3	3
3-4	4
4-5	5
5-6	6
6-7	7
7-8	8
8-9	9
9-	10

Table 16. The average severity of the failures.

The reason of the failure	Number of failures	Workday loss (days)	Average Severity (Severity/Failure)
Grinding	48	48	1.0
Welding	11	13	1.2
Cutting	4	47	11.8
Mounting	34	250	7.4
Crane movement	18	135	7.5
Worker material handling	19	47	2.5
Worker's movement	25	150	6.0
Worker falling off	22	68	3.1

Table 17. The severity of the failures.

The reason of the failure	Severity (S)
Grinding	1
Welding	2
Cutting	10
Mounting	8
Crane movement	8
Worker material handling	3
Worker's movement	6
Worker falling off	4

Table 18. The process analysis of stiffener mounting station (I5).

Activity no	Activity description	Number of activity	Activity duration (min.)
1	Operator walks to the crane	2	0.146
2	Crane goes to profile stock area	36	8.178
3	Operator assistants go to profile stock area	36	3.493
4	Crane comes down the profile	38	18.051
5	Crane holds the profile	38	15.2
6	Crane lifts the profile	38	18.037
7	Crane transports the profile from profile stock area to the porter system	38	8.473
8	Workers walks to the porter system	38	3.609
9	Crane takes down the profile on the porter system	38	12.274
10	Crane leaves the profile surface	38	4.428
11	Workers settle the profile on the porter system	38	3.8
12	Operator walks to the porter system	2	0.118
13	Workers walks to the profile welding area	2	0.404
14	Operator drives the porter system to the welding area	2	2.926
15	Operator walks to profile spot welding machine	2	0.042
16	Operator cleans the welding torch	2	1.5
17	Profile spot welding machine goes to the porter system	37	44.755
18	Profile spot welding machine comes down the profiles	38	3.8
19	Profile spot welding machine transport the profile from the porter system to the flat plate assembly	38	46.486
20	Profile spot welding machine takes down the profile on the flat plate assembly and alignment	38	111.394
21	Profile spot welding is prepared for welding operation.	38	6.328
22	Process of spot welding	38	63.82

The same calculations for the other failures were performed and the number of failures per month was obtained.

Finally, the occurrence probability of the failures were determined. For the grinding failures, the number of failures per month was 1.3. As shown in Table 12, the ranking of the grinding failures was 7. In other words, the probability of occurrence of the grinding failures was 7. Table 14 presents the probability of the failure.

4. Identify the Severity of the Failures (Step 4)

In this step of this study, the severity rates were identified and ranked from 1 to 10. The most severe value is 10 (Table 15). In this study, the severity represents the degree of work loss and is positively related to work loss.

Table 16 shows the number of failures, total work loss of the failures, and average severity. For example, if the number of grinding failure is 48, then the total work loss would be 48, which means the average severity per failure is 1. In other words, if a grinding failure occurs, the average work loss would be 1 day. Regarding mounting failures, the number of the failures was 34, and the total work loss of assembly failures was 250 days. Thus, if an assembly failure occurred, the average work loss would be 7.4 days per failure.

Based on Tables 15 and 16, the severities of the failures were determined, as shown in Table 17. For example, grinding failure caused an average work loss of 1 day, as shown in Table 16. Table 15 indicates that the severity is between 0 and 1 day, and thus, its rate is 1. In other words, the severity of the grinding failure was 1. Mounting failure caused an average work loss of 7.4 days and its severity is between 7 and 8 days, as shown in Table 15. Thus, the severity rate of the mounting failure was 8.

5. Identify the Duration Rates (Step 5)

The durations of the work stations were determined and ranked from 1 to 10; 10 is the longest duration. Every work station was then examined, and the main activities were categorized according to grinding, welding, cutting, mounting, crane movement, worker's material handling, worker's movement, and worker's falling activities.

Process analysis was conducted for calculating the durations. Table 18 shows the activities of the stiffener mounting station (I5) at which the profiles are fixed onto the panel by using spot welding. The profiles were aligned on the marks and fixed. The alignment and spot welding were performed using a spot welding machine.

All of the activities from 16 to 22 were due to mounting operations. The duration of mounting activities was 278

Table 19. The durations of the activities (hours).

Work station	Grinding	Mounting	Worker's movement	Falling off	Worker's material handling	Crane's movement	Welding	Cutting
I1	0.0	0.0	0.8	0.0	0.5	2.3	0.0	1.6
I2	1.9	0.0	0.3	0.0	0.0	1.5	0.0	0.0
I3	0.0	2.6	0.3	0.0	0.3	0.6	4.5	0.0
I4	0.1	0.4	0.1	0.0	0.1	0.0	2.3	1.7
I5	0.0	2.9	1.9	0.0	0.0	1.4	0.0	0.0
I6	0.0	0.0	0.0	0.0	0.0	0.0	5.5	0.0
I7	4.5	9.4	0.4	0.0	0.0	1.5	0.0	0.0
I8	0.0	0.0	0.6	0.0	0.0	0.0	151.5	0.0
I9	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I10	0.3	0.1	2.5	0.0	0.4	7.8	0.0	0.2
I11	0.0	0.0	0.4	0.0	0.0	1.8	0.0	0.0
I12	0.0	0.0	4.8	0.0	1.7	9.3	0.0	9.5
I13	16.1	30.3	0.8	0.0	12.6	9.6	173.6	0.0
I14	3.8	19.5	0.3	0.0	1.8	6.5	136.3	0.0
I15	0.0	0.0	0.3	0.0	0.1	1.7	0.0	4.4
I16	3.8	14.4	0.2	0.0	0.8	4.1	197.2	0.0
TOTAL	40.6	79.7	13.7	0.0	18.0	48.2	671.0	17.4

Table 20. Ranking of the durations.

Time interval (hours) (severity/failure)	Rank
0-2	1
2-4	2
4-6	3
6-8	4
8-10	5
10-12	6
12-14	7
14-16	8
16-18	9
18-	10

minutes. Activity numbers 2, 4, 5, 6, 7, 9, 10, and 11 concerned crane movements. The duration of the crane's movement was 88.4 minutes. Activity numbers 1, 2, 3, 7, 8, 12, 13, 14, 15, 17, and 19 were due to worker's movement. The duration of worker's movement was 118.6 minutes. Similarly, for the other work stations, detailed process analyses were performed and the activities were categorized. For the sake of space, the author presents only the process of the stiffener mounting station. Table 19 presents the durations of the categorized activities for each work station.

After the durations of the activities for each work station were calculated, the durations were ranked. Table 20 shows the rates of the durations. For instance, if a duration of the activity were between 0 and 2 hours, the rate of the activity would be 1, and if a duration of the activity were between 8 and 10 hours, the rate of the activity would be 5.

Table 21. The scores of the durations.

Work station	Grinding	Mounting	Worker's movement	Falling off	Worker's material handling	Crane's movement	Welding	Cutting
I1	0.0	0.0	1	0.0	1	2	0.0	1
I2	1	0.0	1	0.0	0.0	1	0.0	0.0
I3	0.0	2	1	0.0	1	1	3	0.0
I4	1	1	1	0.0	1	0.0	2	1
I5	0.0	2	1	0.0	0.0	1	0.0	0.0
I6	0.0	0.0	0.0	0.0	0.0	0.0	3	0.0
I7	3	5	1	0.0	0.0	1	0.0	0.0
I8	0.0	0.0	1	0.0	0.0	0.0	10	0.0
I9	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
I10	1	1	2	0.0	1	4	0.0	1
I11	0.0	0.0	1	0.0	0.0	1	0.0	0.0
I12	0.0	0.0	3	0.0	1	5	0.0	5
I13	9	10	1	0.0	7	5	10	0.0
I14	2	10	1	0.0	1	4	10	0.0
I15	0.0	0.0	1	0.0	1	1	0.0	3
I16	2	8	1	0.0	1	3	10	0.0

Based on Tables 19 and 20, the rates of the durations are listed in Table 21. For example, the rate of the duration of the crane's movement for the edge-cutting station (I1) was 2.

6. Calculate Risk Number (Step 6)

RPNs were calculated as probability $\times$ S $\times$ D. RPNs were determined for grinding, mounting, worker's movement, worker's material handling, crane's movement, welding, and cutting activities. For RPN calculation, the data shown in Tables 14, 17, and 21 were used.

Tables 22-28 show the risk numbers of grinding, mounting, worker's movement, worker's material handling, crane's movement, welding, and cutting activities, respectively. The RPN calculation for falling was not performed because no work activity associated with falling was available in this implementation.

7. Comparison of the Risks (Step 7)

A minor and subassembly fabrication station (I13) was determined to be the most hazardous station regarding grinding and worker's material handling failures because the RPNs were 63, as shown in Tables 22 and 25.

The prefabrication and jig work stations were the most hazardous stations regarding the assembly failures because their RPNs were 400, as shown in Table 23. Station I12 was the most hazardous station regarding worker's movement and cutting failures because their RPNs were 72 and 50, as shown in Tables 24 and 28.

Stations I12 and I13 were the most hazardous stations

Table 22. Grinding risk number.

Workstation	Probability	Severity	Duration rate	RPN
I1	7	1	0.0	0
I2	7	1	1	7
I3	7	1	0.0	0
I4	7	1	1	7
I5	7	1	0.0	0
I6	7	1	0.0	0
I7	7	1	3	21
I8	7	1	0.0	0
I9	7	1	6	42
I10	7	1	1	7
I11	7	1	0.0	0
I12	7	1	0.0	0
I13	7	1	9	63
I14	7	1	2	14
I15	7	1	0,0	0
I16	7	1	2	14
TOTAL				175

Table 23. Mounting risk number.

Workstation	Probability	Severity	Duration rate	RPN
I1	5	8	0.0	0
I2	5	8	0.0	0
I3	5	8	2	80
I4	5	8	1	40
I5	5	8	2	80
I6	5	8	0.0	0
I7	5	8	5	200
I8	5	8	0.0	0
I9	5	8	0.0	0
I10	5	8	1	40
I11	5	8	0.0	0
I12	5	8	0.0	0
I13	5	8	10	400
I14	5	8	10	400
I15	5	8	0.0	0
I16	5	8	8	320
TOTAL				1560

Table 24. Worker's movement risk number.

Workstation	Probability	Severity	Duration rate	RPN
I1	4	6	1	24
I2	4	6	1	24
I3	4	6	1	24
I4	4	6	1	24
I5	4	6	1	24
I6	4	6	0.0	0
I7	4	6	1	24
I8	4	6	1	24
I9	4	6	0.0	0
I10	4	6	2	48
I11	4	6	1	24
I12	4	6	3	72
I13	4	6	1	24
I14	4	6	1	24
I15	4	6	1	24
I16	4	6	1	24
TOTAL				408

Table 25. Worker's material handling risk number.

Workstation	Probability	Severity	Duration rate	RPN
I1	3	3	1	9
I2	3	3	0.0	0
I3	3	3	1	9
I4	3	3	1	9
I5	3	3	0.0	0
I6	3	3	0.0	0
I7	3	3	0.0	0
I8	3	3	0.0	0
I9	3	3	0.0	0
I10	3	3	1	9
I11	3	3	0.0	0
I12	3	3	1	9
I13	3	3	7	63
I14	3	3	1	9
I15	3	3	1	9
I16	3	3	1	9
TOTAL				135

regarding crane's movement failure because their RPNs were 120, as shown in Table 26. Stations I8, I13, I14, and I16 were the most hazardous stations regarding welding failures because their RPNs were 40, as shown in Table 27.

As shown in Table 29, the highest RPNs were 1560, 696, 408, 192, 175, 135, and 110. Thus, the priorities of the risk could be identified. Mounting operations were the most risky activities because its total RPN was 1560. The second risky activity was crane's movements and its RPN was 696. The third risky activity was worker's movement because its total RPN was 408. Cutting was the least hazardous activity because its RPN was 110.

Table 30 presents the total RPNs of the work stations. The total RPN was the product of the sum of the grinding, mounting, worker's movement, worker's material handling, crane's movement, welding, and cutting RPNs.

Table 26. Crane's movement risk number.

Work station	Probability	Severity	Duration rate	RPN
I1	3	8	2	48
I2	3	8	1	24
I3	3	8	1	24
I4	3	8	0.0	0
I5	3	8	1	24
I6	3	8	0.0	0
I7	3	8	1	24
I8	3	8	0.0	0
I9	3	8	0.0	0
I10	3	8	4	96
I11	3	8	1	24
I12	3	8	5	120
I13	3	8	5	120
I14	3	8	4	96
I15	3	8	1	24
I16	3	8	3	72
TOTAL				696

Table 27. Welding risk number.

Workstation	Probability	Severity	Duration rate	RPN
I1	2	2	0.0	0
I2	2	2	0.0	0
I3	2	2	3	12
I4	2	2	2	8
I5	2	2	0.0	0
I6	2	2	3	12
I7	2	2	0.0	0
I8	2	2	10	40
I9	2	2	0.0	0
I10	2	2	0.0	0
I11	2	2	0.0	0
I12	2	2	0.0	0
I13	2	2	10	40
I14	2	2	10	40
I15	2	2	0.0	0
I16	2	2	10	40
TOTAL				192

The most hazardous work station was Station I13 because its total RPN was 710.

The second most risky station was the jig station, the RPN of which was 583. The least risky station was Station I6 because its total RPN was merely 12.

V. CONCLUSION

Based on the case study, the most risky activities can be prioritized as mounting, crane's movement, worker's movement, welding, grinding, worker's material handling, and cutting.

Table 28. Cutting risk number.

Work station	Probability	Severity	Duration rate	RPN
I1	1	10	1	10
I2	1	10	0.0	0
I3	1	10	0.0	0
I4	1	10	1	10
I5	1	10	0.0	0
I6	1	10	0.0	0
I7	1	10	0.0	0
I8	1	10	0.0	0
I9	1	10	0.0	0
I10	1	10	1	10
I11	1	10	0.0	0
I12	1	10	5	50
I13	1	10	0.0	0
I14	1	10	0.0	0
I15	1	10	3	30
I16	1	10	0.0	0
TOTAL				110

Table 29. Risk Priority Numbers (RPNs) of failures.

The reason of the failure	RPN
Grinding	175
Mounting	1560
Worker's movement	408
Worker's material handling	135
Crane's movement	696
Welding	192
Cutting	110

The failures associated with mounting activities were the most risky because their RPNs were the highest. Risk mitigation efforts should be prioritized for failures yielding high RPN values. However, an action plan should be prepared for reducing the severity, occurrence, and duration ratings of the failures.

Regarding the work stations, the most risky work stations were categorized as the minor and subassembly fabrication, jig, unit assembly, web-mounting, plate piece part preparation, profile piece part preparation, panel production, stiffener mounting, panel-cutting, edge-cutting, plate bending, web-welding, edge-cleaning and sequencing, profile bending, grinding, and stiffener welding stations. Thus, Station I13 was the most critical work station. Planners must consider these work stations and improve the work activities to reduce the risk.

In this study, the most risky work stations and work activities in the ship hull production process were determined. Future studies should investigate piping and outfitting shops

Table 30. The workstations Total Risk Priority Numbers (RPNs).

Work station	Grinding RPN	Mounting RPN	Worker's movement RPN	Falling off RPN	Worker's material handling RPN	Crane's movement RPN	Welding RPN	Cutting RPN	TOTAL RPN
I1	0	0	24	0	9	48	0	10	91
I2	7	0	24	0	0	24	0	0	55
I3	0	80	24	0	9	24	12	0	149
I4	7	40	24	0	9	0	8	10	98
I5	0	80	24	0	0	24	0	0	128
I6	0	0	0	0	0	0	12	0	12
I7	21	200	24	0	0	24	0	0	269
I8	0	0	24	0	0	0	40	0	64
I9	42	0	0	0	0	0	0	0	42
I10	7	40	48	0	9	96	0	10	210
I11	0	0	24	0	0	24	0	0	48
I12	0	0	72	0	9	120	0	50	251
I13	63	400	24	0	63	120	40	0	710
I14	14	400	24	0	9	96	40	0	583
I15	0	0	24	0	9	24	0	30	87
I16	14	320	24	0	9	72	40	0	479

by using the same method. Thereby, the critical work activities and work stations regarding failures can be identified for other shops, and shipbuilders can exert measures on critical activities promptly.

REFERENCES

1. Bakacak, M., *Analysis of the Shipbuilding and Ship Repair Accidents*, Master Thesis, Graduate Institute of Social Sciences, Dokuz Eylul University, Izmir, Turkey (2007).
2. Buksa, T., Pavletic, D., and Sokovic, M., "Shipbuilding pipeline production quality improvement," *Journal of Achievements in Materials and Manufacturing Engineering*, Vol. 40, No. 2, pp. 160-166 (2010).
3. Duffey, M. R. and Van Dorp, J. R., "Risk analysis for large engineering projects: modeling cost uncertainty for ship production activities," *Journal of Engineering Valuation and Cost Analysis*, Vol. 2, No. 4, pp. 285-301 (1999).
4. George, M. L., *Lean Six Sigma: Combining Six Sigma Quality with Lean Speed*, McGraw-Hill, New York (2002).
5. He, C. and Gu, Y., "Fault statistics and mode analysis of steam-induced vibration of steam turbine based on FMEA method," *Journal of Computers*, Vol. 6, No. 10, pp. 2098-2103 (2011).
6. Lee, E., Park, Y., and Shin, J.G., "Large engineering project risk management using a Bayesian belief network," *Expert Systems with Applications*, Vol. 36, pp. 5880-5887 (2009).
7. McCain, C., "Using a FMEA in a services setting," *Quality Progress*, Vol. 39, No. 9, pp. 24-30 (2006).
8. Pyzdek, T., *The Six Sigma Handbook (2nd Ed.)*, McGraw-Hill, New York (2003).
9. Radvanska, A., "Abrasive waterjet cutting technology risk assessment by means of failure modes and effect analysis method," *Technical Gazette*, Vol. 17, No. 1, pp. 121-128 (2010).
10. Shirouyehzad, H., Dabestani, R., and Badakhshian, M., "The FMEA approach to identification of critical failure factors in ERP implementation," *International Business Research*, Vol. 4, No. 3, pp. 254-263 (2011).
11. Stamatis, D. H., *Failure Mode and Effect Analysis: FMEA from Theory to Execution (1st Edn)*, Milwaukee (1995).
12. Welborn, C., "Applying failure mode and effect analysis to supplier selection," *The IUP Journal of Supply Chain Management*, Vol. 7, No. 3, pp. 7-14 (2010).
13. Yao, H. L., Chun, G., Lin, S. Z., Bai, J. X., and Sun, H. X., "Application of analytic hierarchy process (AHP) in shipyard Project investment risk recognition," *Canadian Social Science*, Vol. 5, No. 5, pp. 17-25 (2009).