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Safety Risk Assessment in Manufacturing Systems: An Analytic Hierarchy Process Approach

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ABSTRACT
Safety risks in the manufacturing sector affects activities in manufacturing operations. A poor safety culture results in unplanned downtime in production, accidents, injuries and lost time incidents. Safety risk assessment of manufacturing systems using the Analytical Hierarchy Process (AHP) was carried out in this study.
Hazard identification and risk ranking was done using a structured questionnaire to identify the hazards which include rolling/moving shaft, wet floor due to oil leaks and water spillage, clouds of dust, steam leakages/pressurized hose leakages, bad machine guarding, noise, fire, open drains, transporting/carrying heavy loads, lifting heavy loads above shoulder height and poor housekeeping. The risk analysis of these hazards indicated Risk Priority Numbers (RPN) ranging from 2 to 16.
The analytic hierarchy process (AHP) for the safety risk assessment was carried out using three criteria, namely; human(employee) safety (HS), machine(equipment) safety (MS) and work environment safety (WES). Each criterion has sub-criteria which were found to be consistent after the AHP analysis, thus, it can be used for decision making. This study identified hazards and risks associated with manufacturing systems and analyzed the safety risks by using the analytic hierarchy process (AHP) approach.
Keywords – Consistency, Criterion, Hazard, Risk, Safety.

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I. Introduction

Despite the safety challenges and risks involved in the manufacturing sector and dangers inherent in the manufacturing operations, a lot of lost time incidents/accidents still occur due to bad and uninformed practices. The safety risk assessment of a plant will ensure the risks are reduced or eliminated. A successful industry must ensure safety, reliability and sustainability in its operations. Hazard identification and the assessment of the associated risk is important. This will reduce the risks to an appreciable level [1]. Identifying the risks and evaluating them gives the opportunity of reduction in cost and production time [2]. Risk assessment contributes greatly toward improvements in the safety of various operations and equipment [3].

II. Literature Review

Risk is defined as a chance of danger, damage, loss, injury or any other undesired consequences. These risks sometimes result from the failure of manufacturing processes on the production floor [4]. It is the product of the probability of an event occurring and the severity of the event when it eventually occurs [5]. The risk assessments process of estimates the probability of occurrence of an event and the estimated magnitude of the adverse effects over a stipulated time. [6]. Several accidents mostly occur in the workplace due to lack of inattentiveness of workers, necessary knowledge to perform a certain task and especially when working with new machines. To control such incidents, it becomes unavoidable to take necessary steps to make job places safe by assessing the risks and suggest preventive measures. One way to detect such accidents is to conduct a safety risk assessment and analysis which provide preventive measures for potential hazards [7]. As accidents are common in any workplace, the role of management of occupational health and safety regarding job place is crucial to diminish the negative effect of a production process. A risk assessment is seeking to estimate potential human health and environmental risks caused by current and potential future conditions. Analytic Hierarchy Process (AHP) is a method for decision making in environments in which many variables are prioritized and alternatives are selected. AHP was developed by Thomas Saaty in the 1970s and it is currently used in decision making for complex scenarios, though, several modifications have been done over the years. It is used where people work together to make decisions when human feelings and consequences have long-term implications [8].

III. Materials And Methods

A descriptive design of a survey type was adopted for this study. This includes the administration of the study instrument (questionnaire) on the hazards and the risks inherent in the various activities in the plant. The questionnaire was administered to a total number of sixty operators and engineers in the plant who are directly involved in operations and activities on the facility. Each shift has a minimum of eighteen people per shift. A stratified sample size of at least fifteen people per shift was taken. A random sampling of fifteen people in each of the four shifts was done to meet the sample size of sixty people. The sample size should meet the following specific criteria, that is, the workers should have

1. Worked in the facility for at least two years
2. Been involved in the operation and activities in the plant
3. A requisite technical and theoretical experience and training

Information was gathered by visiting the site (production floor) and observing the work processes. Interviews were conducted with the operators on-site, technicians, production personnel, engineers and production managers of the various sections in the plant.

The risk assessment procedure will follow the order below:

1. Identify the hazards i.e. what can go wrong.
2. Identify who might be harmed.
3. Evaluate the risks and the precautions.
4. Consider the consequences and likelihood of occurrence.
5. Use the Risk Matrix Tool to grade the risk as shown in Table 1

Table 1: Risk assessment matrix

Severity/Probability	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated(F)	Eliminated	Eliminated	Eliminated	Eliminated

The identified hazards and risks were assessed quantitatively i.e. taking into accounts the severity, probability and consequences of occurring an event using the following criteria.

i. The severity for probability or frequency as shown in Table 1
ii. Probability: Concerning probability or frequency as shown in Table 2
iii. Consequences: Also, for the consequences, five categories are used.

Risks proportionate an extent for the probability P of a certain event i.e. the frequency, likelihood etc., and the possible consequences C of that event i.e. impact or effect

$$R = P \times C \quad (1)$$

Table 2: Ratings of the severity of occurrence

Severity	Description	Rating
Catastrophic	Multiple fatalities, Irrecoverable property damage and productivity	5
Fatal	Singular fatality, major property damage if the hazard is realized	4
Serious	Non-fatal injury, permanent disability	3
Minor	Disability but not permanent injury	2
Negligible	Minor abrasions, bruises, cuts, first-aid type injury	1

Table 3: Ratings of Likelihood of Occurrence

Likelihood/Probability	Description	Rating
Very likely	The very likely result of the hazard/event being realized	5
Possible	Has a possible chance of occurring and it is not unusual	4
Conceivable	Might occur in the future	3
Remote	Has not occurred after many years	2
Impossible	It is practically impossible and has never occurred	1

Table 4: RPN (Risk Priority Number) Level of Risk

Ratings	Level of Risk
RPN ≥ 15	High
RPN < 15, RPN ≥ 6	Medium
RPN < 6	Low

Data from interviews and the questionnaire are categorized based on the hazards and the risks identified for various operations and analyzed based on the qualitative data given by the interviewee. The data were further analyzed using the Analytic Hierarchy Process (AHP). It yields both quantitative and qualitative results. It involves dividing problems into the hierarchy of criteria followed by the calculation of their respective weights. Based on the weights obtained, pairwise comparison is done and ranked accordingly. Resultant decisions are obtained depending on the rank of the criteria. [9].

The AHP process involves:

i. Decomposing the decision-making problem into a hierarchical structure consisting of three stages which are;

a. Objective
b. Criteria and
c. Sub-Criteria.

The sub-criteria are defined with respect to the main criteria

ii. Make pairwise comparisons using matrices and establishing priorities among hierarchical elements. The comparison matrix is developed thus:

a. The criteria and the sub-criteria are compared with each other in the subsequent stage respectively.
b. Based on this comparison, sets of matrices are developed for each criterion.
c. Qualitative and quantitative data are defined using the rating scale stated in Table 3.1.
d. If the criteria in the column are preferred to the criteria in the row, the inverse of the rating is defined. If the row is preferred than to column, the row is rated as defined in the scale, else if the column is preferred than to rows, the inverse of the rating value is considered.
e. Using the reciprocal of the upper diagonal, the lower triangular matrix is generated.
f. Normalize the matrix by the addition of all the values in each column and finding the mean (λmax).

iii. Calculate the consistency ratio.

iv. Synthesize judgments and obtain the weights for achieving the goal.

v. Evaluate and determine the consistency of judgments.

3.1 Theoretical calculations of AHP

If there are *n* factors, then

$$\frac{n(n-1)}{2} \tag{2}$$

Pairwise Comparison
Setting C_1, C_2, $C_3 \ldots C_n$ as factors,
Eigen value = λmax

$$\lambda max = \frac{\sum aij \times Wij}{Wi} \tag{3}$$

If A is a consistency matrix, hence, Eigen vector, X will be

$$(A - \lambda maxI)x = 0 \tag{4}$$

$$Consistency\ Index(CI) = \frac{(\lambda \max - n)}{n-1} \tag{5}$$

$$Consistency\ Ratio(CR) = \frac{CI}{RI} \quad (6)$$

Where the RI is a random index as shown in Table 2. When CR ≤ 0.1, the matrix attains consistency.

Table 5: Comparison Scale [10]

Scale	Preferential Degree
1	Equal Importance
3	Moderate importance of one factor over another
5	The strong or essential importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two neighbouring levels
Reciprocals (1/x)	A value attributed when activity i is compared to activity j becomes the reciprocal when j is compared to i

Table 6: Random consistency (RC) index (n = size of the reciprocal matrix)

N	1	2	3	4	5	6	7	8	9	10
RC	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The result also showed that musculoskeletal disorders have the greatest contribution to the high-risk level while entanglement, trips, slips, falls, choking and respiratory disorders, cuts, burns, puncture, hearing disorders, broken bones contributed to the low and medium risk levels.

IV. Results and Discussions

The administered questionnaire resulted in the identification of the following hazards and the associated risks. Table 6 shows the hazards identified and the risks associated with them. The respective Risk Priority Numbers (RPN) was calculated using equation 3.1 and the ratings in Tables 3.1, 3.2, 3.4 and 3.5 respectively. A total of fifteen (15) hazards and their corresponding risks were identified. Two (2) of the identified hazards have a high-risk level, nine (9) have a medium risk level while four (4) have a low-risk level.

Table 7: Risk level classification

Hazards	Risks	Occurrence (O)	Severity (S)	RPN	Risk Level
Rolling/Moving Shaft	Entanglement	3	2	6	Medium
Loose cable/hose connections	Slips/Trips and Falls	3	2	6	Medium
Wet floor due to oil leaks and water spillage	Slips/Trips and Falls	3	3	9	Medium
Confined Spaces	Choking/Death	2	3	6	Medium
Sharp edge –Moving or Stationary	Cuts/ Punctures	4	2	8	Medium
Dusts	Choking/Respiratory disorder	5	2	10	Medium
Steam leakages/pressurised hose leakages	Burns	3	4	12	Medium
Noise	Loss of hearing	2	2	4	Low
Bad machine guarding	Entanglement	3	3	9	Medium
Fire	Burns	1	5	5	Low
Open drains	Slips/Broken bones	2	3	6	Medium
Working at height without a harness	Fall/broken bones	1	2	2	Low
Transporting/Carrying heavy loads	Musculoskeletal Disorders such as back	4	4	16	High

	pains				
Lifting a heavy load above shoulder height	Musculoskeletal Disorders such as back pains	4	4	16	High
Poor housekeeping	Slips, Trips and Falls	2	3	6	Low

The analytic hierarchy process (AHP) for the safety risk assessment was done based on the findings from plant interactions with personnel and staff who work in the plant and other parts of the organization as a whole.
The goal of the AHP is to carry out safety risk assessment while the criteria are as follows:
1. Human Safety
2. Machine Safety
3. Work Environment Safety

The sub-criteria for human safety criterion is;
1. Eye protection
2. Manual Lifting
3. Manual Handling Activities

The sub-criteria for the machine safety criterion is;
1. Revolving Parts Protection
2. Pressure Plant Protection
3. Machine Guarding

The sub-criteria for work environment safety criterion is:
1. Proper Ventilation
2. Heat/Dust Extraction
3. Proper Safety Line Markings
4. Manhole Protection

The goal, the criteria and the sub-criteria are presented in Figure 1.

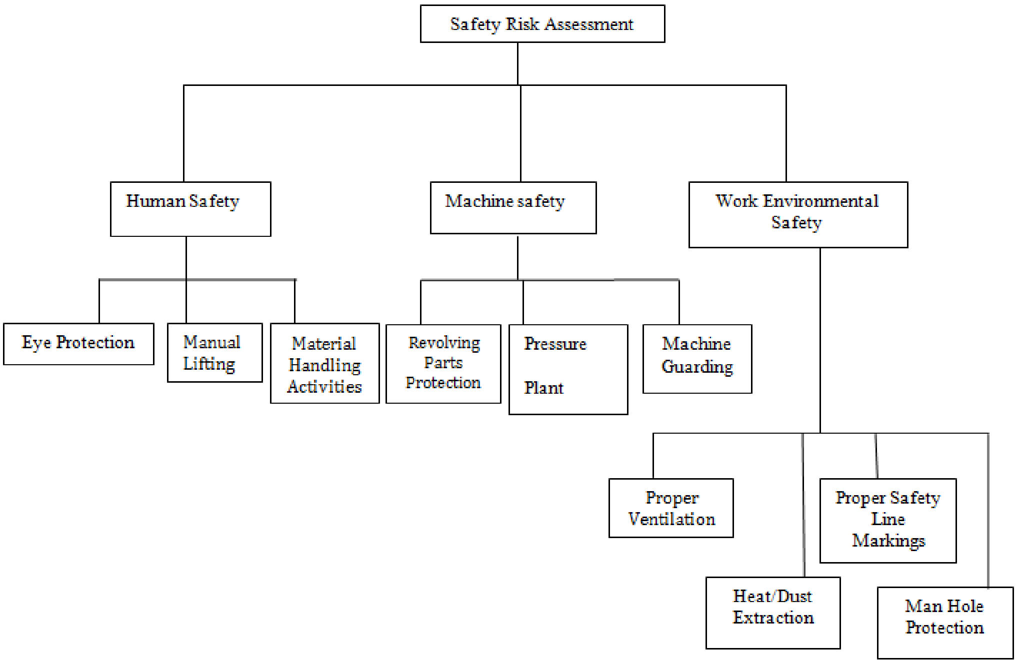

Figure 1: AHP Goal, Criteria and Sub-Criteria Chart

The following acronyms are used for the criteria and sub-criteria;
HS - Human Safety
MS – Machine Safety
WES – Work Environment Safety
EP – Eye Protection
ML – Manual Lifting
MHA – Manual Handling Activities
RPP – Revolving Parts Protection
PPP – Pressure Plant Protection
MG – Machine Guarding
PV – Proper Ventilation
HDE – Heat/Dust Extraction
PSM – Proper Safety Line Markings
MHP – Manhole Protection

Using Table 4, matrix tables are derived for the main criteria which are Human (Employee) Safety (HS), Machine (Equipment) Safety (MS) and Work Environment Safety (WES). Subsequently, the analytic hierarchy process (AHP) was carried out on each criterion to determine if decisions can be taken using these criteria. These matrices are presented in Tables 4.2 to 4.21. The corresponding values for the consistency index (CI) and the consistency ratio (CR).

Table 8: Main criteria initial matrix

Criteria	HS	MS	WES
HS	1	9	4
MS	1/9	1	1/5
WES	¼	5	1

Table 9: Sum of the main criteria initial matrix

Criteria	HS	MS	WES
HS	1	9	4
MS	0.11	1	0.2
WES	0.25	5	1
Sum	1.36	15	5.2

Table 10: Normalised main criteria matrix

Criteria	HS	MS	WES	Criteria Weights
HS	0.7353	0.6000	0.7692	0.7002
MS	0.0809	0.0667	0.0385	0.0620
WES	0.1838	0.3333	0.1923	0.2365

Table 11: Test of consistency (main criteria)

Criteria Weights	0.7002	0.0620	0.2365
Criteria	HS	MS	WES
HS	1 × 0.7002	9 × 0.0620	4 × 0.2365
MS	0.11× 0.7002	1 × 0.0620	0.25 × 0.2365
WES	0.25× 0.7002	5 × 0.0620	1 × 0.2365

Table 12: Result for the test of consistency (main criteria)

Criteria	HS	MS	WES	Weighted Average	Criteria Weights	
HS	0.7002	0.5580	0.9460	2.2042	0.7002	3.1480
MS	0.0770	0.0620	0.0473	0.1864	0.0620	3.0065
WES	0.1751	0.3100	0.2365	0.7217	0.2365	3.0516

$$\lambda max = \frac{3.1480 + 3.0065 + 3.0516}{3}$$

$$\lambda max = 3.0687$$

From Equation 3

$$Consistency\ Index, CI = \frac{\lambda max - n}{n - 1} = \frac{3.0687 - 3}{3 - 1} = \frac{0.0687}{2} = 0.03435$$

$$where\ n = 3$$

$$Consistency\ Ratio = \frac{CI}{RI}\ where\ RI = 0.58$$

$$= \frac{0.03435}{0.58}$$

= 0.05922

0.05922< 0.1

Hence, the main criteria are consistent and can be used for decision making.

Table 12: Human safety criterion initial matrix

Criteria	EP	ML	MHA
EP	1	5	4
ML	1/5	1	½
MHA	¼	2	1

Table 13: Sum of the human safety criterion initial matrix

Criteria	EP	ML	MHA
EP	1	5	4
ML	0.2	1	0.5
MHA	0.25	2	1
Sum	1.45	8	5.5

Table 14: Normalised human safety criterion matrix

Criteria	EP	ML	MHA	Criteria Weights
EP	0.6897	0.6250	0.7273	0.6807
ML	0.1379	0.125	0.0909	0.1179
MHA	0.1724	0.25	0.1818	0.2014

Table 15: Test of consistency (human safety criterion)

Criteria Weights	0.6807	0.1179	0.2014
Criteria	EP	ML	MHA
EP	1× 0.6807	5 × 0.1179	4 × 0.2014
ML	0.2 × 0.6807	1 × 0.1179	0.5 × 0.2014
MHA	0.25 × 0.6807	2 × 0.1179	1 × 0.2014

Table 16: Result for the test of consistency (human safety criterion)

Criteria	EP	ML	MHA	Weighted Average	Criteria Weights	
EP	0.6807	0.5895	0.8056	2.0758	0.6807	3.0495
ML	0.1361	0.1179	0.1007	0.3547	0.1179	3.0090
MHA	0.1702	0.2358	0.2014	0.6074	0.2014	3.0159

$$\frac{\lambda max = 3.0495 + 3.009 + 3.0159}{3}$$

$$\lambda max = 3.0248$$

From Equation 3

$$Consistency\ Index, CI = \frac{\lambda max - n}{n - 1} = \frac{3.0248 - 3}{3 - 1} = \frac{0.0248}{2} = 0.0124$$

$$where\ n = 3$$

$$Consistency\ Ratio = \frac{CI}{RI} where RI = 0.58$$

$$= \frac{0.0124}{0.58}$$

= 0.0214

0.0214< 0.1

Hence, the criterion is consistent and can be used for decision making

Table 17: Machine safety criterion initial matrix

Criteria	RPP	PPP	MG
RPP	1	3	1

PPP	0.3333	1	0.5
MG	1	2	1

Table 18: Sum of the machine safety criterion initial matrix

Criteria	RPP	PPP	MG
RPP	1	3	1
PPP	0.3333	1	0.5
MG	1	2	1
Sum	2.3333	6	2.5

Table 19: Normalized machine safety criterion matrix

Criteria	RPP	PPP	MG	Criteria Weights
RPP	0.4286	0.2000	0.4000	0.3429
PPP	0.1428	0.1667	0.2000	0.1698
MG	0.4286	0.3333	0.4000	0.3873

Table 20: Test of consistency (machine safety criterion)

Criteria Weights	0.3429	0.1698	0.3873
Criteria	RPP	PPP	MG
RPP	1 × 0.3429	3 × 0.1698	1 × 0.3873
PPP	0.3333 × 0.3429	1 × 0.1698	0.5 × 0.3873
MG	1 × 0.3429	2 × 0.1698	1 × 0.3873

Table 21: Result for the test of consistency (machine safety criterion)

Criteria	RPP	PPP	MG	Weighted Average	Criteria Weights	
RPP	0.3429	0.5094	0.3393	1.2416	0.3429	3.6209
PPP	0.1143	0.1698	0.1937	0.4778	0.1698	2.8139
MG	0.3429	0.3396	0.3873	1.0698	0.3873	2.7622

$$\frac{\lambda max = 3.6209 + 2.8139 + 2.7622}{3}$$

$$\lambda max = 3.0657$$

From Equation 3

$$Consistency\ Index, CI = \frac{\lambda max - n}{n - 1} = \frac{3.0657 - 3}{3 - 1} = \frac{0.0657}{2} = 0.03283$$

$$where\ n = 3$$

$$Consistency\ Ratio = \frac{CI}{RI} \qquad where\ RI = 0.58$$

$$= \frac{0.03283}{0.58}$$

= 0.05661

0.05661 < 0.1

Hence, the criterion is consistent and can be used for decision making.

Table 22: Work environment criterion initial matrix

Criteria	PV	HDE	PSM	MHP
PV	1	5	4	7
HDE	1/5	1	½	3
PSM	¼	2	1	3
MHP	1/7	1/3	1/3	1

Table 23: Sum of the work environment safety criterion initial matrix

Criteria	PV	HDE	PSM	MHP
PV	1	5	4	7

HDE	0.2	1	0.5000	3
PSM	0.25	2	1	3
MHP	0.1429	0.3333	0.3333	1
Sum	1.5929	8.3333	5.8333	14

Table 24: Normalised work environment safety criterion matrix

Criteria	PV	HDE	PSM	MHP	Criteria Weights
PV	0.6278	0.6000	0.6857	0.5000	0.6034
HDE	0.1256	0.1200	0.0857	0.2143	0.1364
PSM	0.1570	0.2400	0.1714	0.2143	0.1957
MHP	0.0090	0.0340	0.0571	0.0714	0.0429

Table 25: Test of consistency (work environment safety criterion)

Criteria Weights	0.6034	0.1364	0.1957	0.0429
Criteria	PV	HDE	PSM	MHP
PV	1 × 0.6034	5 × 0.1364	4 × 0.1957	7 × 0.0429
HDE	0.2 × 0.6034	1 × 0.1364	0.5 × 0.1957	3 × 0..0429
PSM	0.25 × 0.6034	2 × 0.1364	1 × 0.1957	3 × 0.0429
MHP	0.1429 × 0.6034	0.3333 × 0.1364	0.3333 × 0.1957	1 × 0.0429

Table 26: Result for the test of consistency (work environment safety criterion)

Criteria	PV	HDE	PSM	MHP	Weighted Average	Criteria Weights	
PV	0.6034	0.6820	0.7828	0.3003	2.3685	0.6034	3.9253
HDE	0.1207	0.1364	0.0979	0.1287	0.4837	0.1364	3.5462
PSM	0.1506	0.2728	0.1957	0.1287	0.7478	0.1957	3.8212
MHP	0.0862	0.0455	0.0652	0.0429	0.2398	0.0429	4.5897

$$\frac{\lambda max = 3.9253 + 3.5462 + 3.8212 + 4.8987}{4}$$

$$\lambda max = 4.0479$$

From Equation 3

$$Consistency\ Index, CI = \frac{\lambda max - n}{n-1} = \frac{4.0479 - 4}{4-1} = \frac{0.0479}{3} = 0.01595$$

$$where\ n = 4$$

$$Consistency\ Ratio = \frac{CI}{RI} \qquad where\ RI = 0.9$$

$$= \frac{0.01595}{0.9}$$

= 0.0177

0.0177 < 0.1

Hence, the criterion is consistent and can be used for decision making

V. Conclusions

From the results of this work-study, a total of fifteen (15) hazards and the risks associated with them were identified in this study. The respective Risk Priority Numbers (RPN) of the hazards were calculated and rated as high-risk, medium risk and low-risk levels. The safety risk assessment was of the manufacturing system was done using the analytic hierarchy process (AHP) approach using three different criteria namely human (employee) safety, machine (equipment) safety and work environment safety. These criteria have their corresponding sub-criteria The AHP analysis done showed that the criteria and sub-criteria are all consistent and can be used in decision making on safety risk assessment in the manufacturing system. The safety risk assessment can be reviewed and updated consistently at least every twelve months to capture other hazards not covered in this study and plant management should ensure that necessary safety precautions and measures are complied with to minimize risks and hazards associated with their operations most especially musculoskeletal disorders.

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