Journal of Marine Science and Technology
DOI: 10.6119/JMST-013-0222-1

This article has been peer reviewed and accepted for publication in JMST but has not yet been copyediting, typesetting, pagination and proofreading process. Please note that the publication version of this article may be different from this version. This article now can be cited as doi: 10.6119/JMST-013-0222-1.

RISK ASSESSMENT IN SHIP HULL STRUCTURE PRODUCTION USING FMEA

Murat OZKOK[1]

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 keep their competitive power. Failures cause some damages to the shipyard such as injuries, deaths and so on. Most of damages lead to the work loss of the shipyard. To be able to deal with those damages, the most risky activities and work stations are required to be known. For this, the risk levels of the failures are needed to be calculated by means of Failure Mode and Effect Analysis (FMEA) method. In this study, the hull structure production process of a shipyard was considered. Obtaining the failure statistical data of the shipyard, the failures were categorized and determined the probability and severity of the failures. After that, the comprehensive process analysis of the workstations were performed and the durations of the activities were determined. Finally, Risk Priority Numbers (RPNs) were calculated and the most risky activities and workstations were determined.

I. INTRODUCTION

In today’s global competitive environment, the shipyards must examine their production processes in order to reduce the failures. The failures cause the injuries and deaths and also lead to work loss which means money loss. Therefore, the shipyards have to determine the risks in production line and they should attempt to reduce the risks. For this, the comprehensive process analysis of the current situation has to be performed and the reasons of the failures have to be identified.

There may take place many different failures in the production line of the shipyards. The greatest risks in shipbuilding are those classified as conventional risks, that is those connected to machine tools, the use of electricity, scaffolding and the movement and lifting of heavy and semi-worked pieces. There are also other kind of failures such as the crushes between the objects, injuries while lifting or carrying material, slipping, falling off, bumping to stationary objects, bumping to moving objects, walking on the objects, crushing under the falling objects, touching hot surfaces, electric shock, fire and explosion and burning.

A shipyard production system comprises many work stations which are involved in the hull structure production process and there may take place a lot of failures on these workstations. The purpose of this study is to determine which work stations and activities are the most critical in terms of failures. For this aim, a shipyard, which is situated in Turkey, was used as illustrative example and, the most risky work stations for hull ship production and the most risky activities are attempted to be found for this shipyard. The statistical previous failure data of the shipyard were obtained and the failures are categorized in accordance with the type of failures and the probabilities and severities of the failures are determined. Then, the comprehensive process analysis of the work stations are performed and the durations of the activities are calculated. After that, the Risk Priority Numbers (RPNs) of the failures are calculated by multiplying probability, severity and duration values. Finally, the comparisons of the RPNs of the failures are carried out and the most risky activities and work stations are found. Because there is no such a comprehensive risk assessment of ship hull production process in literature, the paper presented here may help having idea about the failures in shipbuilding for shipbuilders and researchers. The reason why this shipyard used as illustrative example in this study was chosen is that it has modern flow type production layouts and it documented the accidents orderly. The paper also represents a modified calculation of the RPN by using duration rate.

Failure Modes and Effect Analysis (FMEA) is one of the risk assessments methods. Failure Modes and Effect Analysis is a widely used engineering technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from system, design, process, and/or service before they reach the customer [11]. A traditional FMEA quantifies risks in terms of three categories. The categories are Severity, Occurrence and Detection [6]. Severity represents the impact of the failure if the failure occurs and occurrence is the probability of the failure actually occurring and detection is the system’s process controls to prevent a failure. Each category is rated on a scale from 1 to 10. After the severity, occurrence and detection ratings are developed, the scores are multiplied together to provide a Risk Priority Number (RPN). The RPN value is the product of severity, occurrence and detection values. It is calculated as: Severity x Occurrence x Detection [8]. A higher RPN number represents a higher risk.

Paper submitted 07/06/12; revised 02/18/13; accepted 02/22/13. Author for correspondence: Murat Ozkok (e-mail: muratozkok@ktu.edu.tr).

[1] *Department of Naval Architecture and Marine Engineering, Karadeniz Technical University, Camburnu, Trabzon, TURKEY.*

There have been many risk assessment studies in literature. Risk assessment implementations are carried out in many fields such as machinery information systems, selection of suppliers and so on. Chengbing and Yujiong [3] evaluated the failures which affect steam-induced vibration by means of FMEA. Shirouyehzad et al. [10] seeked to examine the failure factors which lead to the success of ERP (Enterprise Resource Planning) implementation by using FMEA methods. Radvanska [9] made risk assessment of abrasive water jet cutting technology from point of view of operational personnel by using FMEA method and the author calculated the risk number by multiplying occurrence x severity instead of severity x occurrence x detection. Eunchang et al. [5] made a risk assessment of the Korean Shipyards in terms of design change, design manpower and raw material supply and risk number was calculated as: the degree of loss x the probability of occurrence. Duffey and Van Dorp [4] evaluated the risk of the shipyard in terms of labor and overhead costs by means of Monte Carlo Simulation Software. Yao et al. [13] categorized the shipyard failures based on production cost, technology risk and production period instead of human based effects. Bakacak [1] examined in his study for scaffolding accidents and ship repair accidents and made risk evaluation for them. Buksa et al. [2] attempted to improve the shipyard pipeline processes and they quantified the risk priority numbers (RPNs) by means of FMEA and they recommended corrective actions in order to reduce the RPNs.

II. SHIP HULL STRUCTURE PRODUCTION PROCESS

Ship production is extremely hard job since it includes many processes. A ship is manufactured by performing thousands of work activities. In order to manufacture a ship, various types of workstations are needed. Each workstation has a task for ship production. Table 1 shows the work stations which have 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

In edge cutting station (I1), the edge cutting operation of ship hull plates is carried out. Edge cutting operation is the contour cutting of flat plates. And the plates which are subject to edge cutting constitute the panel structure. The edge-cut plates are transferred to I2 station. The edge cleaning operation of the ship hull plates, which are cut in edge cutting station (I1), is carried out in edge cleaning and sequencing station (I2). There are some materials and slags on the edge surfaces of the plates after edge cutting. Using a grinding machine, these materials and slags remove from the edge surfaces of the plates. In I2 station, the plates are also sequenced in accordance with the process turn. Then the plates are sent to I3 station. The hull plates are welded and the panel structure is produced in panel production station (I3). After the panel produced, it is transported to I4 station. In panel cutting station (I4), the panel which is manufactured in panel production station (I3) is subject to counter cutting in accordance with its dimensions. After the panel is cut in I4 station, it heads for I5 station. The profiles are assembled on the panel by spot welding in stiffener mounting station (I5). After that, the profiles are welded by tig welding in stiffener welding station (I6). The minor and sub assemblies are joined on the flat panel assembly by spot welding in web mounting station (I7). The minor and sub assemblies are welded on the flat panel assembly by tig welding in web welding station (I8). Grinding station (I9) is the last station of the panel line. In this station, the grinding operations of the flat panel and major sub assemblies are performed. The cutting operations of the profiles are performed in profile piece part preparation station (I10). Standard-dimensioned profiles, which are sent to profile cutting station, are cut with specific dimensioned profiles. The bending operations of the profiles are performed by frame bender machine in profile bending station (I11). The bending profiles are used in curved panel. Plate piece part preparation station (I12) is the heart of the shipyard production system. In this station, the plates are nested and single plate assemblies are manufactured. Minor and sub assemblies are produced in minor and sub assembly fabrication station (I13). Curved panel assemblies are produced in jig station (I14). Jig structure consists of curved jigs. The curved panels are lied down the jig structure and the curved profiles are welded on this curved plates. In plate bending station (I15), the bending operations of the plates, coming from nest cutting station, are performed. Therefore, the flat plates are transformed to the curved plates. The structures and parts produced in previous work stations are sent to unit assembly station (I16) and the block structure is formed by assembling the corresponding parts.

Above, it’s mentioned that various types of workstations come together in order to manufacture hull ship. Each of work stations has a relation with the other(s). The material flows take place between the stations mentioned in Table 1. After the material is processed in a work station, it’s transported to the other work station (s) to be processed again. So, there is a flow relation between all the work stations. Table 2 and Fig. 1 show the material relationships between the work stations.

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

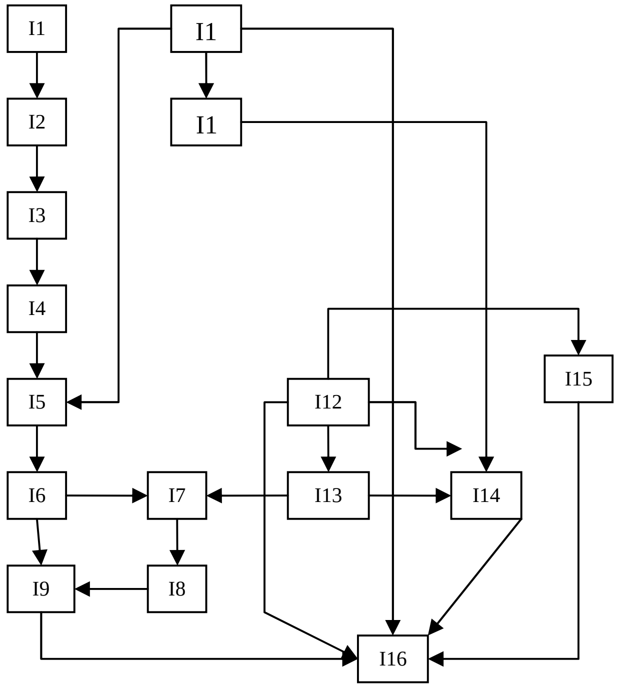

Fig. 1. Work flow in the shipyard production system.

Ship production is categorized as production stages and these stages are named such as A, B, C, D, E, F, G, H, J and K. These categorization allow for easy control of production processes. Production stage A and B represent the single section part and single plate part respectively as shown Fig. 2 and Fig. 3. Both single section and single plate parts have specific dimensions and fabricated when standard-dimensioned profile and plate are cut in profile piece part preparation (I10) and plate piece part preparation (I12) stations.

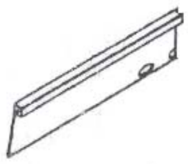

Fig. 2. Single section part (A).

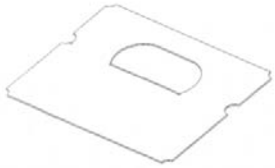

Fig. 3. Single plate part (B).

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, sub assembly (production stage D) is built (Fig. 5). Both production stages are performed in minor and sub assembly fabrication station (I13).

Fig. 4. Minor assembly (C).

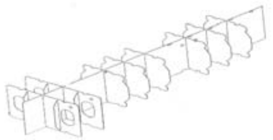

Fig. 5. Sub assembly (D).

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 manufactured. If single section parts (production stage A) are fitted on the panel, the panel with profiles is created, which is called as flat plane assembly (production stage F). While flat plate assembly (E) is being performed in panel production station (I3), flat panel assembly (F) is performed in stiffener mounting station (I5). Fig. 6 and Fig. 7 show E and F production stages respectively.

Fig. 6. Flat plate assembly (E).

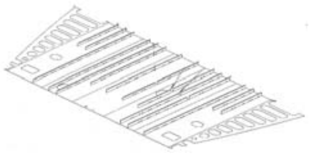

Fig. 7. Flat panel assembly (F).

As minor and sub assemblies (C and D production stages) are fitted on the flat panel assembly (F), major sub assembly (production stage G) is manufactured. Major sub assembly is carried out in web mounting station (I7). Fig. 8 shows G production stages. Curved plate assembly (production stage H) consists of curved panel, minor assemblies and profiles as shown in Fig. 9 and it is produced in jig station (I14).

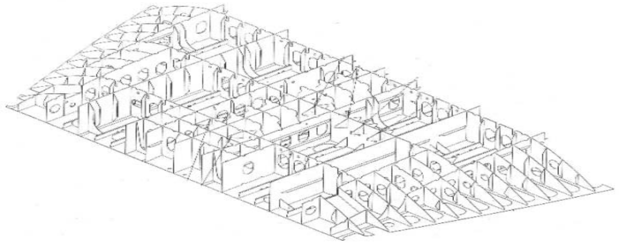

Fig. 8. Major sub assembly (G).

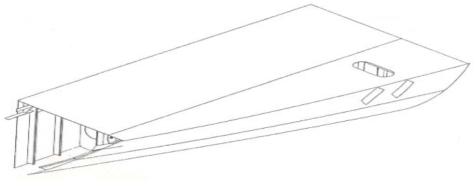

Fig. 9. Curved plane assembly (H).

When major sub assembly leaves the panel line, it transfers to block assembly area. If the top of the major sub assembly is covered by a panel, it is named as sub unit assembly (production stage J). When sub unit assembly is up down and curved plate assembly (production stage H) is assembled on it, it is named as unit assembly. Both sub unit assembly (J) and unit assembly (K) are manufactured in unit assembly station (I16). Fig. 10 and 11 depict production stage J and K.

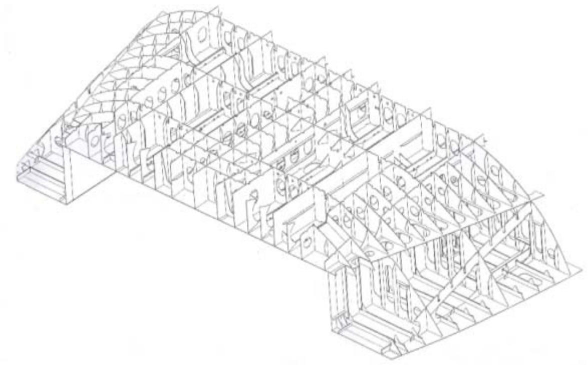

Fig. 10. Sub unit assembly (J).

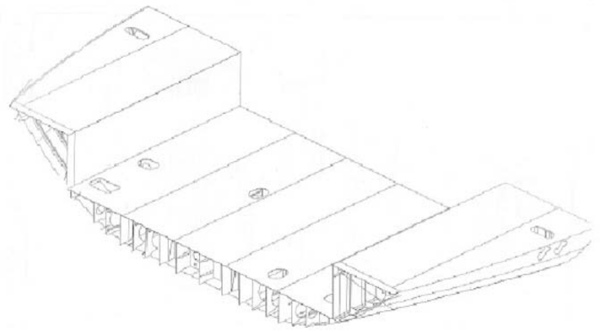

Fig. 11. Unit assembly (K).

III. METHODOLOGY

As described in Section 1, Failure Mode and Effect Analysis quantifies the risks of the failures by means of Risk Priority Number which is the product of Severity, Occurrence and Detection. Risk priority number in traditional FMEA is calculated by multiplying Severity (S) x Occurrence (O) x Detection (D). According to McCain [7], the FMEA process can be modified to satisfy unique applications. Welborn [12] modified traditional FMEA in his study and calculated the risk priority number by multiplying Severity (S) x Occurrence (O) x Frequency (F). Here, frequency represents a rating of how often the activity is performed. In this study, the Risk Priority Number is calculated as: Severity (S) x Occurrence (O) x Duration (D). Here, duration represents how long the activity takes. The reason why the duration term is used in risk priority number is that the duration of the activity plays an important role in determining the risk. The longer the duration of the activity is, the higher risk the activity has. For example, let's think about welding activity and two men who are welding. The first man is welding along 2 hours and the second man is welding along 4 hours. In this case, the second man has higher risk along the welding than the first man.

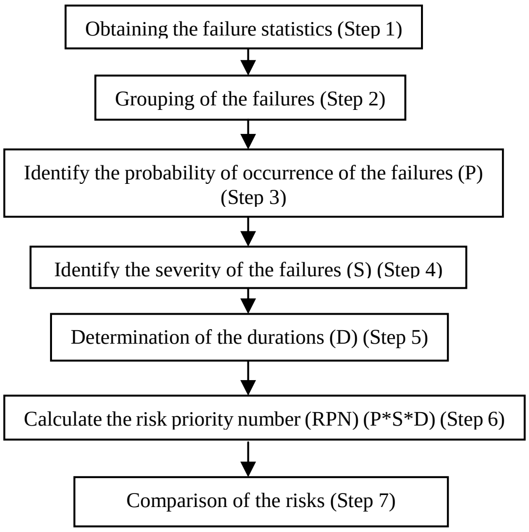

Fig. 12. The phases of the methodology.

Fig. 12 represents the phases of the methodology of the study. The first phase of the methodology is the obtaining of failure statistics. In this phase, the previous failures of the shipyard are achieved. The more statistical data are obtained, the better it is. After the previous failure statistics are obtained, the grouping of the failures is done. This shows what kind of failures the shipyard faces. Then, the failures probability is identified by using the statistical data. After that, the severity of the failures are determined. In the fifth step, the durations of the activity are calculated. For this, the detailed process analysis is required. The work stations which constitute the hull structure production line are identified and the work activities and their durations are determined. In the sixth step, the risk priority numbers (RPNs) are calculated and finally the risk priority numbers are compared each other.

IV. CASE STUDY

1. Obtaining the failure statistics (Step 1)

Number of 181 failures, which are belonging to 2009-2010-2011, were investigated for the study. These failures were achieved from a shipyard which is situated in Turkey. The shipyard has a capacity of 20.000 tonnes of steel per year. The accidents took place in a period of 3 years (36 months).

2. Grouping the failures (Step 2)

After the failures lists were obtained, they were required to be classified. 181 failures were categorized into 8 main failures, as can be seen from Table 11. These are based on grinding, welding, cutting, mounting, crane movement, worker's material handling, worker's movement, worker's falling off.

Some slags and burr appear after the cutting and welding works. Grinding process is carried out in order to remove the slags or burr from the plates and sections. During grinding process, pieces of burr or slags might penetrate to the eyes due to not using the individual means of protection. Furthermore, while working, the grinding stone might cut worker’s hand. There are number of 48 failures with regard to grinding. The failures based on grinding caused the workday loss of 48 days along 36 months. Table 3 represents failures based on grinding activity along 36 months in shipyard.

Table 3. Failures based on grinding activity.

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

Welding is permanently fixed the materials each other and it is very significant activity. During welding, some failures such as the impression from the welding gas and the penetration of the slags to the eyes and electric shock happen. Number of 11 failures occurred with respect to welding and these failures caused workday loss of 13 days along 36 months. Table 4 illustrates the failures based on welding activity.

Table 4. Failures based on welding activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Electric shock while the position of welding machine is 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

In a shipyard, edge cutting, nest cutting and profile cutting activities occur so as to fabricate the single parts. In these activities, some injuries and damages might take place. Number of 4 failures occurred with respect to cutting and these failures caused workday loss of 47 days along 36 months. Table 5 shows the cutting failures in the shipyard.

Table 5. Failures based on cutting activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	While removing the scrap from the plate, wound 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 the finger while cutting corner piece	1	7
TOTAL		4	47

During the mounting the parts each other, many failures have been occurring in shipyards. Frequently, the worker’s hands are crushed in the assembly places and some pieces penetrate to the eyes or the worker’s hands are injured while using hammer and so on. Number of 34 failures have taken place in 36 months. The failures based on assembly caused workday loss of 250 days. In Table 6, the mounting failures can be seen.

Table 6. Failures based on mounting activity.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	Getting caught the hand while assembling	3	50
2	Injuring by hitting hand with hammer	3	2
3	Wound by cutting while assembling	1	20
4	The material dropped on the worker’s hand while trying to take the material	2	70
5	Breaking the finger while assembling	1	30
6	Pipe bumped into the hand while pipe dismantling	1	2
7	Pipe dropped to the finger during pipe assembly	2	13
8	Getting caught the finger during HVAC assembly	1	1
9	Getting caught the finger during pipe assembly	1	7
10	Getting caught the finger during pipe dismantling	1	15
11	Getting caught the finger between pipes	2	5
12	While screwing the bolt, wrench hit to eyebrow	1	7
13	Slag penetration to eye during assembling	1	0
14	Bumping the finger into eye while screwing the bolt	1	2
15	Injured the arm during cable assembly	1	9
16	Injured the back while screwing the bolt	1	0
17	Burr penetration to eye during pipe assembly	6	2
18	Getting caught the finger while assembling	2	9
19	Getting caught the hand during pipe assembly	1	5
20	Pipe bumped into the head during pipe assembly	1	0
21	Injuring by hitting foot with hammer	1	1
TOTAL		34	250

The heavy materials are transported by the cranes in shipyard. During the transportation with crane, some failures such as dropping the material and the bumping someone take place.

Number of 18 failures occurred with respect to crane's movement and these failures caused workday loss of 135 days along 36 months. Table 7 shows the failures due to crane's movement.

Table 7. Failures based on crane's movement.

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

In shipyard production system, there are light materials in weight as well as heavy materials. In most cases, the light materials are carried by the worker without using any crane. During carrying the materials, the worker might drop the materials and his hands or ankles are injured. Furthermore, the worker's back might be damaged due to carrying the material. Number of 19 failures occurred with respect to worker's material handling and these failures caused workday loss of 47 days along 36 months. Table 8 represents the failures because of worker's material handling.

Table 8. Failures based on worker's material handling.

Failure no	Failure reason	Number of failures	Workday loss (days)
1	The material dropped onto the worker's hand while carrying it and crushing happened.	1	1
2	The material dropped onto the worker's shoulder	1	2
3	The pain from back happened during material transportation	1	2
4	Wound by cutting from hand during offloading the scrap into the box	1	10
5	The worker slipped and injured during machine set-up	1	1
6	The material dropped onto the worker's ankle while carrying	1	2
7	The material dropped onto the worker's foot while carrying	3	4
8	The other worker in the same place dropped the material onto his friend's foot	1	1
9	The other worker in the same place dropped the material onto his friend's back	1	2
10	While emptying the scrap box, the material splattered and hit the worker's eyebrow	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	Wound by cutting the hand during scaffold dismantling	1	5
TOTAL		19	47

Work power is one of the most significant resources for a shipyard. In the production process, the workers often move and during moving, some failures take place. While walking, the worker hits his foot to corner of the materials on floor and he sprains his ankles or he falls down and so on. Number of 25 failures occurred with respect to worker's movement and these failures caused workday loss of 150 days along 36 months. In Table 9, the failures due to worker's movement can be seen.

Table 9. Failures based on worker's movement.

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

The blocks of the ship are very huge structures and especially painting works require to build scaffolds and ladders so that the workers can paint the hull. During this activity, the worker might fall or slip from scaffolds or ladders while going up or down. Number of 22 failures occurred with respect to falling off and these failures caused workday loss of 68 days along 36 months. Table 10 shows the failures based on worker's falling off in the shipyard.

Table 10. Failures based on worker's falling off.

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

Above, the failures that occurred in the shipyard along 36 months (in the years of 2009-2010-2011) were categorized as detailed. As the above tables are investigated, the failures due to activities such as grinding, welding, cutting, mounting, crane movement, worker's material handling, worker's movement and worker's falling off can be easily found out. Table 11 represents the summary of the above tables. Accordingly, number of failures and workday losses of the activities can be seen. There have been number of 181 failures in the shipyard and these failures caused workday losses of 758 days.

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

3. Identify the probability of the failures (Step 3)

In this section, the probabilities of the occurrence of the failures are identified and ranked from 1 to 10. 10 is the highest probability. Here, the ratings are done in accordance with the number of failures which occurred per month. Table 12 represents the ranks of the probability. For example, if a failure happens between 0-0,1 times per month, the ranking of the probability is 1. In the same way, if a failure happens between 1-1,1 times per month, the ranking of the probability is 6. To calculate how often the failure happens per month, it is necessary to achieve number of failures occurred. After the failure numbers are obtained, it is needed to know how long these failures have been taking place.

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 shows the number of failures per month. Number of failures based on grinding is 48 and these failures took place along 36 months. Therefore, number of 1,4 failures due to grinding occurred per month (48 failures/36 months). Similarly, number of failures based on mounting is 34 and the failures occurred along 36 months so the number of failures based on mounting per month is 0,9. In the same way, the same calculations for the other failures are done and the number of failures per month is achieved.

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

Finally, the occurrence probability of the failures are determined. For the grinding failures, number of failures per month is 1,3. As shown in Table 12, number of 1,3 is in the row 1,2-1,3. Therefore, the ranking of the grinding failures is 7. In other words, the probability of occurrence of the grinding failures is 7. Table 14 represents the probability of the failure.

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

4. Identify the severity of the failures (Step 4)

In this step of the study, the severity rates are identified and ranked from 1 to 10. 10 is the most severe. Table 15 shows the rates of the severity. In this study, the severity represents the work loss. In other words, the higher the work loss is, the higher the severity is. As shown in Table 15, if the work loss of the failure is between 0-1 days, the rate of the failure severity is 1 or if the work loss of the failure is between 4-5 days, the rate of the failure severity is 5.

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

In Table 16, the number of failures, total work loss of the failures and average severity are shown. For example, the number of grinding failure is 48 and total work loss is 48. The meaning of that is the average severity per failure is 1. In other words, if a grinding failure happens, the average work loss of that is 1 day. When considered mounting failures, it is seen that the number of the failure is 34 and the total work loss of assembly failures is 250 days. That means, if an assembly failure occurs, the average work loss is 7,4 days per failure.

Table 16. The average severity of the failures.

The reason of the failure	Number of failures	Work-day 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

Making use of Table 15 and Table 16, the severities of the failures are determined as shown in Table 17. For example, a grinding failure causes an average work loss of 1 day, as can be seen from Table 16. In Table 15, it is between 0-1 days and therefore its rate is 1. In other words, the severity of the grinding failures is 1. Mounting failure causes an average work loss of 7,4 days and it is between 7-8 days in Table 15. So. the severity rate of the mounting failure is 8.

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

5. Identify the duration rates (Step 5)

Here, the durations of the work stations are determined and ranked from 1 to 10. 10 is the longest duration. Then, every work station is examined and the main activities are categorized according to grinding, welding, cutting, mounting, crane movement, worker material handling, worker’s movement, worker falling off activities.

The comprehensive process analysis is required in order to calculate the durations. Table 18 shows the activities of the stiffener mounting station (I5). In this station, the profiles are fixed on the panel by spot welding. Profiles are aligned on the markings and fixed. The alignment and spot welding are carried out by spot welding machine.

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

Activity no	Activity description	Number of activity	Activity duration (min.)
1	The operator walks to the crane	2	0,146
2	The crane goes to profile stock area	36	8,178
3	The operator assistants go to profile stock area	36	3,493
4	The crane comes down the profile	38	18,051
5	The crane holds the profile	38	15,2
6	The crane lifts the profile	38	18,037
7	The crane transports the profile from profile stock area to the porter system	38	8,473
8	The workers walks to the porter system	38	3,609
9	The crane takes down the profile on the porter system	38	12,274
10	The crane leaves the profile surface	38	4,428
11	The workers settle the profile on the porter system	38	3,8
12	The operator walks to the porter system	2	0,118
13	The workers walks to the profile welding area	2	0,404
14	The operator drives the porter system to the welding area	2	2,926
15	The operator walks to profile spot welding machine	2	0,042
16	The operator cleans the welding torch	2	1,5
17	The profile spot welding machine goes to the porter system	37	44,755
18	The profile spot welding machine comes down the profiles	38	3,8
19	The profile spot welding machine transport the profile from the porter system to the flat plate assembly	38	46,486
20	The profile spot welding machine takes down the profile on the flat plate assembly and alignment	38	111,394
21	The profile spot welding is prepared for welding operation.	38	6,328
22	The process of spot welding	38	63,82

All the activities from 16 to 22 are based on mounting operations. The duration of mounting activities is 278 minutes. Activity numbers 2,4,5,6,7,9,10 and 11 are concerned with crane movements. The duration of crane's movement is 88,4 minutes. Activity numbers 1,2,3,7,8,12,13,14,15,17 and 19 are based on worker's movement. The duration of worker's movement is 118,6 minutes. In the same way, for the other work stations, the detailed process analysis are performed and activities are categorized. Because there is no enough room here, the author was able to present only stiffener mounting station's process. Table 19 represents the durations of the categorized activities for each work station.

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

After the durations of the activities for each work station is calculated, the durations are required to be ranked. Table 20 shows the rates of the durations. For example, if a duration of the activity is between 0-2 hours, the rate of the activity is 1 and if a duration of the activity takes between 8-10 hours, the rate of the activity is 5.

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

Utilizing from Table 19 and Table 20, the rates of the durations are listed in Table 21. For example, the rate of duration of crane's movement for edge cutting station (I1) is 2.

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

6. Calculate risk number (Step 6)

Risk priority number (RPN) is calculated as: Probability x Severity x Duration. In this section, Risk Priority Numbers are determined for grinding, mounting, worker's movement, worker's material handling, crane's movement, welding and cutting activities based on work stations. For RPN calculation, the data from Table 14, Table 17, and Table 21 are employed. Tables 22-28 represent grinding, mounting, worker's movement, worker's material handling, crane's movement, welding and cutting risk numbers, respectively. It should be noted that RPN calculation for falling off will not be done since no failure due to falling off is available in this implementation.

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

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

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

7. Comparison of the risks (Step 7)

Minor and sub assembly fabrication station (I13) is the most hazardous station in terms of the grinding and worker's material handling failures since its Risk Priority Numbers (RPNs) are 63 from Table 22 and Table 25. Pre-fabrication and jig work stations are the most hazardous stations in terms of the assembly failures as their RPNs are 400 from Table 23. Plate piece part preparation work station (I12) is the most hazardous station in terms of worker's movement and cutting failures because its RPNs are 72 and 50 from Table 24 and Table 28. Plate piece part preparation (I12) and minor and sub assembly fabrication (I13) workstations are the most hazardous stations in terms of crane's movement failure since their RPNs are 120 from Table 26. Web welding (I8), minor and sub assembly fabrication (I13), jig (I14) and unit assembly (I16) work stations are the most hazardous stations in terms of welding failures since their RPNs are 40 from Table 27.

As shown in Table 29, the highest RPN numbers are 1560, 696, 408, 192, 175, 135 and 110 respectively. Therefore, the priorities of the risk can be identified. Mounting operations are the most risky activities because its total RPN is 1560. The second risky activity is crane's movements and its RPN is 696. The third risky activity is worker's movement as its total RPN is 408. The less hazardous activity is the cutting since its RPN is 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

Table 30 represents the total Risk Priority Numbers (RPNs) of work stations. The total RPN is the product of the sum of grinding, mounting, worker's movement, worker's material handling, crane's movement, welding, cutting RPNs. The most hazardous work station is minor and sub assembly fabrication station (I13) since the total Risk Priority Number is 710. The second risky station is the jig station which RPN is 583. The less risky station is stiffener welding station (I6) since its total RPN is only 12.

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

V. CONCLUSIONS

As considered in 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 respectively. The failures due to mounting activities are the most risky of the other failures since the Risk Priority Number is the highest one. The failures with higher RPN values are given a higher priority for risk mitigation efforts than the failures with lower RPN values. Therefore, an action plan may attempt to reduce the severity, occurrence and duration ratings for the failures.

As for workstations, the most risky ones can be categorized as: minor and sub assembly 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 respectively. According to this, minor and sub assembly fabrication (I13) is the most critical one. The planners must consider this station and improve the processes again in order to reduce the risk.

In this study, the most risky workstations and work activities in ship hull production process were determined. In the future works, the similar study can be performed for piping and outfitting shops by using the same method. In this way, the critical work activities and work stations can be determined for the other shops and the shipbuilders can take measures according to this.

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. Chengbing, H. and Yujiong, G., “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).
4. 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).
5. Eunchang, L., Yongtae, P., and Jong, G. S., “Large engineering project risk management using a Bayesian belief network,” *Expert Systems with Applications*, Vol. 36, pp. 5880-5887 (2009).
6. George, M.L., *Lean six sigma: Combining six sigma quality with lean speed*, McGraw-Hill, Newyork (2002).
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 edn)*, McGraw-Hill, Newyork (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).