Quantitative assessment of RAM driven risk matrix of offset printing machine

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Abstract. Quantitative assessment of risk matrix through analysis of reliability, availability and maintainability (RAM) is used as quick visual tool for managing potential risk in any continuous production system which can be used for further improved maintenance planning. Fault tree analysis along with failure mode and effect analysis support in assessing risk of minor or major failures associated with different consequences of human impact, production loss, maintenance loss etc. For developing risk matrix, scoring of likelihood and severity are necessary to identify the potential risk zone. An attempt has been made in the present study to assess overall failure scenario of offset-printing machine by analysing reliability of different machine component. Different types of failure frequencies and corresponding failure probability of the machine are set as a value representative likelihood failure data. The critical consequences of these failures are discussed for estimation of actual risk and risk index. Matrix of risk and risk priority number is developed here on the basis of likelihood scores of each kind of failure probability and severity scores by considering different types of breakdown and their associated responsible machine component. Moreover, prioritization of different failure types is validated by MonteCarlo simulation. Based on the risk matrix developed, maintainability and maintenance interval time has been determined which seems to be a novel approach for reduction of risk and breakdown time. Finally, maintenance and safety recommendation on the basis of corresponding risk level and maintainability indicator rating are discussed.

Keywords: risk index, risk priority number, breakdown causes, reliability, availability, maintainability.

1. Introduction

The printing industry comprises of different kind of printing machines which generally aims at client satisfaction, prerequisite profitability and high productivity with quality output. The commercial printing houses are one of such production units where meeting deadline is of utmost importance hence any unforeseen failure or downtime can affect the productivity detrimentally. The high-class quality and efficiency of printing production is achieved by minimizing the failure frequency and breakdown time with proper well-structured maintenance technique. Risk-based maintenance (RBM) management or reliability availability maintainability (RAM) methodology concerns the estimation of frequency of inspection and maintenance scheduling of any running equipment.

Research activities on RBM and RAM has been expanded in many domains throughout the decades. Some of the important research development from 2001 to till date are shown in Table 1. The significant related works carried out recently as illustrated in Table 1 represents a comparative overview of the approaches towards estimation of failures and risks of machineries in different industries like offshore, mining, marine, power generation, electrical, medical etc. Although there are considerable amount of reported works in risk matrix-based assessment in different manufacturing and engineering fields, but in printing industry such works are not well reported to the best of the knowledge of the authors. Considering the research gap the present investigation brings a new perspective on how the productivity parameters such as failure probability, reliability and risk index of the machine can be integrated with the estimation of risk matrix.

Table 1. Summary of recent literature review of risk matrix and maintenance for risk assessment

Research or industry domain and year of paper published	Tools or technique used	Problem addressed	Benefits obtained	Research gap
Circuit breaker of electrical devices (Polimac et. al., 2001) [1]	Maintenance scheduling and semi-quantitative analysis of interval	High maintenance cost w.r.t mean time between failure (MTBF) target	Improvement of performance	Semi-quantitative approach
Heating, ventilation and air conditioning (HVAC) system - (Khan and Haddara, 2003) [2]	Probabilistic approach, fault tree analysis (FTA), quantitative risk estimation	High failure rate in separate subsystem	Exploring of different factors of consequence, risk analysis, primary maintenance planning	Complex quantitative assessment of different risk parameter and lesser focus on maintenance interval time (MaIT) estimation
Power generating plant (Krishnasamy et al., 2005) [3]	Quantitative risk estimation, FTA, probabilistic approach	Higher criticality rate in discrete subsystem	Reduction of risk, scheduling maintenance, improved maintenance planning	Lesser focus on MaIT estimation
Offshore industry (Siswanto and Kurniati, 2018) [4]	Optimal maintenance interval between preventive and corrective maintenance cycle	High failure rate (FR) and maintenance cost	Improvement of mean time to failure (MTTF), mean time to repair (MTTR), availability, maintainability	Need of risk matrix assessment
Newspaper printing house - (Kar and Pal, 2019a) [5]	Pareto analysis, quantitative risk assessment of non-identical machines, availability analysis	High FR and maintenance cost	Finding of highest risky machine and suggestions for failure reduction in cost	Risk zone identification and estimation of maintenance interval time is missing
Offshore industry (Leonia et al., 2019) [6]	Bayesian network for risk assessment, FTA, risk matrix, maintenance interval time (MaIT)	High risk for different component	Identifying of critical component on the basis of respective maintenance time, prediction of maintenance interval by failure probability of minor, major and catastrophic risk zones of each component	Study need on redundant and standby component for comparison, risk analysis on the basis of cost need to consider
Silica sand production plant (Akaeje et al., 2021) [7]	FTA, reliability block diagram (RBD), failure mode, effect and criticality analysis (FMECA), Delphi exercise for maintainability indicator rating (MIR)	Breakdown and maintenance	Improvement of MTTR	Various attributes of maintainability assessment are qualitative and mostly based on linguistic scale

mining industry (Tubis et al., 2022) [8]	Identification of fuzzy based risk	Safety issues, discrete failure scenarios on different machineries	Estimation and analysis of risk, maintenance decision	Absence of data driven model, resource allocation problem on maintenance, lacking multi-criteria decision-making methods
Unmanned aerial vehical (UAV) drone industry (Imani et al., 2022) [9]	FTA, failure mode and effect analysis (FMEA)	Failure of costly components	Damage identification and analysis	Intensive analysis of reliability and maintenance are missing along with safety recommendation
Propulsion machinery and marine industry (Domeh et al., 2022) [10]	Equipment based failure analysis, risk modelling, MaIT	Breakdown in different components in fishing vessel	Risk reduction, profitability analysis, easy MaIT estimation	Lacking consequence analysis of non-monitory event
Medical instrumentation (Sukma et al., 2022) [11]	FMEA, risk priority number (RPN) estimation, fish bone diagram (FBD)	Failure, wastage, six big losses	Improvement of overall equipment effectiveness (OEE) and failure reduction	Qualitative RPN calculation, analysis needed for longer span with sensor data
CNC production machineries (Atikno et al., 2022) [12]	FMEA, FBD, 5Why+1How technique, RPN estimation	high downtime		Qualitative estimation of RPN value
Nonwoven textile process (Pohlmeyer et al., 2022) [13]	FMEA, FTA, risk matrix	Unscheduled process downtime	Optimization of failure occurrence for availability increment	Need to analyse improvement of frequency and damage classes of risk matrix, also need large amount of production data for the model implementation
Cement industry (Taufik et al., 2023) [14]	Reliability, availability and Maintainability (RAM) analysis, maintenance interval on the basis of age replacement model	High failure and downtime	Increased reliability and availability	Unchanged for maintainability
Govt. and international agencies (Vaezi et al., 2023) [15]	Extension of different kind of risk formulation and resilience-based risk matrix	Local, national and global disaster risk due to socio-political and technological shifts	Improves accuracy for risk mapping in matrix	Resilience in terms of human error, human health, key human expert loss etc. may be more subjective for drawing final conclusion for risk matrix
Offshore platform (Attia and Sinha, 2024) [16]	Generic failure frequency (GFF), variances of consequences, risk matrix	High failure rate and loss of containment	Risk comparison	Need of comparison between risk matrix and RPN matrix, need of availability, maintainability and MaIT estimation

Construction project (Acebes et al., 2024) [17]	Monte Carlo simulation-based risk prioritisation, risk matrix	Risk impact on duration objective and cost objective	Quantitative approach for probability and impact of risk	Resilient factors of failure or severity are not considered, need MaIT and maintainability estimation and maintenance planning
Newspaper printing house (Kar and Pal, 2024) [18]	Lean six-sigma and statistical techniques like SPC and ANOVA	High machine downtime, lower machine operating time and higher machine idle time	Improvement of productivity parameters	Integration of IIoT and machine learning
Medical devices (Haimerl and Reich, 2025) [19]	Risk matrix, machine learning (ML) classification model	High risk events and their severity in terms of cost	Ranking of risk in w.r.t cost	Test performed on simple decision case with exemplary period of time. Need to focus on real life complex system where high maintenance cost is associated. Resilient factors are not considered, maintenance planning missing on the basis of risk prioritization etc.
Printing and packaging (This Paper)	Quantitative resilient approach for risk Matrix estimation, RBM, reliability, availability, FTA, FMEA, Pareto analysis, Monte Carlo simulation-based risk prioritization, risk index (RI), RPN, maintainability, MaIT, IIoT, maintenance recommendation guidelines	Breakdown causes and affects machine unit. High inspection-repair time and breakdown loss cost	Analysis and improvement scope for reliability, maintainability, availability and MaIT, MIR etc. and reduction of risk, failure, downtime and breakdown cost, improved maintenance planning, etc.	

The risk matrix approach has been widely practiced in several industries as a straightforward technique for analysing risks and aiding in decision-making regarding priority actions. Risk matrix serves as a tool for subjective assessment and mapping of a discrete risk category to each combination of consequence and likelihood. Risk-based maintenance (RBM) allows the company to improve machine performance and reduce maintenance costs. RBM methodology mainly depends on statistical or historical data, and it accurately measures the detectability and probability of failure along with its consequences which helps the study to reduce the dependency on expert opinion and make it proper for quantitative assessment of matrix of actual risk status of risk priority number (RPN) of a system.

In the present investigation, the offset printing machine of a commercial printing company is considered where different root causes of breakdown and their effect are analyzed by fault tree analysis (FTA) and systematic failure mode and effect analysis (FMEA) technique. The monthly

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availability and reliability is checked along with their failure probability and consequences. Different types of causes for breakdown are identified and scored in terms of likelihood, severity and inspection (or detectability) etc. which are mapped in the risk matrix and RPN matrix to identify the high-risk zone. Then 80-20 % rule of Pareto analysis and MonteCarlo simulation is used for the validity of estimated high risk zone. Maintenance interval time (MaIT) are also estimated for individual breakdown types. In this study quantitative resilience factors are considered for the estimation of severity in terms of breakdown time, breakdown loss cost and detection in terms of inspection time to develop the RPN matrix. Apart from this, presented work also provides an outline of improved maintenance planning based on both the risk matrix and RPN matrix.

The objective of this research is to estimate the risk matrix in terms of actual risk and risk priority number for the different breakdown causes along with responsible machine components by considering both breakdown time and breakdown loss cost. It is also aimed to determine the maintenance interval time for different breakdown causes for improved maintenance planning.

2. Materials and methods

This section deals mainly with the details of the machine under study followed by representation of basic data of failure number, breakdown time, runtime, good pieces and wastages for a period of one year. Then breakdown details, causes and the responsible machine components are analyzed by both fault tree analysis (FTA) and failure mode and effect analysis (FMEA). Lastly, the procedure for assessment of risk index has been discussed. Also scores for criteria of different levels of failure, risk and interval time have been assessed for the purpose of evaluation of risk matrix. The proposed methodology for conducting this study has been demonstrated in the framework as shown in Fig. 1.

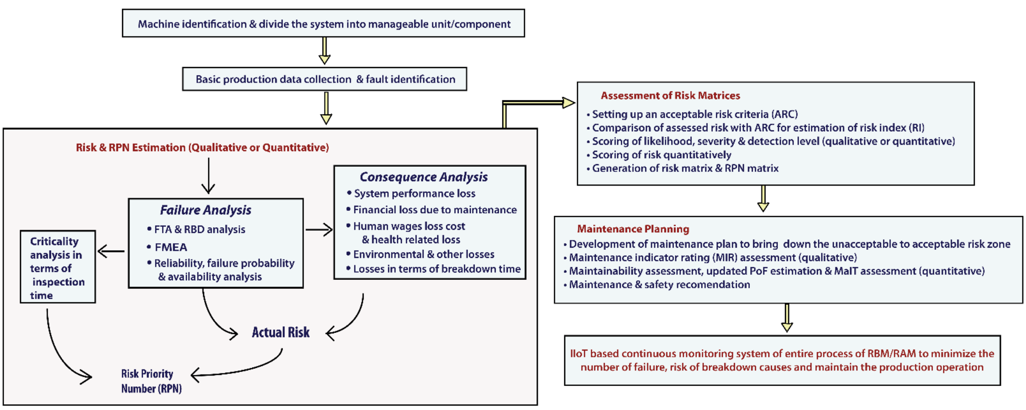

Fig. 1. Proposed framework of RBM/RAM methodology for risk assessment

2.1. Machine details

The proposed assessment was conducted on a sheetfed offset printing machine (make: Heidelberg, Germany; model No.: CD102). It was manufactured in 2002 and installed in 2005 at United Arab Emirates (UAE) based printing company. It is four-color printing machine having black, cyan, magenta, yellow printing couple with one special colour printing couple. This machine also consists of seven units namely feeding unit, inking unit (in each couple), dampening unit (in each couple), printing unit (in each couple), coating/varnish unit, drying unit, delivery unit as illustrated in Fig. 2. Special printing couple and varnishing unit are generally used for specialty printing. It is to be mentioned that prepress section and post press section are not included in Fig. 2 but play an important role for print production. The machine components as mentioned are marked in Fig. 2 for further processing.

Its plate size is 79×103 cm, maximum paper size is 72×102 cm and maximum print format is 71×102 cm. Different types of coated, uncoated, recycled, texture, matte, glossy, wood-free paper are used on the basis of job. Paper grammage is used in the printing machine in between 80-450 gsm as per job requirement. Offset inks and normal consumables are used for printing. Inside the printing press, the temperature is maintained between 20-26 °C and average relative air humidity was 75-85 %. Most of the printing jobs were scheduled mainly in day shift, however it has both 2-shift roaster and 3-shift roaster depending on job load. Though its maximum speed is up to 15000 impressions per hour, hence it operates at an average printing speed of 4560 impressions per hour as per job requirement from client and availability of paper type and paper grammage. Out of many printing machines, CD102 printing machine is chosen due to its age and failure scenario however it is assumed that the operational condition of the machine is the same.

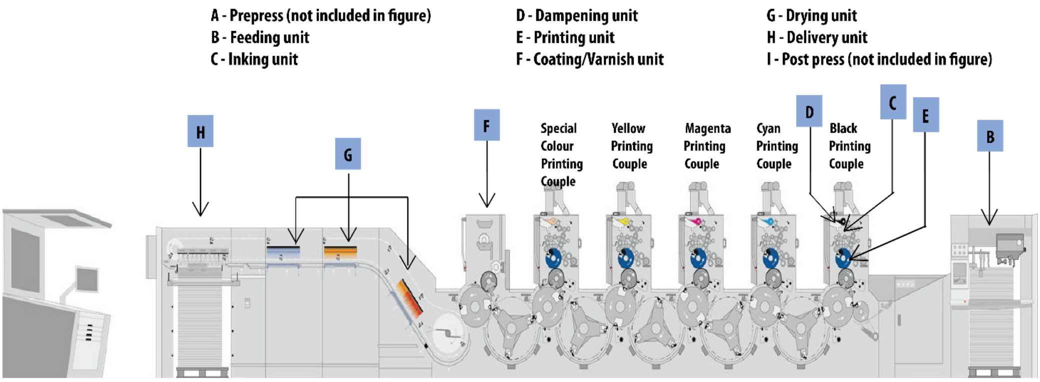

Fig. 2. Four colour sheetfed offset printing machine with special colour couple

2.2. Data representation

The basic operational data of failure number, breakdown time, runtime, good pieces and wastages has been obtained for 309 days out of 365 days which are represented in 3D bubble plot as shown in Fig. 3. The plot shows the numerical values of runtime, breakdown time and number of failures in a 3-Dimensional space best on their X-Y-Z coordinates. Each bubble represents the category of all input variables namely runtime, breakdown time, number of failures, number of good pieces and number of waste pieces. The size of each bubble indicates the number of good pieces obtained from the machine while the colour (from green to red) of each bubble represents the number of waste pieces obtained from the machine. Effect of runtime and breakdown time and good pieces and waste pieces on failure number is also observed here. It is seen that failure number is well dependent on the breakdown time and number of wastages.

2.3. Breakdown details and causes

The basic data are failure number, runtime, breakdown time, number of wastage and good pieces of the printing machine which are observed and then collected from the daily management information system (MIS) during the period of 1st January 2021 to 31st December 2021. From the collected data, various breakdown times and number of failures are identified and the total number of 16 breakdown causes are analysed yearly by failure mode and effect analysis (FMEA) approach which is shown in Table 2. Here the responsible machine components or units are identified for respective breakdown causes. Fig. 4 shows the corresponding pareto analysis of failure number in where dominant failures for different breakdown types will be prioritized for improvement based on the FMEA results. This analysis will again lead to risk estimation both qualitatively and quantitatively later in this study.

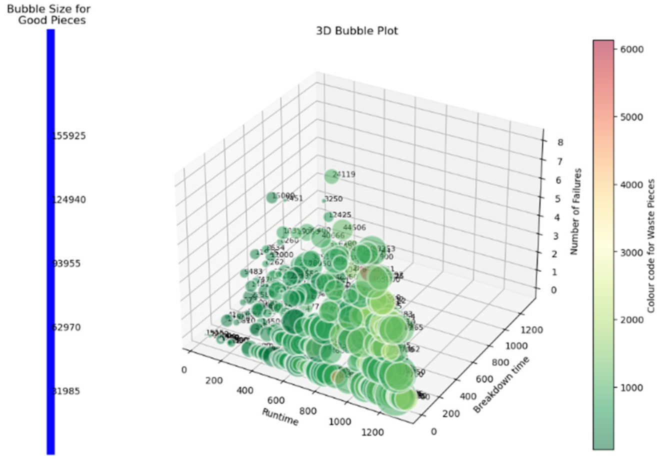

Fig. 3. 3D Bubble plot of runtime, downtime, failure number, good pieces and waste pieces on daily basis

Table 2. Failure mode and effect analysis of CD102 printing machine in terms of failure types and affected responsible machine unit

Breakdown cause	Breakdown effect	Abbreviation of breakdown type	Combination of affected responsible machine unit	Breakdown time (in minute)	Failure number
• Plate delay (p) due to prepress. • Plate change (pc) due plate tear or damage.	• Printing operation is delayed. • Printing quality will deteriorate leading to slurring, misregistration, scumming etc. and gave unwanted mark or presence of debris in paper etc.	p/pc	A, E	6785	137
• Drying of printed ink (id) on paper (i). Malfunction in IR dryer section or improper mixture of drying solvent (drying accelerators) to the ink.	• Witnessed issue of printing quality and smeared on the backside of the printed paper which will delay the post press operation.	d/id	G	2600	94
• Ink mix (i) due to pantone colour generation. • Ink change (ic) due to new job. • Ink waiting (iw) for prepress confirmation or inventory or logistic delay.	• Delay on printing	i/ic/iw	A, C	2340	65
• Client approval delay.	• Delay on printing and affected other scheduled jobs.	ca	A, I	4320	54

• Paper delay due to inventory management or availability. Paper loading (pl) and paper cutting. • Paper change due to non-uniform stock surface, paper unable to withstand the tack of ink or printing force. • High or low relative humidity (RH) affected on paper printing quality.	• Delay on printing • Mottling and delamination observed. • Due to high RH, paper curled and observed dot doubling, smudging dots on paper, sticking of multiple printed sheets together which affect the overall printing operation. Also, due to low RH, paper faced problem of stacking, trimming and folding. As dry paper is more prone to static electricity thus frequent paper jam is observed.	paper	A, E	1515	41
• Blanket clean of foreign particle and dust including blanket pressure balance	• Showed several problems like slurring, hickeys, piling, picking/contamination, mottling on print.	b	E	930	30
• Breakdown or schedule maintenance	• Production are delayed for maintenance action	mb/ms	B, C, D, E, F, G, H	6647	30
• Other delay (Plate tear, pneumatic leakage, gear failure, impression seating problem etc.)	• Observed mark on paper, colour mismatch, paper mis-registration problem and other problems etc.	other delay	B, C, D, E, H	2865	30
• Quality check or management approval delay	• Delay on printing and reworks	qc/ma	A, I	1465	24
Setting error	Printing quality	s	C, D, E	770	24
• Job down for several minor reasons but repairable by in press worker	• Minor or moderate effect on printing quality and quantity	jd	B, C, D, E, F, G, H	1205	14
• Varnish section problem due to IR curing section malfunction. • Residue of varnish substance deposited in servo-valves, clogging of oil etc inside flow lines	• Low printing quality, print looks milky or cloudy. • As a result caused premature bearing and gear wear in compressor.	v	F	805	8
• Blanket damage	• Printing quality issue and monetary loss	bc	E	200	6
• Dampening setting problem due to improper fountain solution mix, ink is waterlogged and blanket is too tacky	• Piling problem	ds	D	215	4

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• Coating blade damage due to premature wear, imbalance pressure or scoring problem in doctor blade	• Loss of volume in anilox roll or loss of ink transfer to substrate thus blade repaired or completely replaced.	cb	F	145	2
• Maintenance for pipe leakage	• Printing quality and malfunction of system	mpl	B, D, H	150	1
		Total		32957	564

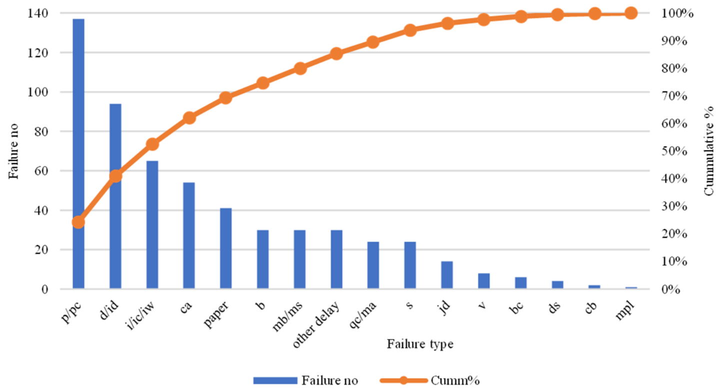

Fig. 4. Pareto analysis of failure number of individual breakdown type

2.4. Risk assessment

Risk assessment of any machine identifies the present status of the machine and helps production team to plan for the reduction of the probable risk of hazards, continuous production and improve production efficiency along with its economical profitability. It is a technique that identifies, characterizes, quantifies and evaluates the loss from an event. The risk assessment needs failure mode and effect analysis (FMEA) and pareto analysis for each failure. After estimation of probability of these breakdown occurrences, the effects are monitored in terms of time, cost, performance loss, human, environment, business interruption etc. Then the combination of these failures and its effects are used to understand and compare the risk scenario to minimize each kind of risk present in the machine.

Risk assessment of any machine might either be quantitative or qualitative depending on the resource availability in the existing setup. Quantitative risk estimation is the product of probability of failure (PoF) and consequence of a failure (CoF) events. The proposed risk-based maintenance (RBM) based on RAM aims to reduce the overall risk scenario of the operating printing facility. RBM/RAM implementation will reduce the occurrence of unexpected failure by implementing three modules namely risk determination, risk index evaluation and maintenance planning.

The first module of RBM/RAM methodology consists of the combination of sequential failure event which is to be quantified and calculated probability. To do that, time-motion study are conducted to identify the failures with proper systematic fault-finding techniques like FTA, reliability block diagram (RBD) and FMEA. Then an in-depth analysis are made with those identified failures for further reliability assessment. However, reliability assessment is one of most popular and important parameters to analyse potential failure scenarios of a machine. By definition, it is the ability of an item to perform a required function under given conditions for a given interval of time before it is undergone a breakdown. Mathematically, reliability function is derived from Eq. (1) where, $R(t)$ is the reliability at time t, $F(t)$ is cumulative failure distribution (CDF) function or correlation coefficient and $f(x)$ is failure probability density function (PDF). This probabilistic failure model can be estimated by Pearson correlation technique as shown in

Eq. (2):

$$R(t) = 1 - PoF = 1 - F(t) = 1 - \int_0^t f(x)dx, \tag{1}$$

$$PoF\ (or\ F(t)) = \frac{[N * \Sigma\{x * f(x)\}] - \{\Sigma x * \Sigma f(x)\}}{\sqrt{[\{N * \Sigma(x^2)\} - (\Sigma x)^2][\{N * \Sigma f(x^2)\} - \{\Sigma f(x)\}^2]}}, \tag{2}$$

where, x – breakdown time (in minute), $f(x)$ – Cumulative % of failure (calculated from number of failures per day and sum of number of failures for one year), N – sum of total operating time for one year (in minute) and $F(t)$ – correlation coefficient.

From the concept of probability, it is known that the correlation coefficient must be in between +1.0 to –1.0 [5]. If the correlation coefficient estimates positive value, then the failure rate is increasing, otherwise the rate is decreasing. The analysis of bathtub curve [20] explains the different significant stages of failure i.e. showing infant mortality, useful life and wear-out stage of machine by the help of estimated failure rate (λ) as shown in Eq. (3) where MTBF is mean time between failure:

$$Failure\ rate\ (\lambda) = \frac{\text{failure number}}{\text{total runtime}} = \frac{1}{MTBF}. \tag{3}$$

During risk analysis availability is also important factor as it explores the availability of a machine during breakdown and repairment. Hence, availability and reliability are two different and necessary criteria in practicing maintenance methodologies. Reliability deals with the system in use which completes its task before failure occurs within a specified period of time. By definition availability is the probability of a system that has been failed and experienced by a repair action during its available time. It can also be defined as the probability of system which is readily available to perform the required function in the given work environment for a specified period of time and under stipulated working conditions. In general the availability A_s of a system is a complex function of reliability $R(t)$, maintainability $M(t)$ and supply effectiveness S_E which can also be expressed by Eq. (4):

$$A_s = f\{R(t), M(t), S_E\}. \tag{4}$$

Mathematically availability can be sub-categorized into inherent availability (A_{in}) and operational availability (A_{op}) which is defined by Eq. (5) and Eq. (6) for better understanding:

$$A_{in} = \frac{MTBF}{MTBF + MTTR} = \frac{\text{Runtime}}{\text{Runtime + Repair time}}, \tag{5}$$

$$A_{op} = \frac{MTBF}{MTBF + MDT} = \frac{\text{Runtime}}{\text{Runtime + Breakdown time}}. \tag{6}$$

Here, mean time to repair or MTTR is the ratio of repair time to failure number and mean downtime or MDT is the ratio of breakdown time to failure number where breakdown time is the summation of inspection time and repair or replacement time of each and every failure causes etc.

After reliability or failure assessment, consequence assessment are conducted whose main objective is to prioritize equipment and their components on the basis of their contribution to a system failure. So, consequence or severity of failure are estimated on the basis of different accounted loss caused from human wages loss cost, system performance loss, financial loss due to maintenance, environment loss, human health loss, any other losses etc.

Human wages loss cost (HWLC) is the loss which includes the cost of workers idleness due to machine breakdown. Breakdown time-period (DT) is the combination of both inspection time and repair time. System performance loss during production due to component failure which can be assessed [10, 20] either by expert's opinion or by calculating the production loss cost (PLC). Maintenance loss cost (MLC) accounts for damage to the property or asset which is the summation of different cost of inspection, specialized equipment or personnel hired, maintenance, spare parts repair or replacement etc. Human health loss cost (HHLC) is the cost of health-related expenses of all the affected staffs during production due to illness or accident or hospitalization or disability etc. Environment loss cost (ELC) is the cost of damage per area zone within the building, plant, residence, agricultural land etc. to restore from the damaged state to natural ecofriendly state. However, in this study environmental loss is neglected and human health loss didn't occur during production. All the losses and consequences of failure (CoF) are summarized in Eqs. (7) to (10):

$$HWLC = DT \times \text{human labour cost per unit time}, \quad (7)$$

$$PLC = (\%\text{wastage}) \times (\text{raw material cost}), \quad (8)$$

$$MLC = \sum \begin{pmatrix} \text{cost of inspection , repair, specialized hired personnel,} \\ \text{spare parts replacement etc. of different breakdown} \end{pmatrix}, \quad (9)$$

$$CoF = \sum (HWLC, PLC, MLC, HHLC, ELC, \text{other lossess}). \quad (10)$$

In the second module of RBM/RAM acceptable risk criteria (ARC) is set according to the ALARP (as low as reasonably possible) to determine the risk index (RI) as shown in Eq. (11). If the RI value is more than 1 then it is said to be highly risky:

$$RI = \frac{\text{Actual risk}}{ARC} = \frac{PoF \times CoF}{ARC}. \quad (11)$$

Risk of the machine in terms of both breakdown causes and machine components can be assessed quantitatively with the help of risk matrix by representing possible system risk levels or risk score values. The components of the risk matrix are likelihood, severity and risk impact. The likelihood of risk or probability of failure occurrence from an event or historical data has been considered as five ranges like remote, unlikely, possible, probable and highly probable which is quantified by giving scores from 1 to 5 as illustrated in Table 3. The failure impact is the severity or consequence of failures which have been considered as five ranges i.e. negligible, minor, significant, major, catastrophic which is again quantified by giving scores from 1 to 5 which is also illustrated in Table 3. The risk level criteria have been set as per industrial norms and regulations which is illustrated in Table 4. Table 5 shows also the criteria for setting scores for different level of inspection time.

Risk priority number (RPN) measurement is important for subjective assessment of risk and for prioritizing breakdown occurrence for corrective actions where inspection (or detectability) factor is considered. It can be said that if inspection time can be lowered then downtime can be reduced and if inspection is zero then downtime consists of repair time only. As per availability analysis, breakdown time is the combination of time of inspection (or detection) and repair. An attempt has been made to quantify the detection score level by assessing the inspection time (or detection time). Risk priority number (RPN) is the product of PoF or likelihood or occurrence (O), CoF or severity (S) and inspection or detection (D) level as shown in Eq. (12). Finally, in RPN matrix format, detection or inspection score and risk score (product of PoF and CoF) is set on x-axis and y-axis respectively for matrix visualization:

$$\text{RPN} = \text{occurrence (O)} \times \text{severity (S)} \times \text{detection (D)} = \text{Risk score} \times \text{Detection score}. \quad (12)$$

In the third module of RBM/RAM methodology, reduction of risk level is executed by reducing PoF with the help of proper maintenance planning and managerial implication. Maintenance planning includes maintainability parameters and proper implementation of maintenance decisions made by management. For proper maintenance action implementation, estimation of optimal maintenance duration along with re-estimation of the updated PoF, CoF and RI are generated to account for the probable profit gain or improvement of other parameter. Maintainability can be derived both qualitatively and quantitatively, which is the characteristics of maintenance planning, material design and installation.

Table 3. Scores for criteria of likelihood and severity of failure

Likelihood criteria						
PoF category	Probability (quantitative)	Likelihood (qualitative)	Industry norms (qualitative)	Historical data (quantitative)	Management opinion (qualitative)	Score
Highly probable (near certain)	0.8-1	Regularly	Very common in industry	Extensive record of occurrence	Almost certain	5
Probable (or likely)	0.6-0.8	Often	Often happens in industry	Record of frequent occurrence	Likely	4
Possible	0.4-0.6	Sometimes	Sometime occurs in industry	Record of occasional occurrence	Possible	3
Unlikely	0.2-0.4	Rare	Rarely expected in industry	Few records of occurrence	Unlikely	2
Remote (or near zero)	0-0.2	Almost never	Not expected in industry	No record of occurrence	Very unlikely	1

Severity criteria						
CoF category	People (quantitative)	Property (quantitative)	Economic assets (quantitative)	Information (qualitative)	Human health, industrial and market reputation (qualitative)	Score
Catastrophic	Multiple fatalities	Complete destruction of property	Bankruptcy or severe financial loss	Total loss of critical data	Catastrophic damage to public image, company integrity irreparably damaged	5
Major	Serious injuries leading to hospitalization	Major damage requires extensive repair	Major financial loss	Major loss of data, partially recoverable	Major damage to public image, long term impact	4
Significant	Major injuries requiring medical treatment	Significant damage requiring extensive repair	Significant financial loss	Significant loss of data, recoverable with effort	Significant damage to public image, recoverable with effort	3
Minor	Minor injuries requiring first aid	Minor damage or easily repairable	Minor financial loss	Minor loss of data, quickly recoverable	Minor public image damage, easily recoverable	2
Negligible	Nil or insignificant injury	Minimum or no damage	Negligible financial loss	No loss of data	Negligible impact on public image	1

Maintainability indicator rating (MIR) can be derived by Delphi technique [7, 21] for easy and quick analysis of maintenance. It is a qualitative approach on the basis of scaling of maintenance complexity level criteria as tabulated in Table 6 with a expert panel made up of managers, engineers, technicians and operators who are operating and maintaining the required assets or equipment. It may also require repetitive sets of structured questionnaires session for probable best fitted maintenance criteria outcome.

Table 4. Scores for criteria of different risk level

Category	Risk zone	Risk level criteria	Score
Extreme	Very risky	Highly intolerable, executive or topmost management should address immediately	21 to 25
High	Risky	Intolerable, senior management need to address urgent basis	16 to 20
Medium	Medium	Tolerable or moderate, senior or mid-level management should monitor and reduce as low as reasonably practicable (ALARP)	11 to 15
Low	Safe	Risk should be managed by frontline manager using routine procedures to reduce them to ALARP	6 to 10
Very low	Very safe	Acceptable risks managed by routine check-up	1 to 5

Table 5. Scores for criteria of different level of inspection time

Inspection level criteria			
Category	Inspection period	Significance	Score
Extreme	Very high time period	Very critical breakdown and very hard to identify the problem with very high inspection cost	21 to 25
High	High time period	Critical breakdown and hard to identify the problem with high inspection cost	16 to 20
Medium	Medium time period	Moderate breakdown and normal inspection time with medium inspection cost	11 to 15
Low	Low time period	General breakdown and easy to inspect with lower inspection cost	6 to 10
Very low	Very low time period	Minor breakdown and very easy to inspect with zero inspection cost	1 to 5

Table 6. MIR criteria under Delphi approach

Level of maintenance complexity along with its criteria remark
L1 Basic maintenance approach is performed when the unit is online or semi-operative. It includes easy repair, adjustment or replacement of small components without total shutdown, dismantling or disassembling etc.
L2 Maintenance action require repair or replacement of machine components in partial offline or online mode of machine operations. As such intensive failure finding is not required as the maintenance task are known scheduled or corrective actions
L3 Maintenance action as complaint approach which requires failure identification and diagnosis keeping the unit off-line or partial shutdown mode
L4 It undergoes predictive maintenance actions, requiring extensive amount of inspection, testing or corrective task whenever the unit is in total off-line mode
L5 It undergoes pro-active maintenance approach with total unit modification or upgradation which includes total unit shut down before maintenance action is performed

It is known that maintainability of an equipment is the restoration property from breakdown to its original position within a specific time period after completion of the recommended maintenance action. Similar to reliability investigation, theory of probability distributions plays a significant role in maintainability analysis as well. Maintainability percentage of the machinery was predicted according to the repair time, begins with time $t = 0$ and will be finished at time t [20, 22]. The mathematical form of maintainability function is mentioned in Eq. (13), where t indicates the time to repair, $g(t)$ denotes the repair time of probability density function (PDF) and $M(t)$ indicates the function of maintainability:

$$M(t) = \int_0^t g(t)dt. \tag{13}$$

However, for quantitative approach, the percentage of maintainability is estimated by using Pearson correlation technique and shown in Eq. (14), where, x – repair or replacement time of said breakdown (in minute), $g(x)$ – cumulative % of repairment of existing failure (which is calculated from number of repair per day and sum of number of repairs for one year), N – sum of total operating time for one year (in minute) and $M(t)$ – correlation coefficient:

$$M(t)) = \frac{[N * \Sigma\{x * g(x)\}] - \{\Sigma x * \Sigma g(x)\}}{\sqrt{[\{N * \Sigma(x^2)\} - (\Sigma\, x)^2][\{N * \Sigma\, g(x^2)\} - \{\Sigma\, g(x)\}^2]}}. \quad (14)$$

Here prediction of optimal maintenance duration is accomplished for affected machine or subsystem by determining maintenance interval time (MaIT). It is estimated for the justification of the improved maintenance planning, reliability or efficiency of machine in a production system. The mathematical expression of MaIT is shown in Eq. (15) [6, 10]:

$$MaIT = \left\{\frac{\ln(1 - PoF_U)}{\ln(1 - PoF_E)}\right\} \cdot t, \quad (15)$$

where PoF_U is the updated failure probability after maintenance planning and PoF_E is the existing failure probability and t is the annual runtime (in days) for maintenance interval.

3. Results

This section shows the results of probability of failure, consequences of failure and availability of the machine under study which are analysed both monthly and annually. Based on these results, actual risks and risk indices are estimated. Prioritization of actual risks is obtained using MonteCarlo simulation method. Also, different interval criteria of scoring of different risk parameters are analysed and status of score results of risk values and RPN values for different combinations of breakdown types are assessed. Based on these score values, different types of risk matrices and RPN matrices are generated. Then maintenance interval time for each cause of breakdown type is estimated for improved maintenance planning.

3.1. Failure and system vulnerability analysis

The production system line investigation in Table 2 shows that the main systems that affect the product quality are caused by different failure causes of different units of sheetfed printing machine of Heidelberg CD102. To identify all these possible causes of failure leading to undesired system stoppage fault tree analysis (FTA) is conducted [23]. It is a probabilistic top-down approach and used in safety and reliability engineering to show how a system can fail and to determine the best ways to reduce risk. To perform FTA, failures are identified and defined then it is constructed with graphical logic representation of fault events as shown in Fig. 5(a). Here the basic events namely the reasons or items are placed at the bottom, then they are connected with respective logic gates to form intermediate events and finally top undesired event of ‘breakdown of machine’. It is important to note that OR gates are used only when any one input event happens/occurs from all the input events then the output event will occur whereas AND gate are used when all inputs have occurred then output event occurs. For example, failure cause of ‘p/pc’ is formed with ‘OR’ logic gate by the basic events of plate change (p) and plate crack (pc). Similarly, ‘paper’ is constructed with paper loading (PL), paper cutting, inventory delay, non-uniform stock of paper, improper relative humidity (RH) etc. There are few individual and undeveloped events like ‘ca’, ‘qc/ma’, ‘s’, ‘mpl’, ‘bc’ etc. which are directly connected to top event for machine failure. The corresponding failure probabilities for each breakdown causes are also analysed later.

The vulnerability of the said production system under investigation is analysed by applying reliability block diagram (RBD) analysis tool [7]. RBD is an important tool in maintenance operation that can be applied in prospective and retrospective events (redesign, modification or continuous improvement) of a machine. It displays the logical connections and interaction among the different components that make up the system using asset blocks. Then these blocks can be analysed using mathematical methods to determine the level of system vulnerability. The input of the RBD is obtained from the FTA in Fig. 5(b), since RBD is the natural outcome of FTA. In designing the equivalent RBD of the FTA as shown in Fig. 5(b), the OR-gate was represented in a series, whereas the AND-gate is a parallel arrangement in the RBD.

However, FTA is the complementary tool of FMEA in risk analysis but the only difference is that it does not give account on the prioritization of failure event modes whereas FMEA can capture potential failures and their impact and risk which can be used for prioritizing and scaling for the estimation of risk priority number for failure mode effect and criticality (FMEA/FMECA) assessment as shown earlier in Table 2. Thus, after completing the system failure investigation and its vulnerability to producing poor quality products or system breakdown, FMEA analysis is carried out to drill down to component level. This is vital to understand the failure mode of each basic event from the FTA and thus gives clarity to the risk priority of individual event and later directs to the estimation of RI and RPN in terms of both breakdown time and breakdown loss cost.

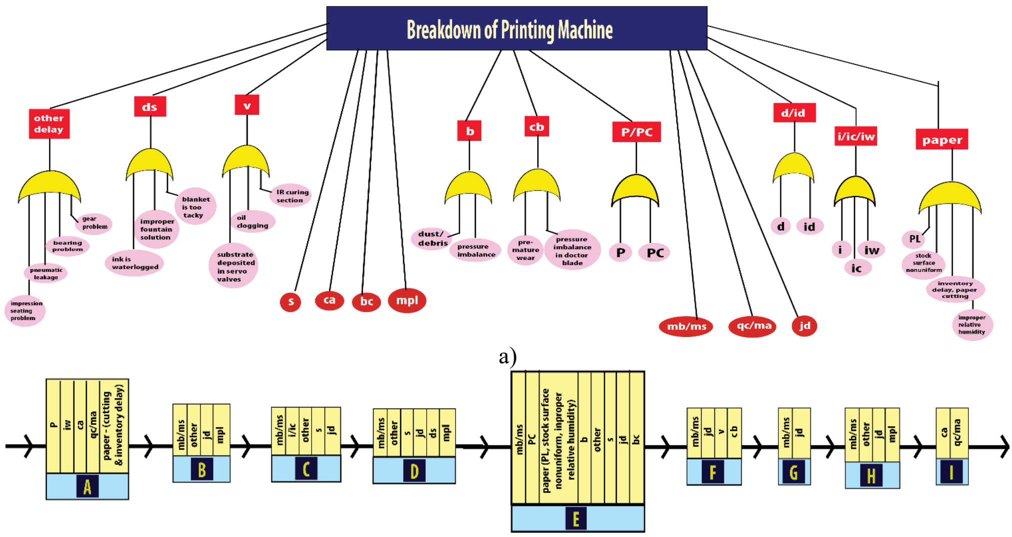

Fig. 5. Analysis of CD102 on the basis of breakdown causes or type in their respective printing machine unit a) FTA and b) RBD

3.2. Probability of failure (PoF)

Failure probability is estimated from the collected press data as it is the function of runtime, breakdown time and failure number. Table 7 represents the monthly reliability; probability of failure and failure rate estimated from Eqs. (1), (2) and (3). Applying Pearson's correlation method, the PoF and reliability value of the printing machine is 0.6228 and 0.3772 for 309 production day in a year. Also, failure rate is used for the representation of bath-tub curve obtained from the daily production data of one year as shown in Fig. 6. Fig. 7 shows the graphical representation of monthly failure probability and its reliability analysis. The bathtub curve presented here indicates that the machine under study is entering into the 'wear-out' stage from its 'useful life cycle' stage.

Table 7. Failure analysis

No of months	No of days	$F(t)$	$R(t)$	λ
Jan	27	65.32 %	34.68 %	0.00336
Feb	24	64.26 %	35.74 %	0.00581
Mar	26	56.45 %	43.55 %	0.0023
Apr	23	72.12 %	27.88 %	0.00317
May	23	61.95 %	38.05 %	0.00132
June	26	56.20 %	43.80 %	0.00131
July	26	49.46 %	50.54 %	0.00163
Aug	27	60.33 %	39.67 %	0.00101
Sep	26	54.65 %	45.35 %	0.0016
Oct	25	62.34 %	37.66 %	0.00146
Nov	29	60.77 %	39.23 %	0.00337
Dec	27	53.14 %	46.86 %	0.00438
Total for 1 year	309	62.28 %	37.72 %	0.00247

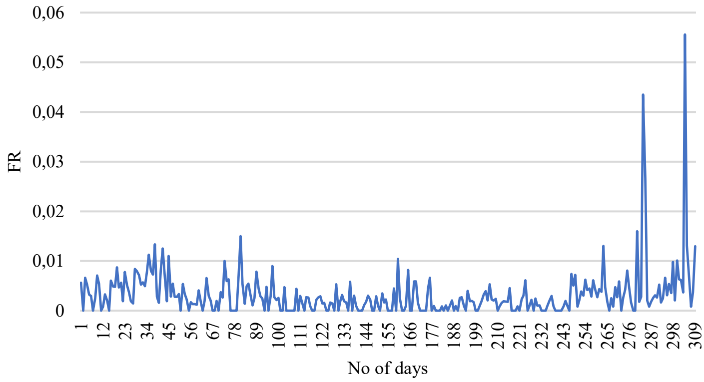

Fig. 6. Bath-tub curve for 309 operational days out of 365 days

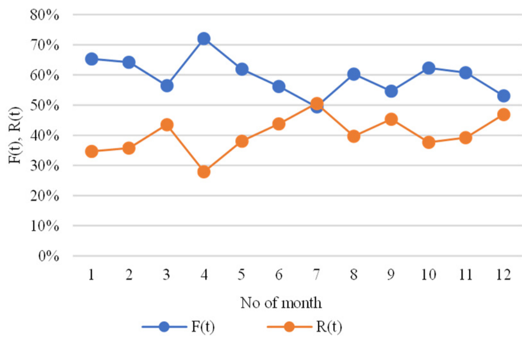

Fig. 7. Monthly failure probability and reliability analysis

After reliability and failure analysis, different availability parameters are checked to understand the inspection and repair status and scenario of printing machine which are tabulated in Table 8 and illustrated in Fig. 8 on monthly basis. It is important to note that the inspection rate (IpR) is the ratio of failure number to inspection time. Also repair rate (RpR) is the ratio of failure number and repair time. IpR and RpR is the integral part of availability analysis and also linked to maintenance analysis. It is seen that lower the failure rate in terms of IpR and RpR, higher the availability of a machine which implies improved productivity. But as the machine is slowly entering into wear-out stage from useful life period, the failure rate is increasing with respective inspection and repairment operation and as a result availability is decreasing gradually.

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Table 8. Availability analysis of CD102

	Ain	Aop	(IpR)	(RpR)
January	0.936721	0.879885	0.0487627	0.049777
February	0.898454	0.832527	0.0659631	0.05144
March	0.944459	0.916267	0.0706638	0.039146
April	0.908451	0.824144	0.0281426	0.031447
May	0.968452	0.938705	0.0403587	0.040541
June	0.962805	0.9218	0.0282486	0.033784
July	0.959171	0.877506	0.0167742	0.038235
August	0.971439	0.92892	0.0214876	0.034437
September	0.938008	0.854313	0.0153527	0.024262
October	0.948097	0.903764	0.0282158	0.026667
November	0.908097	0.874495	0.0796964	0.03332
December	0.855595	0.764886	0.0315754	0.025931

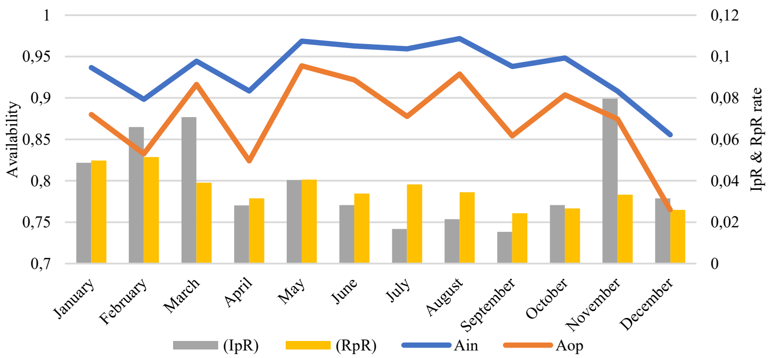

Fig. 8. Availability analysis of CD102

3.3. Consequence of failure (CoF)

The CoF analysis of printing machine under study has been conducted by using the Eqs. (7), (8), (9) and (10). It is also important to note that PLC estimation obtained from the product of percentage wastage $\left(i.e.\ \frac{\text{wastage}\times 100}{\text{total output}}\right)$ and raw material cost (which is the summation of the daily plate and exposing cost, paper cost, thinner and chemical cost, other material cost etc.). HWLC is obtained from the product of breakdown time or downtime and human labour cost per minute (i.e. salary of printer, feeder man, helper per month converted to United Arab Emirates Dirham (AED) considering 26 working days per month and 8 hours shift per day). MLC is the summation of inspection, repair or replacement and maintenance cost of different breakdown and here observed major costs are the blanket change, breakdown/scheduled/preventive maintenance, pipeline leakage, varnish section, coating blade replacement/repair, dampening section and other costs etc. However, there is less impact on environment due to these breakdowns and wastage/ink/chemical residual etc. and no injuries or accidents witnessed during the period of study due to different preventive measures taken in advance by the company thus the environmental loss and human health loss has taken as zero severity in this study and not included. The other losses observed during this period are considered as negligible and therefore not considered. Finally, the CoF calculation is done using Eq. (10) and the results are tabulated below in Table 9.

Table 9. Consequence analysis

Month	No. of days	PLC (AED)	HWLC (AED)	MLC (AED)	CoF (AED)
January	27	10775.6	1525.64	23500	35801.24
February	24	7783.428	1455.528	7000	16238.96
March	26	8981.185	734.7751	0	9715.96
April	23	10237.34	1699.518	26400	38336.85
May	23	8847.069	499.1983	6800	16146.27
June	26	13147.67	911.4576	3500	17559.13
July	26	11468.78	1250.8	13800	26519.58
August	27	14414.08	1102.163	25800	41316.25
September	26	16070.93	2207.13	18500	36778.06
October	25	16938.91	1391.025	30900	49229.94
November	29	17679.92	2005.207	24100	43785.12
December	27	15053.81	3703.042	62500	81256.85
Total for 1 year	309	151149.9	18485.48	242800	412435.4

3.4. Actual risk and RI estimation

From the above results, actual risk in United Arab Emirates Dirham (AED) is estimated on both annual basis and monthly basis to understand the current risk status of machine using Eq. (11) as shown in Table 10. This actual risk is then needed to compare with the allotted yearly or monthly budget for maintenance. The yearly acceptable risk criteria (ARC) for an annual or monthly basis is 227280 AED or 18940 AED which has been collected from the accounts department of the printing company. The estimated overall risk index is 1.13 which is greater than 1 by using Eq. (11). This implies the machine needs a maintenance action for reduction of risk in terms of failure and its corresponding cost. As the overall risk index is higher than 1, it indicates that the system needs to reduce the risk index. This motivates the analysis of risk factors for individual breakdown causes for which scoring of actual risk and RPN is useful to generate risk matrix.

Table 10. Actual risk (AED) and corresponding risk index (RI)

Month	No of days	Actual risk (AED)	Risk index (RI)
Jan	27	23383.93	1.23
Feb	24	10435.83	0.55
Mar	26	5484.37	0.29
Apr	23	27648.66	1.46
May	23	10003.42	0.53
June	26	9867.43	0.52
July	26	13115.34	0.69
Aug	27	24924.64	1.32
Sep	26	20098.32	1.06
Oct	25	30689.01	1.62
Nov	29	26608.60	1.40
Dec	27	43180.68	2.28
Total for 1 year	309	256850.4	1.13

Fig. 9. shows the comparative analysis between different kinds of availability parameters (like A_{op} and A_{in}) and risk index on monthly basis. Availability percentage was measured by the dataset distribution which includes failure and repair times but excludes inspection times to understand how fast the maintenance, repair or replacement was made after inspection. While the availability ratio or percentage is reducing, the risk on that respective period or month is increasing again which validate the previous failure and reliability analysis.

Moreover, once the risks is identified, their probabilities of failure along with their impacts have been modelled in terms breakdown loss cost or breakdown time. It is then needed to conduct quantitative risk prioritisation for better understanding of priority-based scenario of risk pattern of every failure causes present in the machine components. To accomplish this, Monte Carlo Simulation (MCS) method has been performed by considering only the stochastic uncertainty of activities to learn the total failure duration or cost. Generally, in MCS, expert judgement and numerical methods are combined to generate a probabilistic result through simulation routine. This mathematical approach is noted for its ability to analyse uncertain scenarios from a probabilistic perspective. MCS also allows the analysis of opportunities, uncertainties, and threats. This technique can be invaluable to risk managers and helpful for estimating project durations and costs [17]. Fig. 10 shows the MCS based prioritization of failure type based actual risk in terms of breakdown loss cost. This simulation has been generated with the assistance of Python Jupyter Network and Anaconda Prompt environment. The Numpy and Pandas library with 10,000 simulations are utilised to achieve accurate prioritization. Similarly, simulation based on MCS based prioritization of failure type on actual risk in terms of breakdown time can also be generated for better understanding of risk. This analysis will help for the scaling of actual risk and can be extended to RPN as well.

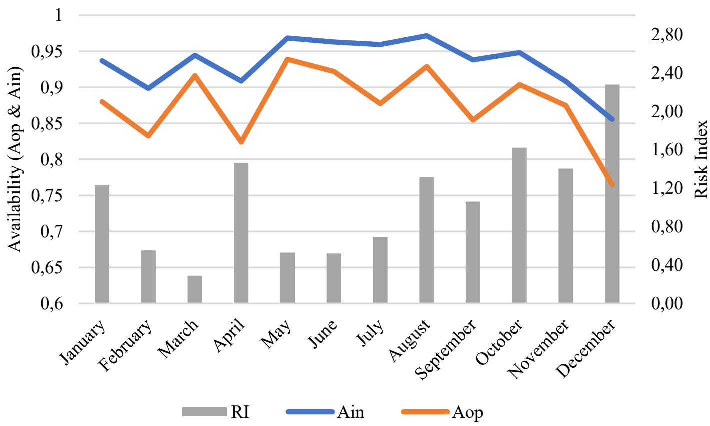

Fig. 9. Comparative analysis between availability vs risk index

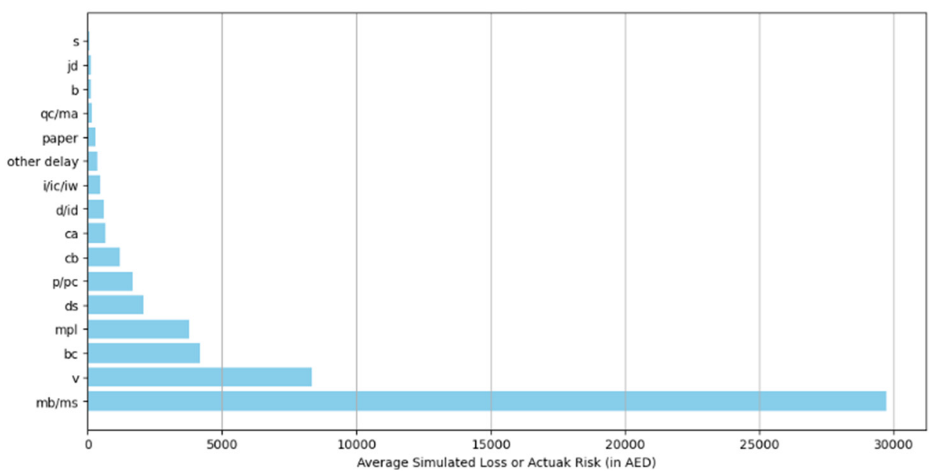

Fig. 10. Monte Carlo based simulation for the prioritization of failure type based on actual risk or loss in terms of cost

3.5. Risk scoring and RPN scoring

In this section an attempt has been made to develop risk matrices by considering failure number as likelihood and breakdown time and its loss cost both as severity. The criteria of likelihood is fixed by considering highest failure occurrence value of 137 which is divided by 5 (due to 5 levels of likelihood) to estimate the criteria intervals of 27.4, 54.8, 82.2, 109.6 and 137 respectively and fix the scores of likelihood from 1 to 5 accordingly as shown in Table 11 (Part a). On the basis of opinion of management and finance department, severity in terms of both breakdown time and breakdown loss cost are given by different levels of score interval from 1 to 5 as shown in Table 11 (Part b) and Table 11 (Part c). Similar methodology has been adopted to estimate the risk interval and inspection interval as illustrated in Table 11 (Part d) and Table 11 (Part e) respectively.

Table 11. Interval criteria for scoring of likelihood (Part A), severity (w.r.t time) (Part B), severity (w.r.t cost) (Part C), risk (Part D) and inspection time (Part E)

A		B		C	
Failure probability	Likelihood score	Breakdown time (minute)	Severity score	Breakdown loss cost (AED)	Severity score
up to 0.0882	1	upto 1000	1	Up to 900	1
0.0882 to 0.1765	2	1000 to 2000	2	900 to 1700	2
0.1765 to 0.2647	3	2000 to 3000	3	1700 to 4000	3
0.2647 to 0.3530	4	3000 to 4000	4	4000 to 30000	4
0.3530 to 0.4412	5	above 4000	5	above 30000	5
D		E			
Risk interval	Risk score	Inspection interval (minute)	Inspection score		
1 to 5	1	up to 789	1		
6 to 10	2	789 to 1578	2		
11 to 15	3	1578 to 2367	3		
16 to 20	4	2367 to 3156	4		
21 to 25	5	3156 to 3945	5		

Table 12. Results of likelihood, severity, risk and RPN scoring for combination I

Failure type	Affected machine unit	PoF	Likelihood score	Breakdown time (minute)	Severity score	Risk value	Risk score for RPN calculation	Inspection time (minute)	Inspection scale	RPN value
p/pc	A, E	0.4413	5	6785	5	25	5	3400	5	25
d/id	G	0.4034	5	2600	3	15	3	308	1	3
i/ic/iw	A, C	0.3369	4	2340	3	12	3	800	2	6
ca	A, I	0.2662	4	4320	5	20	4	3945	5	20
paper	A, E	0.3393	4	1515	2	8	2	505	1	2
b	E	0.2723	4	930	1	4	1	118	1	1
mb/ms	B, C, D, EF, G, H	0.2810	4	6647	5	20	4	3560	5	20
other delay	B, C, D, E, H	0.2304	3	2865	3	9	2	1160	2	4
qc/ma	A, I	0.2064	3	1465	2	6	2	1213	2	4
s	C, D, E	0.1757	2	770	1	2	1	95	1	1
jd	B, C, D, E, F, G, H	0.1772	3	1205	2	6	2	840	2	4
v	F	0.1518	2	805	1	2	1	180	1	1
bc	E	0.1545	2	200	1	2	1	15	1	1
ds	D	0.0904	2	215	1	2	1	100	1	1
cb	F	0.0740	1	145	1	1	1	10	1	1
mpl	B,D,H	0.2294	3	150	1	3	1	65	1	1

For risk assessment of the printing machine, it is now necessary to evaluate the risk values and RPN values for each type of breakdown causes by considering the following combination.

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Combination I: Failure numbers, breakdown times and inspection times for each breakdown type

Combination II: Failure numbers, breakdown loss cost and inspection times for each breakdown type

Table 12 and Table 13 represent the results of risk values and RPN values of each breakdown type for combination I and combination II respectively. It is to be noted here that during estimation of breakdown loss cost (as shown in Table 13), production loss cost (PLC) is considered as zero because of zero wastage due to non-functioning of the machine at the stage of failure condition.

Table 13. Results of likelihood, severity, risk and RPN scoring for combination II

Failure type	Affected machine unit	PoF	Likelihood score	Breakdown loss cost (AED)	Severity score	Risk value	Risk score for RPN calculation	Inspection time (minute)	Inspection scale	RPN value
p/pc	A, E	0.4413	5	3805.69	3	15	3	3400	5	15
d/id	G	0.4034	5	1458.33	2	10	2	308	1	2
i/ic/iw	A, C	0.3369	4	1312.50	2	8	2	800	2	4
ca	A, I	0.2662	4	2423.08	3	12	3	3945	5	15
paper	A, E	0.3393	4	849.76	1	4	1	505	1	1
b	E	0.2723	4	521.63	1	4	1	118	1	1
mb/ms	B, C, D, EF, G, H	0.2810	4	108728.28	5	20	4	3560	5	20
other delay	B, C, D, E, H	0.2304	3	1606.97	2	6	2	1160	2	4
qc/ma	A, I	0.2064	3	821.71	1	3	1	1213	2	2
s	C, D, E	0.1757	2	431.89	1	2	1	95	1	1
jd	B, C, D, E, F, G, H	0.1772	3	675.88	1	3	1	840	2	2
v	F	0.1518	2	54851.52	5	10	2	180	1	2
bc	E	0.1545	2	27112.18	4	8	2	15	1	2
ds	D	0.0904	2	23320.59	4	8	2	100	1	2
cb	F	0.0740	1	17081.33	4	4	1	10	1	1
mpl	B, D, H	0.2294	3	16284.13	4	12	3	65	1	3

3.6. Risk matrix

A risk matrix is generally used to assess the level of risk of a machine and assist the management decision making process. It takes into consideration the category of probability or likelihood against the category of consequence severity. In this present investigation the risk assessment matrix of printing machines under study for different types of breakdown causes has been developed by considering both breakdown time and breakdown loss cost. Table 14 represents the risk matrix for different breakdown causes on the basis of breakdown time and breakdown loss cost respectively. Whereas Table 15 represents the RPN matrix for different breakdown causes by considering breakdown time and breakdown loss cost respectively. These risk matrices help the management to prioritize the risk for different causes of breakdown and develop an appropriate mitigation strategy. Here the extremely lower risk values for the particular breakdown causes are positioned in the first cell situated in an extreme downward left side of the matrix. Higher the risk, it tends to the extreme right side of the topmost corner in the matrix. In other words, it can be said that red colored situated in the top right corner of the matrix indicates the high-risk zone whereas green color situated in the left bottom corner indicates the low-risk zone. It is recommended for organizations to schedule periodic assessments of risk matrix as it needs regular monitoring and iteration to meet the challenges of constantly changing scenario of production process. With the help of an up-to-date risk assessment matrix, it is possible to identify emerging threats and properly allocate resources to mitigate their impact.

The mapping of risk is based on the different levels of consequences of failure probability for each type of breakdown. It is not necessary that highest PoF should possess highest consequence level thus it may vary case to case. For example, 'p/pc' has highest PoF of 0.4413 with different consequence level of breakdown time of 6785 minutes and inspection time of 3400 minutes and breakdown loss cost of 3805.69 AED thus it gives a result of different risk zones in risk matrix and RPN matrix under study. It is also observed that the breakdown cause 'p/pc' under machine component 'A' and 'E' falls on the high-risk zone for both risk matrix and RPN matrix with respect to breakdown time, whereas these causes under machine component 'A' and 'E' shifts to the medium risk zone for both matrix zone with respect to breakdown loss cost. This may be due to the effect of less running cost required for this cause i.e. 'p/pc'. The position of the maintenance time for breakdown or schedule (mb/ms) remains same in the risk and RPN matrices for both breakdown time and breakdown loss cost due to negligible consequences for these causes. Therefore, it can be said that overall, three breakdown causes namely 'p/pc', 'ca' and 'mb/ms' are responsible for high-risk zones during the study period. In other words, it can be stated that all nine number of machine components falls under high-risk zone when breakdown time is considered. While seven number of machine components falls under high-risk zone when breakdown loss cost is considered.

Table 14. Risk matrix for different breakdown types along with its affected responsible machine units on the basis of failure number and breakdown time, failure number and breakdown loss cost

Failure number and breakdown time					
Likelihood score			d/id-(G)		p/pc-(A,E)
	b-(E)	paper-(A, E)	i/ic/iw-(A, C)		ca-(A,I); mb/ms-(B, C, D, E, F, G, H)
	mpl-(B, D, H)	qc/ma-(A, I); jd-(B, C, D, E, F, G, H)	other dealy-(B, C, D, E, H)		
	s-(C, D, E); v-(F); bc-(E); ds-(D)				
	cb-(F)				
	Severity score				
Failure number and breakdown loss cost					
Likelihood score		d/id-(G)	p/pc-(A,E)		
	paper-(A, E); b-(E)	i/ic/iw-(A, C)	ca-(A, I)		mb/ms-(B, C, D, E, F, G, H)
	qc/ma-(A, I); jd-(B, C, D, E, F, G, H)	other delay-(B, C, D, E, H)		mpl-(B, D, H)	
	s-(C, D, E)			bc-(E); ds-(D)	v-(F)
				cb-(F)	
	Severity score				

3.7. Maintenance interval (MaIT)

The risk of operation consisting of five aforementioned levels of 5×5 matrix for both actual risk and RPN are shown into the study. For high profitability point of view, the updated PoF is assumed to be 0.01 (on the basis of ALARP methodology) for lowest risk zone located at the extreme bottom left cell in the matrix which also lies under the lowest score criteria of the likelihood interval scale. Now out of 365 days of financial year of 2021, 309 operational days are used as t for the estimation of MaIT as shown in Eq. (15). The maintenance interaval time in days for different breakdown causes/types are shown in Table 16. It is observed that the printing machine under study must undergo an overall maintenance interval of 76 days annually by considering all the breakdown types. It is also seen that the maximum probability of failure for breakdown type 'p/pc' requires lowest needed maintenance interval and minimum failure probability for breakdown type 'cb' requires highest maintenance interval time. However very few breakdown types seem to have higher MaIT for higher failure probability due to the effect of severity factor of the same. Thus, this will help the printing machine to be more reliable to the press organization for their improved printing production as well as it will prevent the machine from entering to 'wear-out stage' from its 'useful life cycle'.

Table 15. RPN matrix for different breakdown types along with its affected responsible machine units on the basis of inspection time and risk (in terms of breakdown time), inspection time and risk (in terms of breakdown loss cost)

Inspection time and risk (in terms of breakdown time)					
Risk (PoF × CoF)					p/pc-(A, E)
					ca-(A, I); mb/ms-(B, C, D, E, F, G, H)
	d/id-(G)	i/ic/iw-(A, C)			
	paper-(A, E)	other delay-(B, C, D, E, H); qc/ma-(A, I); jd-(B, C, D, E, F, G, H)			
	b-(E); s-(C, D, E); v-(F); bc-(E); ds-(D); cb-(F); mpl-(B, D, H)				
	Inspection score				
Inspection time and risk (in terms of breakdown loss cost)					
Risk (PoF × CoF)					mb/ms-(B, C, D, E, F, G, H)
	mpl-(B, D, H)				ca-(A, I); p/pc-(A, E)
	d/id-(G); v-(F); bc-(E); ds-(D)	i/ic/iw-(A, C); other delay-(B, C, D, E, H)			
	paper-(A, E); b-(E); s-(C, D, E); cb-(F)	qc/ma-(A, I); jd-(B, C, D, E, F, G, H)			
	Inspection score				

4. Discussion

From the analysis of risk matrix, it is evident that for both risk matrices and RPN metrices approximately 6 % to 20 % of the breakdown causes possess in the extremely high-risk zone. Remaining portions of breakdown causes are situated in the lesser zones of risk metrices. So, it can be postulated that the results obtained from both metrices validate the 80 %-20 % rule of Pareto analysis in RBM and reliability study. To enhance the precision and accuracy of risk assessment different resilience factors are considered. Different types of losses such as human wage loss, inspection time loss, material loss, production loss are considered as resilience factors in respect of both breakdown time and breakdown cost. Resilience factors associated with breakdown time cause a huge amount of production time loss whereas resilience factors associated with breakdown cost also causes a huge amount of loss of money. Obviously, these factors have a great effect on the productivity of the machine as well as its risk assessment. Again, inspection time is considered to convert the risk matrix into RPN matrix to understand the detectability status of the breakdown of the printing machine. So, it can be said that the targeted minimization of the overall failure probability up to 0.01 % machine needs a maintenance schedule of 76.16 days interval.

Table 16. Maintenance interval time (MaIT) for different causes

Breakdown type	Existing PoF	MaIT (day)
p/pc	0.4413	5.3350
d/id	0.4034	6.0118
i/ic/iw	0.3369	7.5594
ca	0.2662	10.0343
paper	0.3393	7.4918
b	0.2723	9.7689
mb/ms	0.2810	9.4128
Other delay	0.2304	11.8556
qc/ma	0.2064	13.4303
s	0.1757	16.0752
jd	0.1772	15.9220
v	0.1518	18.8596
bc	0.1545	18.5026
ds	0.0904	32.7595
cb	0.0740	40.3980
mpl	0.2294	11.9172
Overall PoF and MaIT	0.623	76.16

5. Improved maintenance planning and safety recommendation

Reliability based maintenance planning is very important in maintenance management, specially in RBM methodology. Reliability is the probability of success or not failing of an substance. But with time all machines will degrade and reduce its performance and fails over time. Now the challenge or task for maintenance team is to keep the machine in operative condition with proper technical and maintenance skills. Reliability metrics along with high-risk zone helps to identify risky parts, machine units due to breakdown causes so that correct maintenance action can be implemented. Based on the result of repair rates, maintainability of each critical parts has been estimated. Maintainability is also useful, the same as reliability as it gives an account of MTTR i.e. how well and fast machines are coming back to operative state from breakdown. In fact, maintainability illustrates the measure of the time required to restore the operational status in a given percentage of the whole system failures. Table 17 shows the present status of the failure probability, MTBF, reliability and maintainability for each breakdown causes and affected machine units. In improved maintenance planning, an increase of maintenance interval time is observed for most of the breakdown types when compared with existing mean time between failure and updated failure number. It is also found that updated maintenance interval time and failure number leads to potential savings in breakdown loss cost for most of the breakdown types. The breakdown loss cost increases drastically for a few breakdown types which can be ignored during improved maintenance planning as these breakdown types are observed in the less risky zone in risk matrices. Based on these recommendations on maintenance and safety are proposed for each affected machine components.

Table 17. Maintenance and safety recommendations based on improved maintenance planning

Breakdown type	Focus on Affected Machine unit	Maintainability indicator rating (MIR) (Qualitative or Delphi approach)	Failure probability $F(t)$	Reliability $R(t)$	Maintainability M(t) (Quantitative approach)	Existing MTBF	MaIT (days)	Updated failure no	% change in breakdown loss cost	Maintenance and safety recommendations
p/pc	A, E	L4	0.441	0.558	0.527	2.255	5.335	30	–78.10 %	Proper training, skilled designer and job scheduling. To avoid Slurring – printing pressure adjustment, clean-adjust gripper, maintain suggested packing thickness, attach blanket carefully in press indicating weave direction and use torque wrench during stretching. To avoid scumming – switch to stronger pigmented ink to achieve desired ink density with thinner film and increase concentration or switch, to more acidic solution. To avoid misregistration – adjust the plate properly with trained operator
d/id	G	L2	0.403	0.597	0.419	3.287	6.012	26	–72.340 %	Avoid ink emulsification, use of lower pH value ink (in between 4.0-4.5) and high pigmented ink, Use predefined dose additives by manufacturer's indication, use modern IR drying section, coat it with oil or dispersion varnish in order to rescue print job

i/ic/iw	A, C	L1	0.337	0.663	0.175	4.754	7.559	21	–67.692 %	Proper training and skilled operator
ca	A, I	L1	0.266	0.734	0.236	0.072	10.034	16	–70.370 %	Interference of management for approval and efficient client handling
paper	A, E	L3	0.339	0.661	0.353	7.536	7.492	21	–48.780 %	Efficient inventory management with modern ERP software Proper management and scheduling Consult with paper manufacturer, adjust printing pressure or maintenance of roller or blanket with proper setting. Reduction of ink tack on roll or operate at different production run of paper Maintain at optimal RH environment
b	E	L2	0.272	0.728	0.274	10.3	9.768	16	–46.667 %	Picking/contamination (as a result void is made in print). To avoid piling problem – cleanup rubber blanket, change the printing velocity, check the compatibility of ink and paper change the ink if required or add antioxidant, adjust dampening stability
mb/ms	B, C, D, E, F, G, H	L5	0.281	0.719	0.311	10.3	9.413	17	–43.333 %	Predictive maintenance for failure and efficient production management by experienced manager or engineer
Other delay	B, C, D, E, H	L2	0.230	0.769	0.228	10.3	11.855	13	–56.667 %	Corrective and breakdown maintenance
qc/ma	A, I	L1	0.206	0.794	0.223	12.875	13.430	12	–50.00 %	Continuous monitoring and commissioning of expert/experience personnel

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s	C, D, E	L1	0.176	0.824	0.176	12.875	16.075	10	–58.333 %	Corrective maintenance
jd	B, C, D, E, F, G, H	L1	0.177	0.823	0.138	22.071	15.922	10	–28.571 %	Corrective and breakdown maintenance
v	F	L3	0.152	0.848	0.156	38.625	18.859	8	0.00 %	Check and repair the IR or UV lamp for curing. Use of good quality varnish chemical
bc	E	L3	0.155	0.845	0.151	51.5	18.503	9	50 %	Change of blanket
ds	D	L2	0.090	0.909	0.103	77.25	32.759	5	25 %	Run the press with ideal ink/water stability. Maintenance of blanket or change to less tacky blanket. To avoid piling - adjust dampening stability
cb	F	L3	0.074	0.926	0.076	154.5	40.398	4	100 %	use of noncorrosive substance during cleaning, proper adjustment of pressure and alignment are maintained, replacement on total breakdown
mpl	B, D, H	L4	0.229	0.771	0.229	309	11.917	13	1200 %	Proper monitoring and scheduled maintenance

6. Integration of industrial internet of thing (IIoT)

In modern print production houses all the activities are synchronized using workflow management system (WMS). This WMS is driven by job definition format (JDF) with an extensible mark-up language (XML) based communication language which can convey the internal productivity parameters as well as machine information between different production module. It can also interact with management information system (MIS) which can be accessed through internet. Moreover, with the advent of artificial intelligence (AI) technology in intelligent manufacturing and IIoT, various types of cyber physical systems including machine/deep learning algorithms can be applied to print production houses [24]. Hence, management as well as clients can get actual current status of the machine and assigned works from any corner of the work using MIS interface through the dashboard placed in the machine. Users may also use the web-based or android based interactive system for convenience. Taking the advantage of databases, cloud computing services, big data processing and data analytics module, the proposed prediction model for quantitative risk assessment can be integrated to workflow system. Fig. 11 shows a possible integration schematics for the same. This cyber-physical system will help the machine operators to identify the risky zones instantly. With the help of integration of IIoT, each type of failures will be identified and displayed in risk matrix as well as in machine dashboard which may lead to improved maintenance as well as safety recommendations for better productivity of the machine.

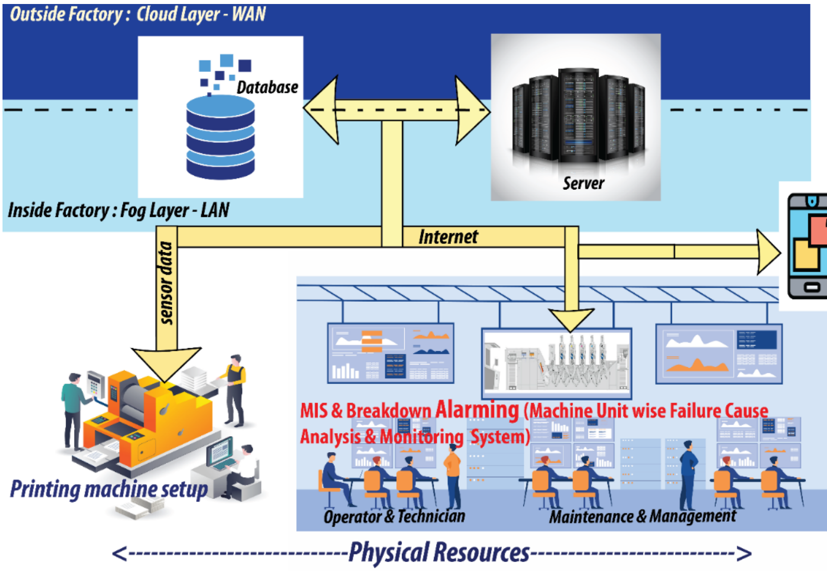

Fig. 11. Schematic workflow diagram of job description for printing operation and its maintenance management

7. Conclusions

In this study, the risk status of a printing machine in a printing production house has been assessed both qualitatively and quantitively by considering different factors of breakdown occurrence and its consequences in terms of both time and cost. The results based on FTA and FMEA analysis demonstrate that there is a correlation between risk index and risk priority number of a machine. The analysis of MonteCarlo simulation for risk prioritization shows that nearly 20 % of the breakdown types causes extremely high risk whereas remaining 80 % causes comparatively less risk. It is also observed that improved maintenance interval time can be achieved by considering the probability of failure of the corresponding breakdown times. Assessment of RAM driven risk matrices in this study will help the management to design suitable maintenance planning, to track the repair rate scenario and reduce maintenance cost which leads to improved maintenance planning.

Two key contributions have been made by this study which may reflect the novelty of this research work. Firstly, the mapping and comparison of risk matrix and RPN matrix developed make this analysis unprecedented and it will significantly help the management to focus on those severe breakdown types along with the affected machine components which can be used for further improvement of productivity. Secondly the estimation of maintainability and its indicator rating for different breakdown types make the analysis quantitative for risk-based maintenance. Finally it can be concluded that the proposed methodology may be considered as a promising and potential tool for any continuous production process to implement Industry 4.0/5.0.

With the advent of artificial intelligence technology, the emerging field of maintenance management can be explored by the application of machine learning algorithms. The present study can also be extended explicitly to hardware implementation of automated sensing and continuous monitoring of internal productivity data of machines. Thus, considering the findings and the scope of future work, the proposed approach for quantitative assessment of risk matrix may be considered as an important tool for RBM/RAM methodology.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author contributions

Avijit Kar: writing draft preparation, formal analysis, conceptualization, data curation, investigation and methodology. Arun Kiran Pal: writing review, editing and supervision.

Conflict of interest

The authors declare that they have no conflict of interest.

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