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Risk-based maintenance—Techniques and applications

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Abstract

Plant and equipment, however well designed, will not remain safe or reliable if it is not maintained. The general objective of the maintenance process is to make use of the knowledge of failures and accidents to achieve the possible safety with the lowest possible cost. The concept of risk-based maintenance was developed to inspect the high-risk components usually with greater frequency and thoroughness and to maintain in a greater manner, to achieve tolerable risk criteria. Risk-based maintenance methodology provides a tool for maintenance planning and decision making to reduce the probability of failure of equipment and the consequences of failure. In this paper, the risk analysis and risk-based maintenance methodologies were identified and classified into suitable classes. The factors affecting the quality of risk analysis were identified and analyzed. The applications, input data and output data were studied to understand their functioning and efficiency. The review showed that there is no unique way to perform risk analysis and risk-based maintenance. The use of suitable techniques and methodologies, careful investigation during the risk analysis phase, and its detailed and structured results are necessary to make proper risk-based maintenance decisions.

Keywords: Risk-based maintenance; Risk assessment; Quality of risk analysis; Decision making

1. Introduction

Downtime has always affected the productive capability of physical assets by reducing production, increasing operating costs and interfering with customer services. In manufacturing, the effects of downtime are being aggravated by the world wide move towards just-in-time systems, where reduced stocks of work-in-progress mean that quite small breakdowns are now much more capable to stop a whole plant [1]. Further, more failures affect our ability to sustain satisfactory quality standards. This applies as much to standards of service as it does to product quality. More and more failures have serious safety or environmental consequences, at a time when standards in these areas are rising rapidly. The cost of maintenance itself is still rising, in absolute terms and as a proportion of total expenditure. In some industries, it is now the second highest or even the highest element of operating costs. As a result, in only 30 years it has moved from almost nowhere to the top of the league as a cost control priority. Certain critical elements such as product quality, plant safety, and the increase in maintenance department costs can represent from 15 to 70% of total production costs [2]. The universal objective of the maintenance process is to make use of the knowledge of failures and accidents to achieve the possible safety with the lowest possible cost.

The major challenge of maintenance engineer is to implement a maintenance strategy, which maximizes availability and efficiency of the equipment, controls the rate of equipment deterioration, ensures the safe and environmentally friendly operation, and minimizes the total cost of the operation [3]. The challenge enhances further when the maintenance engineers deal with equipment handling toxic or hazardous materials, either during production or transportation. For example, chemical process industries often process and transport toxic or hazardous materials. Further, it is common to have industrial complexes where groups of chemical industries are situated in close proximity, so the possibility of chain of accidents or domino effects increases. As the density of the industries as well as the population continues to grow everywhere, the risk posed by probable accidents in chemical industries and transportation of hazardous materials also continues to rise. There is also a close relationship between maintenance and product quality, as product quality depends on equipment condition. So, it is necessary to develop maintenance planning to minimize frequency and consequences of system failure. Such a development would also add a hygienic atmosphere to industries as well as surroundings. At the end of the first half of the 20th century, data bases on failures of pressure vessels, piping components and systems were being collected

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with the result showing that the American Society of Mechanical Engineers (ASME) code based on performance criteria provided highly reliable systems. However, with low probability data they are not meaningful without considering the consequences or severity of a system failure. Thus, the importance of risk was recognized as an important measure of system safety [4]. The risk-based maintenance methodology is designed to study all the failure modes, determining the risk associated with those failure modes, and developing a maintenance strategy that minimizes the occurrence of the high-risk failure modes.

In this paper, most of the available recent literature on risk analysis and risk-based maintenance were reviewed in order to identify the proposed techniques and methodologies of risk analysis and risk-based maintenance in diverse fields. Further, the identified techniques and methodologies were classified to reveal their characteristics and applications. Finally, the factors affecting the quality of a risk analysis were discussed.

2. Development of maintenance philosophies

Maintenance management techniques have been through a major process of metamorphosis over recent years. Today, the maintenance progress has been provoked by the increase in complexity in manufacturing processes and variety of products, growing awareness of the impact of maintenance on the environment and safety of personnel, the profitability of the business and quality of products [3]. There is a paradigm shift in implementing maintenance strategies like condition-based maintenance (CBM) and reliability-centered maintenance (RCM). Then the risk-based maintenance (RBM) has been emphasized. The development of maintenance philosophies is shown in Fig. 1 ([1,5] revisited). Fig. 1 reveals that maintenance policies are evolved over time and can be categorized as first, second, third and recent generations.

2.1. First generation

First generation typically belongs to the time before the World War II. Industries were not very highly mechanized. Equipment were simple and redesigned which made them reliable and easy to repair. Machines were operated until they broke down and there were no way to predict failures. The typical maintenance practices were (i) basic and routine maintenance, (ii) reactive breakdown service (fix it when it broke) and (iii) corrective maintenance [1,5].

2.2. Second generation

Second generation belongs to the time period in between the Second World War and the late 1970s. Industries become more complex with great dependency on machines. Maintenance cost became higher than other relative operating cost. The maintenance policies adopted were (i) planned preventive maintenance, (ii) time based maintenance and (iii) system for planning and controlling work. However, this generation was criticized for imposing quite often unnecessary treatments, which disrupted normal operations, and also induced malfunctions due to missed operations [12].

2.3. Third generation

The maintenance strategies within 1980 and 2000 are termed as third generation policies. This generation was typically characterized by (i) continued growth in plant complexity, (ii) accelerating use of automation, (iii) just in time production system, (iv) rising demand for standard of product and service quality and (v) more tight legislation on service quality [5]. Condition based maintenance (CBM), reliability centered maintenance (RCM), and computer aided maintenance management were adopted for maintenance during this period (see Fig. 1, for more details).

2.4. Recent generation

In 1990s, risk-based inspection and maintenance methodologies started to emerge and gain popularity beyond 2000. This generation is highly characterized by the inception of risk-based inspection and maintenance in addition to RCM and CBM. Up till 2000, maintenance and safety were treated as separate and independent activities [6]. Several authors suggested that an inte-

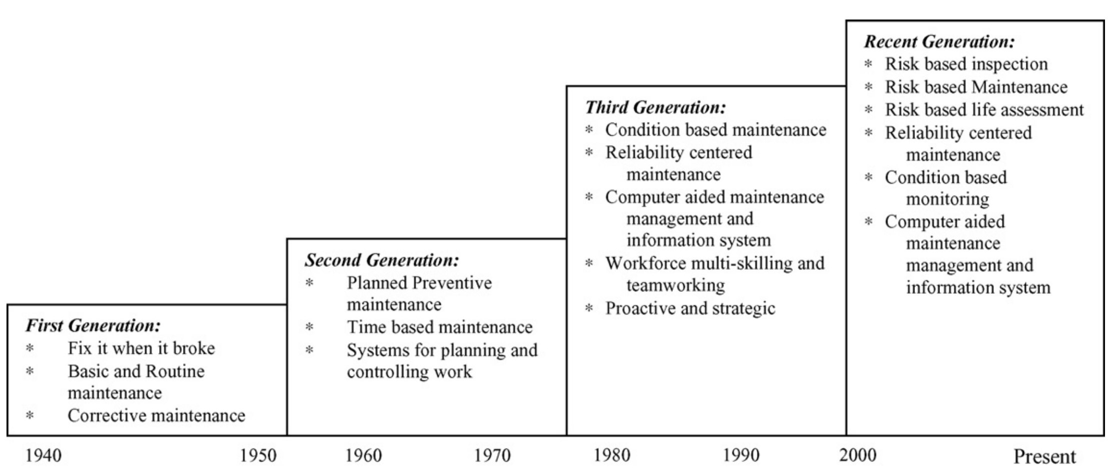

Fig. 1. Development of maintenance philosophies ([1,5] revisited).

grated approach incorporating maintenance and safety is the appropriate mean for optimizing plant capacity, as safety and maintenance are not mutually exclusive functions. The overall objective of the maintenance process is to increase the profitability of the operation and optimize the total life cycle cost without compromising safety or environmental issues. Inspection and maintenance planning based on risk analysis minimizes the probability of system failure and its consequences. It helps management in making correct decisions concerning investment in maintenance and related fields.

3. Risk-based maintenance

Risk-based maintenance framework is comprised of two main phases:

1. Risk assessment.
2. Maintenance planning based on risk.

The main aim of this methodology is to reduce the overall risk that may result as the consequence of unexpected failures of operating facilities [7]. The inspection and maintenance activities are prioritized on the basis of quantified risk caused due to failure of the components, so that the total risk can be minimized using risk-based maintenance. The high-risk components are inspected and maintained usually with greater frequency and thoroughness and are maintained in a greater manner, to achieve tolerable risk criteria [4].

The risk-based maintenance methodology consists of six modules as shown in Fig. 2.

Hazard analysis. Hazard analysis is done to identify the failure scenario. The failure scenarios are developed based on the

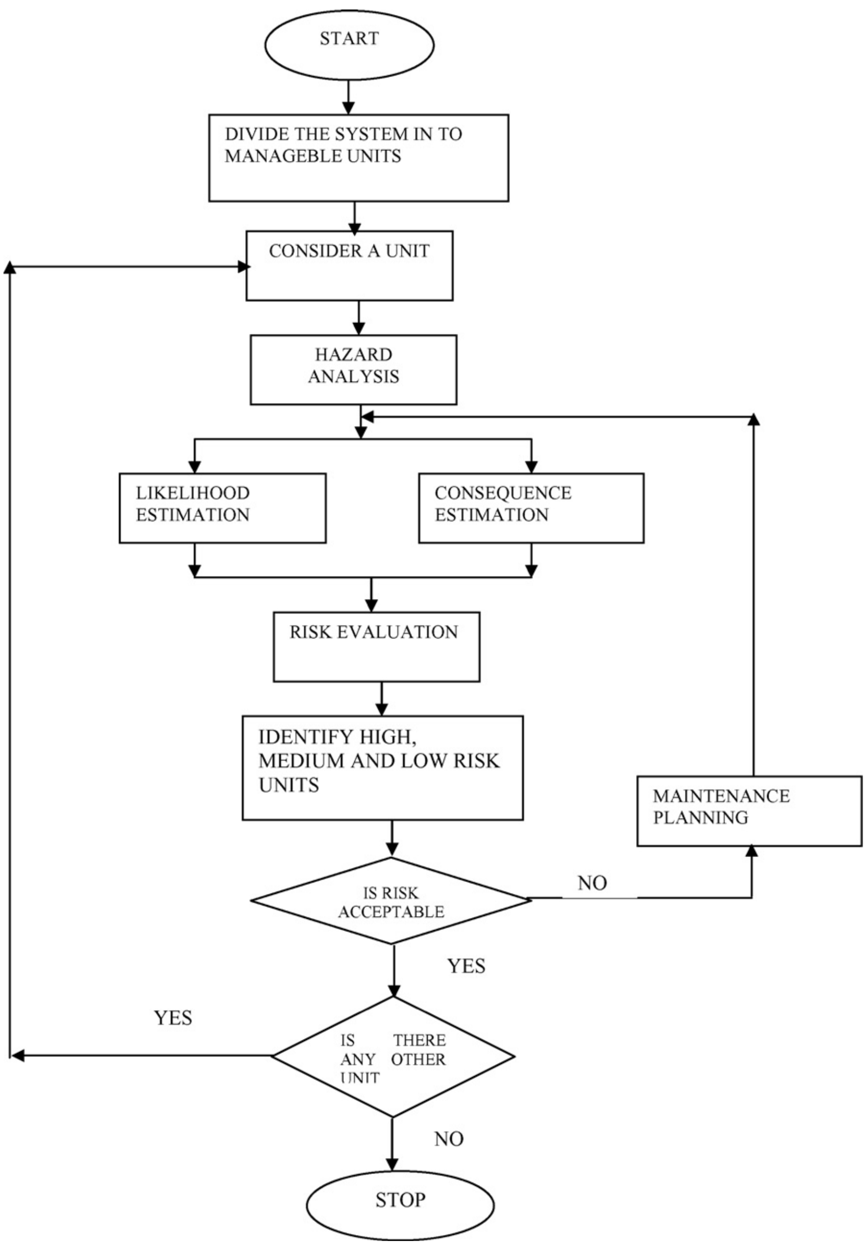

Fig. 2. General risk-based maintenance approach [3,7,72].

operational characteristics of the system, physical conditions under which operations occur, geometry of the system and safety arrangements.

Likelihood assessment. The objective here is to calculate occurrence of the undesired event. The frequency of failure or failure probability for defined period of time is calculated in this step.

Consequence assessment. The objective here is to quantify the potential consequences of the credible failure scenario. The consequences are production loss, asset loss, environmental loss, and health and safety loss. In some of the literature, the production loss is specified as performance loss and operational loss [7].

Risk estimation. Based on the result of consequence analysis and probabilistic failure analysis, the risk is estimated for each unit.

Risk acceptance. The computed risk is compared against the risk acceptance criteria. If any of the unit/component risk exceeds the acceptance criteria, maintenance is required to reduce the risk.

Maintenance planning. Maintenance planning is adopted to reduce the risk.

3.1. Risk assessment

Out of two main phases of risk-based maintenance, risk assessment is the critical and foremost important phase, as the maintenance decisions are going to be made with the assessed risk as centre.

Risk can be defined as "the considered expected loss or damage associated with the occurrence of a possible undesired event" [8]. Hazard refers the source of loss or damage. Risk is the probability of occurrence of the loss or damage. Sophisticated techniques are being used to identify the high-risk operations and to identify means for reducing the risk of accidents in these operations. As shown in Fig. 3, risk assessment involves nothing more than identifying potential threats, estimating their likelihood (number of events/time interval), and estimating the consequences (impact/event) [9]. The combination of these estimates represents the risk (impacts/time interval) associated with the activity being evaluated. As more and more industries are commissioned and more and more accidents come to light, there is ever increasing importance being attached to risk assessment. Rimington [10] explains that risk assessment is the way of systemizing our approach to hazard with a view to determining what is more and what is less risky. It helps to optimize the risk and benefits.

Risk assessment approach integrates reliability and consequence analysis, and attempts to answer the following questions [9]:

- What can go wrong?
- How can it go wrong?
- How likely is its occurrence?
- What would be the consequences?

Risk assessment may be quantitative or qualitative. Quantitative risk assessment is done by the estimation of frequency and its consequences. Quantified risk assessment is only appropriate where it is both reasonable and practicable, reasonable in that the cost of doing it is not high compared with the value of solving the problem, and practicable in terms of the availability of information and data [11]. Qualitative risk assessment is applicable when the risks are small and well known, and the site is not located in the vicinity of possible incompatible development. A simple description of the types of major accidents, their consequences and their likelihood and a review of compliance with standards are sufficient. The results are represented in the form of risk matrix where probability and consequences represent the axes [3,12].

3.1.1. Risk analysis methodologies

Tixier et al. [13] listed 62 risk analysis methodologies from his varied references. Similar to his survey, here the risk analysis methodologies and techniques are categorized from diverse references into deterministic, probabilistic, and combination of deterministic and probabilistic approaches. The deterministic

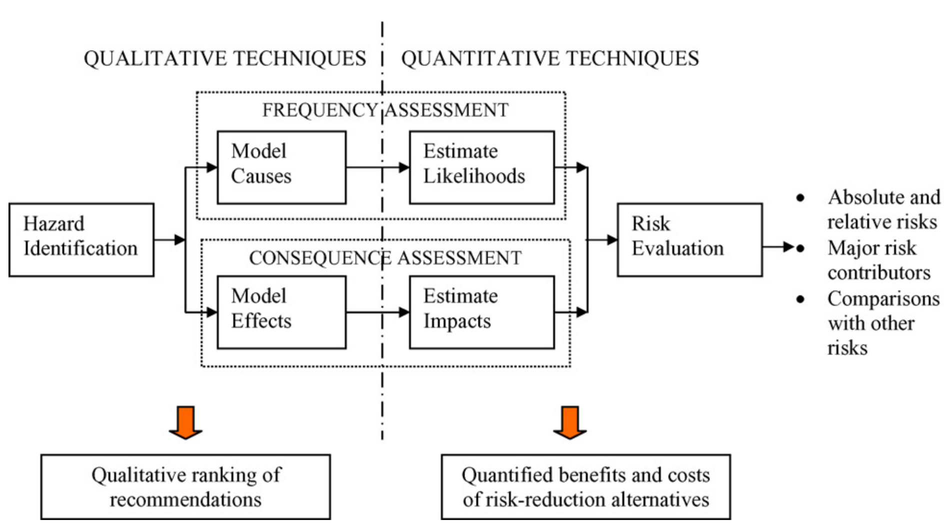

Fig. 3. The process of risk assessment [9].

Table 1
Classification of risk analysis methodologies ([13] Revisited)

Method types	Deterministic	Probabilistic	Deterministic and probabilistic
Qualitative	Action error analysis [14], checklist [15], concept hazard analysis [15], goal oriented failure analysis [14], hazard and operatibility (HAZOP) [15–22], failure mode effect analysis (FMEA) [15,19], human hazard operability (HumanHAZOP) [23], hazard identification system (HAZID) [24], master logic diagram [25], optimal hazard and operatibility (OptHAZOP) [15,26], plant level safety analysis (PLSA) [27], preliminary risk analysis [14], process hazard analysis (PHA) [28–30], reliability block diagram (RBD) [14], task analysis [14], Whatif? analysis [14,15,18], sneak analysis [31], risk matrix [32–34]	Delphi technique [14], expert judgment [35], rapid ranking [36]	Maximum credible accident analysis, [15,37–40], safety culture hazard and operability (SCHAZOP) [23], structural reliability analysis (SRA) [14]
Quantitative	Accident hazard index [41], chemical runaway reaction hazard index [42], Dow's chemical exposure index (CEI) [43,15], Dow's fire and explosion index (FEI) [44,15], fire and explosion damage index (FEDI) [15], hazard identification and ranking (HIRA) [15], instantaneous fractional annual loss (IFAL) [15], reactivity risk index (RRI) [45], safety weighted hazard index (SWeHI) [46], toxic damage index (TDI) [15]	Event tree analysis (ETA) [14,15,47,48], fault tree analysis (FTA) [14,15,48], petri nets [48], probabilistic fault tree (PROFAT) [49], fuzzy fault tree analysis [50,51], risk integral [52]	Method organised systematic analysis of risk (MOSAR) [14], quantitative risk analysis (QRA) [9,15,45,53–55], rapid risk analysis [15,56–59], probabilistic risk analysis (PRA) [15,60], international study group on risk analysis (ISGRA) [15], optimal risk assessment (ORA) [15,61], IDEF methodology [62]
Semi-quantitative	Domino effect analysis [15,63], layers of protection analysis (LOPA) [64], predictive risk index [65], world health organization (WHO) [15], risk priority number [14]	IAEA-TECDOC-727 [66,67], maintenance analysis [14], semi-quantitative fault tree analysis [68], short cut risk assessment [14,69]	Safety analysis [15], failure mode effect criticality analysis (FMECA) [15], facility risk review (FRR) [19,70]

methods take into consideration the product, the equipment, and the quantification of consequences for various targets such as people, environment and equipment. This approach assumes that the occurrence of a hazard and its consequences are known and certain. The probabilistic methods are based on the probability or frequency of hazardous situation apparitions or on the occurrence of potential accident [13]. Again they are cross classified into qualitative, quantitative and semi-quantitative as shown in Table 1.

In the above classification, the majority of methods are deterministic. For example, Fig. 4 shows that out of 75 research studies, 35 are deterministic, while 16 and 24 are probabilistic, and combination of deterministic and probabilistic in nature, respectively. Of the 35 deterministic studies, 24 employed qualitative techniques of evaluation while the quantitative and semi-quantitative techniques were adopted for 8 and 3 studies, respectively. Out of the 16 studies considering probabilistic methods, 3 used qualitative techniques, whereas 8 and 5 are quantitative and semi-quantitative in nature. The techniques coming under deterministic and qualitative group are highly used for hazard identification step in risk assessment process. The techniques categorized in deterministic and quantitative group are mainly hazard indices, which are used to assess the risk immediately and easily. The most of the techniques categorized in probabilistic and quantitative group are applied to quantify probability of accident scenarios and top event failure.

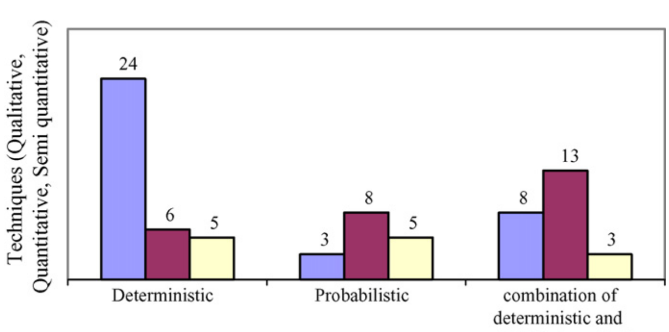

Fig. 4. Cross classification of risk analysis methodologies.

3.1.2. *Factors affecting quality of the risk analysis*

In order to make proper maintenance decisions, careful study of the risk analysis approaches and their results is necessary. Trivial risk source, vague risk analysis approach, and ambiguous results lead to unacceptable safety levels. To facilitate proper decisions, quality of the risk analysis should be improved. Backlund and Hannu [71] identified the factors affecting quality of risk analysis and evaluated the risk analysis approaches. He made a comparative study based on three independent risk analyses performed on a specific hydropower plant in his study. The comparison and evaluation of the analyses revealed major differences in performance and results, along with various factors that affect the quality of risk analyses. Along with hazard identification, initial consequence analysis, and risk estimation

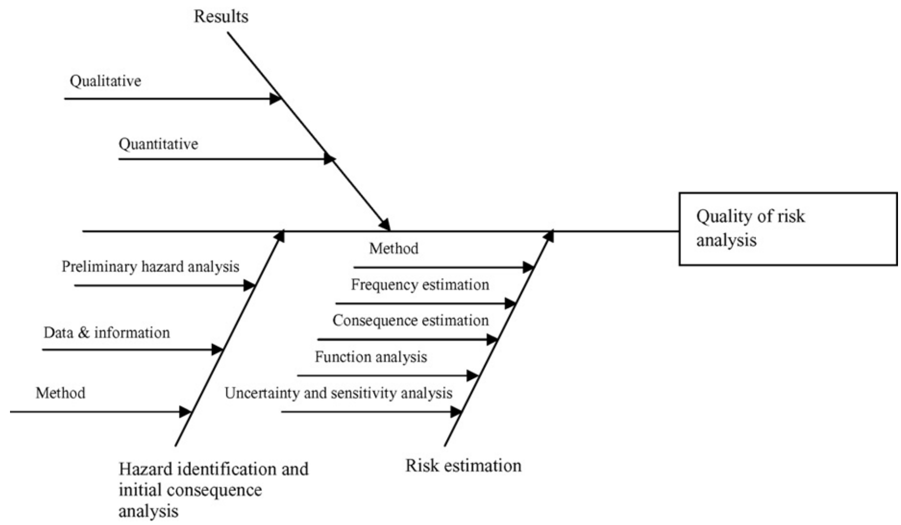

Fig. 5. Factors affecting the quality of a risk analysis (modified after Backlund and Hannu [71]).

factors suggested by Backlund and Hannu [71], result factors are also very important and should be taken into consideration for effective decision making. The cause and effect diagram for factors affecting quality of a risk analysis is shown in Fig. 5.

The factors affecting the quality of a risk analysis are:

1. Hazard identification and initial consequence analysis:
   - preliminary hazard analysis;
   - data and information;
   - method.
2. Risk estimation:
   - method;
   - frequency estimation;
   - consequence estimation;
   - function analysis (identifying critical functions of the system);
   - uncertainty and sensitivity analysis.
3. Results:
   - qualitative;
   - quantitative.

The specific risk analysis methodology should have frequency estimation, consequence estimation, and risk estimation modules. Out of all the reviewed papers, 25 studies are having these three basic specific risk analysis modules. From these 25 studies, the distribution of the factors affecting the quality of a risk analysis are identified and plotted in Fig. 6.

In majority of the papers, the hazard identification and the preliminary hazard analysis to identify the vulnerable subsystems were not reported. This might be due to the fact that either they were not conducted or they were done based on experience of the analyst and his team, which were not documented as pointed out by some of the studies [45,55]. However, documenting these analyses should be encouraged, as they are very important factors affecting the quality of a risk analysis. The data and information, and frequency estimation parts are available in all the 25 papers. The consequence estimation is omitted in some papers. Only two papers did uncertainty and sensitivity analysis.

3.2. Maintenance planning based on risk

The maintenance planning should be assigned to lower the risk to meet the acceptable criterion and to reduce the probability of failure [3,7,73]. So far the reverse fault tree analysis is used in the calculation of maintenance interval based on risk. It involves top to bottom analysis approach. A reverse fault tree analysis is conducted to calculate the probability of failure of the basic events, by assigning a desired failure probability to the top event (failure scenario of the unit). This assigned value for the failure probability is estimated considering acceptable risk value. The new probabilities of failure of the basic events were used to calculate the corresponding maintenance interval [3,7,73].

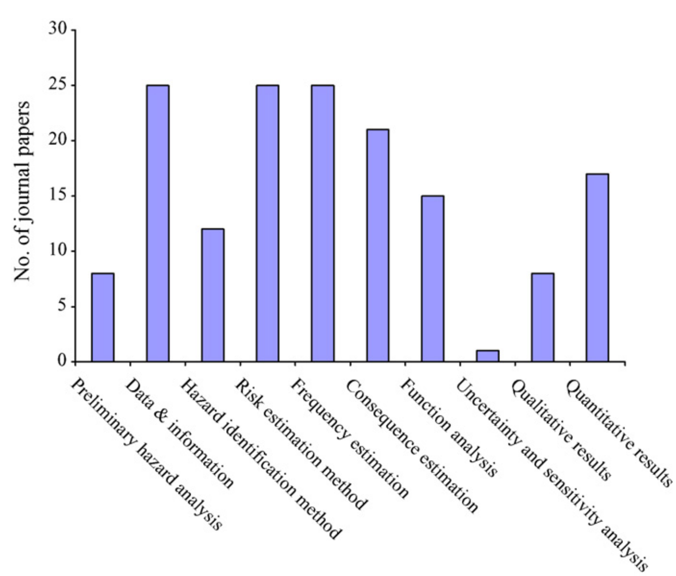

Fig. 6. Distribution of factors for quality of risk analysis in selected journal papers.

Table 2
Classification of risk-based maintenance techniques based on modules

Modules	Models and techniques
Hazard analysis (failure scenario development)	Maximum credible accident scenario (MCAS) [3,7,12], event tree development [72]
Consequence estimation	Source models, impact intensity models, toxic gas models, explosions and fires models [3,12], expert opinion [73,74]
Likelihood estimation	Fault tree analysis (FTA), probabilistic fault tree analysis (PROFAT) [3,7,12,73], expert opinion [33,74,75]
Risk estimation	Fuzzy logic [76], risk matrix [4,33,34,74], simple product of probability of failure and damage loss [3,7,12]
Risk acceptance	Dutch acceptance criteria, ALARP (as low as reasonably possible), USEPA acceptance criteria [3,7,12]
Maintenance planning	Reverse fault analysis [3,7,12,73], analytical hierarchy process (AHP) [2,33,75]

3.2.1. Classification of risk-based maintenance techniques

Based on literature published so for, the framework for risk-based maintenance is identified as qualitative [4,33,34,74,75], quantitative [3,7,12,72,73] and semi-quantitative [76]. Following Tixier et al. [13], the studies were also classified based on the type of applications, input data and output data to get some meaningful insights in the risk-based maintenance scheme. They are described below.

3.2.1.1. Classification based on modules. The techniques and models of risk-based maintenance methodologies are sorted out on the basis of the hazard analysis, consequence estimation, likelihood estimation, risk estimation, risk acceptance, maintenance planning, which is shown in Table 2 (see Section 3, for more details).

3.2.1.2. Type of applications. Mainly two types of applications were highlighted in the studies on risk-based maintenance: (i) industrial applications and (ii) transportation systems. As risk-based maintenance concept is relatively new and applied recently, a few papers were identified in the current literature review. The salient references are listed below:

- Industrial applications [3,7,12,34,72,75].
- Transportation system [33,75].

The industrial applications are mainly quantitative in nature and were developed for static specific applications in chemical, mechanical and electrical fields. The methodology for transportation systems seems highly subjective. Dey [75] has admitted that the subjectivity and weightage factors are main limitations of this methodology. The reduction of subjectivity might give reasonable results.

3.2.1.3. Types of input data. Based on input data required, the risk-based maintenance studies can be classified into two classes as follows:

- Failure probability and databank including historical knowledge [3,7,12,72,73].
- Expert opinion [33,34,73,75,76].

Failure probability and databank including historical knowledge are associated with probability and frequency of failure of components. Expert opinion is associated with experience of the experts and the analysts. The availability of reliability data and other related information is very important to do the risk analysis. If reliability data are unavailable then there is a need for expert opinion. In expert opinion, due to limited experience there is a possibility for uncertainty in the results. In that case, uncertainty and sensitivity analysis should be performed.

3.2.1.4. Types of output data. The risk-based maintenance papers are classified into two classes based on output data and they are qualitative like recommendations [33,34,72,76] and quantitative like index of risk level [3,7,12,73,72].

The output results are qualitative in nature due to unavailability of data. As the results are based on expert choices, they are not precise. The quantitative results are highly useful for further refining and improving work such as maintenance optimization. The results are having more accurate information.

4. Conclusions

An effective use of resources can be achieved by using risk-based maintenance decisions to guide where and when to perform maintenance. This paper based on literature review underlines the state-of-art risk-based maintenance techniques and applications to industrial sectors. The risk analysis methodologies and techniques are categorized into deterministic, probabilistic and combination of deterministic and probabilistic. Again the categories are classified into qualitative, quantitative and semi-quantitative. The risk-based maintenance methodologies are identified and grouped based on applications, input data and output data. The review of these identified methodologies shows that there is no unique way to perform risk analysis and risk-based maintenance. The application of these methodologies highly depends on the depth of the analysis, area of application and quality of results. Other than this, the experience of the analysts to use these methodologies is also an important factor to consider.

Most of the risk analysis approaches are deficient in uncertainty and sensitivity analysis. This has to be rectified to yield proper results. Any decisions based on misleading results may generate non-essential maintenance efforts. This misinterpretation will result in the failure to reduce or eliminate significant sources of risk. The risk analysis should be evaluated in well-planned manner to avoid maintenance efforts spent in less important areas and to put more efforts in highly important areas. For example, the increasing diversity of products and complexity of manufacturing in chemical process industries has made it to handle hazardous substances at elevated temperature and pressure. Release of hazardous materials in such conditions could cause serious environmental and other consequences. So, the use of suitable techniques and methodologies, careful investigation during the risk analysis phase, and its detailed and structured results are necessary to make proper risk-based maintenance decisions.

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