Development of a risk assessment selection model for asset maintenance decision making

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Abstract

In today's industries, asset maintenance plays a strategic role in sustaining the organization's competitiveness through enhancing equipment availability, reliability and productivity. In recent years, considerable research work on asset management (AM) has been undertaken. This stems from the fact that AM considers the assets life cycle where the operational and maintenance phase is important. Core to asset maintenance is the proposed use of various risk assessment techniques/tools. These tools propose a structured approach through which critical failure modes are identified, analyzed and mitigated. Commonly applied risk assessment tools in AM include the failure mode and effect analysis (FMEA), static/dynamic fault tree analysis (FTA) and static/dynamic Bayesian networks (BN). Despite considerable effort directed towards developing individual risk assessment (RA) tools, few papers propose a structured framework that allows selection of tools best suited for the organization, considering the often varying business or operational context. Thus, this paper proposes a conceptual risk assessment tool selection model. Based on an extensive literature review, the model enumerates generic selection criteria accounting for the well-known 'factors of production', i.e. manpower (personnel), machines (assets complexity), methods (procedures), and materials (tools and aids). Next, the selection criteria are assigned priority weights based on the analytic network process (ANP) methodology that accounts for the type of RA tool and business context. Finally, applicability of the conceptual model as an audit tool where the organization assesses its suitability against the varied RA tools is demonstrated.

Keywords: Asset management, Risk assessment, Selection model, ANP

1. Introduction

In the last few decades, the business environment organizations operate in has undergone considerable changes. As such, organizations are nowadays confronted by challenges such as changing market dynamics and shifting consumer preferences. Moreover, operational and maintenance (O&M) costs are increasingly becoming an important aspect that cannot be ignored. Indeed research shows that the O&M cost constitutes as much as 70% of the asset's total cost of ownership [Koronios et al., 2007]. As such, the maintenance function is no longer perceived as "necessary evil", but an important contributor to the organizations competitiveness [Van Horenbeek, 2014].

Thus to remain competitive, organizations are increasingly adopting asset management strategies where all phases in the asset's life cycle are considered, i.e. right from inception to disposal. In literature, several definitions for AM are discussed. One such definition is the PAS-55:2008. Here, AM is defined as "*the systematic and coordinated practices through which the organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over the asset's life-cycle for the purpose of achieving the organization strategic plan*." This definition clearly situates risk management in the context of management of technical assets.

In risk management, a wide range of risk assessment (RA) techniques/tools have been developed and applied for in diverse sectors such as finance, insurance, and more recently, asset management [IEC, 2009]. In asset management, such techniques present a structured approach where asset failures are systematically identified, analyzed, evaluated and mitigated. Often, mitigation is achieved through implementing appropriate maintenance policy(s), e.g. condition based maintenance (CBM). In AM, commonly applied risk assessment techniques include the failure mode and effect analysis (FMEA), fault tree analysis (FTA) and Bayesian network (BN) [Khan, 2004; Langseth and Portinale, 2007; Moubray, 2001].

Whilst numerous RA tools are discussed in literature, current research effort is largely directed towards enhancing the capabilities of individual tools. However, such improvements seldom take into account the practical use of these tools in maintenance decision making. For instance, Liu et al. [2013] reviews research focused on FMEA where the conventional risk priority number (RPN) is enhanced. Here, some enhancements include adapting linear programming and fuzzy rule base approaches. However, such enhancements often increase the complexity of the FMEA, thus inhibiting its use in maintenance decision making. Moreover, the maintenance decision makers are often confronted by numerous RA tools and selecting an appropriate tool can be quite a daunting task. This is attributed to the lack of a clear selection framework. Thus, in absence of such a selection framework, the decision maker may opt for an ad-hoc selection or not use a specific RA tool at all. Yet, these tools play a vital role in structured maintenance decision making where failure risks are identified, prioritized and mitigated [Pintelon, 2006].

To address the aforementioned gap, this paper proposes a generic RA tool selection model. The objective of the selection model is to propose a structured framework for selecting appropriate RA tool(s) best suited for the organization. This paper is organized as follows. Section 2 describes different RA tools applicable in maintenance decision making. Section 3 reviews current literature on RA tools where classification schemes and selection frameworks are discussed. Next, the different steps that constitute the methodology are presented starting with deriving the generic selection criteria, followed by prioritizing the selection criteria using the ANP approach, and lastly developing the audit and selection model. Finally, the results are presented in Section 4.

2. Theoretical Background

2.1 Situating risk assessment in maintenance decision making

Maintenance decision making encompasses several important aspects which include decision support, resource management and performance assessment [Pintelon, 2006]. Indeed maintenance decision support has received considerable research attention given that it addresses important aspects influencing the maintenance function. These aspects include the *maintenance action*, *maintenance policy* and *maintenance concept* [Pintelon, 2006].

Ideally, *maintenance action(s)* implies the elementary interventions performed by the technician where common actions include repair or equipment restoration following breakdown [Pintelon, 2006]. Often, the maintenance actions are dependent on specific *maintenance policy(s)*. For instance, corrective maintenance actions are considered in failure based maintenance (FBM). In addition to FBM, well-known maintenance policy(s) include the use/time based maintenance (UBM/TBM), condition based maintenance (CBM) and opportunity based maintenance (OBM) [Pintelon, 2006].

Often, maintenance actions and policies are planned via a structured decision making framework, described through the *maintenance concept*. The decision structure assists decision makers' select appropriate policy(s) in a structured approach. Well-known maintenance concepts include the reliability centered maintenance (RCM) [Moubray, 2001; Pintelon, 2006], total productive maintenance (TPM) [Nakajima, 1988], and risk based inspection and maintenance (RBIM) [Khan, 2004]. Notably, several maintenance concepts such as the RCM and RBIM are linked to RA tools, where selection of maintenance policy(s) is based on failure risk. For instance, the FMEA and FTA are embedded in the RCM and RBIM concept respectively. On the other hand, the BN is considered as a stand-alone technique, i.e. not linked to any maintenance concept. Nonetheless, the BN is an important tool that attempts to replicate the formalism of the FTA especially with regards to modeling system dependencies. These dependencies may be technical (i.e. between components), functional or logical (e.g. system failure sequence) [Van Horenbeek, 2010]. For this reason, the BN is included as a risk assessment technique in this article.

2.2 Risk assessment classification and selection schemes

In this section, a brief discussion on several classification schemes for RA tools is presented. The schemes are largely based on review articles detailing varied RA techniques. For instance, Tixier et al. [2002] reviews 62 RA tools commonly applied in industrial plants. The review classifies the techniques according to the type of input data, methodology, and nature of output data. Marhavilas [2011] reviews RA tools applicable in manufacturing and process facilities and broadly classifies the techniques three groupings, i.e. qualitative, quantitative and semi-quantitative techniques. The aforementioned review articles propose classification frameworks that could potentially guide users on which tools to adapt for risk assessment.

However, several deficiencies are noted with the classification frameworks discussed above. First, several of the RA techniques included in the review are largely qualitative (i.e. describe risk in terms such as low, medium, or high). Yet, maintenance decision making is often characterized by quantitative risk assessment approaches, e.g. FMEA, FTA or BN [Khan, 2004; Langseth and Portinale, 2007; Moubray, 2001]. Secondly, some of the techniques in the review are not explicitly linked to supporting decision structure, i.e. defined through the maintenance concept. As such, applying the proposed classification schemes for selection of suitable RA techniques may lead to sub-optimal choices especially in maintenance decision making context.

Recently, few research studies proposing RA technique(s) selection frameworks are presented. Notable examples include the ISO 31010; 2009 international standard where selection of appropriate RA tools is achieved on the basis of several attributes. Examples of these attributes include, resource capacity (e.g. manpower); complexity of the specific technique; and type of risk index (qualitative or quantitative). However, the attributes defined in the standard are derived in a rather ad-hoc manner, with no systematic approach considered. Dey and Ogunlana [2004] propose a different approach where selection of the appropriate RA technique is achieved via a logical decision tree. In the study, a user follows several decision variable structured as queries, and as such leading to the right tool. However RA tools considered in the study are tailored for project and risk management in civil construction projects. As such, suitability of the proposed tools in maintenance decision may yield sub-optimal maintenance policy(s). Indeed risks in asset management often differ to those in construction project. For instance, construction risks will account for project completion time, while as asset maintenance largely focuses on equipment failure.

More recently KarimiAzari et al. [2011] formulate the RA tool selection as a multi-criteria decision making (MCDM) problem. As such they propose a conceptual selection framework based on the fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodology. The TOPSIS is a MCDM technique and based on the premise that the selected alternative, i.e. RA tool, should have the shortest distance to the positive ideal solution (PIS) and furthest from negative ideal solution (NIS). The study by KarimiAzari et al. [2011] is quite important in that it formulates the RA tool selection as a MCDM problem. Likewise, in this article, we structure the RA tool selection as an MCDM problem. The study proposes four decision making criteria, each assigned priority weights based on the fuzzy TOPSIS approach. However, the fuzzy TOPSIS approach ignores inter-dependencies between decisions criteria which often influence selection of the right RA tool. For instance, the decision criterion "complexity" is assumed independent of "usability of RA tool". However, it is intuitive that the complexity of a certain risk assessment technique influences its usability.

Thus to address some of the above limitations, a RA tool selection model applicable for asset maintenance is proposed. The model formulates the selection process as a MCDM problem. The proposed approach is based on the analytic network process (ANP) where the inter-dependencies amongst the decision criteria are taken into account. Moreover, the selection model addresses an important gap, i.e. lack of RA tool selection framework specific to the asset maintenance domain.

3. Research Methodology

In this section, the main steps for developing the conceptual RA tool selection model are discussed. The selection model focuses on the maintenance decision making context and considers three main RA techniques. These include; the FMEA, FTA and BN. For the FTA and BN, a distinction is made between static and dynamic techniques. Thus the DFTA and DBN are included in the list of tools evaluated in the selection model.

The proposed model proposes four main steps namely:

1. Deriving the generic selection criteria based on extensive literature survey on RA tools applicable in maintenance decision making;
2. Develop ANP model linking the decision criteria to alternative RA tools;
3. Assign priority weights to the decision criteria and decision elements;
4. On the basis of assigned priority weights, develop the RA tool selection model that allows decision makers evaluate the organization against decision criteria and as a consequence select the most appropriate RA tool.

3.1 Deriving the Generic Selection Criteria

The first step of the proposed RA tool selection model entails deriving decision criteria decision makers ought to consider prior to selecting suitable RA tool. The decision criteria and respective elements are derived from extensive review of RA tools applicable in asset maintenance. The articles reviewed include articles from electronic databases, journals, conference websites, reputed textbooks and well-known standards detailing RA techniques. In addition, the search is restricted to quantitative risk assessment techniques applied in maintenance decision making. As such, qualitative RA techniques were omitted from the review. The databases selected include Google Scholar, Science Direct, and Elsevier. Examples of some standards include the US military MIL-STD-1629, the US Navy's Naval Air Systems Command (NAVAIR 00-25-403) and the IEC/ISO 31010. To enhance the search rigor, search terms such as "quantitative risk assessment", "risk analysis AND maintenance", and "quantitative risk analysis" were used in the search.

Deriving the generic selection criteria follows the approach depicted in Figure 1 and largely borrows the risk management process discussed in the ISO 31000 international standard. The risk assessment process forms an important part of risk management where three steps are described: (1) risk identification; (2) risk analysis; and (3) risk evaluation [IEC, 2009]. The assessed risks provide an opportunity for risk mitigation through selecting and implementing effective maintenance policy(s). Here, choice of an appropriate maintenance policy is achieved through an appropriate decision support structure, described by the maintenance concept, e.g. RCM. In asset maintenance, the risk assessment process is aided through varied RA tools which include the FMEA, FTA, DFTA, BN and DBN.

However, selecting specific RA tool(s) takes into account several decision elements. Often, such elements are influenced by the type of RA tool and the organizational context. Moreover, the elements are linked to the risk assessment process depicted in Figure 1. Thus the decision elements are rather varied and constitute tools, aids, materials, documentation, or procedures necessary for assessing risk at different stages in the risk assessment process.

For instance, consider a case where the FMEA is applied in risk assessment. At the *risk identification* step, failure modes are identified with the aid of process description diagrams, e.g. piping and instrumentation diagrams (P&ID) and maintenance records. Here, the description diagrams facilitate functional analysis where functional failures are identified [Moubray, 2001]. In addition, the maintenance staff should possess skills necessary to interpret the process description diagrams (e.g. the P&ID) and also perform the functional analysis.

In the *risk analysis step* causes of the functional failures and their potential consequences are analyzed. Here, several materials/aids are necessary. Moreover, important data aspects such as spare part costs or production loss are necessary for defining consequence attributed to the functional failure [Echeverry and Leverette, 2004]. As such, materials/aids such as maintenance cost or failure *databases* could aid in risk analysis. Moreover, the databases may be linked to customized *FMEA software* where statistical analysis is achieved via appropriate *statistical models* [Barberá et al., 2012]. As such, important risk metrics such as probability of failure and consequence of failure are computed via appropriate failure distributions, e.g. Weibull or logistic distribution functions [Braaksma, 2012]. Of course, using the FMEA software requires appropriate *personnel skills.*

The *risk evaluation step* requires largely the same materials/aids and resources required for risk analysis. Indeed, the evaluation step largely entails establishing a suitable risk threshold. The threshold in this case could be the maximum allowable maintenance cost derived from periodic maintenance budget. Lastly, applying the FMEA technique requires a *methodological* approach, here defined by the RCM. Thus, the material/aids, methods/procedures and resources/personnel skills describe requisite decision elements an assessor has to consider prior to selecting the FMEA as an appropriate technique for conducting FMEA. Although the importance of specific decision elements described above may vary, the selection criteria are considered generic and therefore applicable to different RA tools, i.e. the FTA and BN. Thus absence of essential decision elements, e.g. low personnel skills combined with lack of process description diagrams may result in failure of the FMEA exercise.

Likewise, the same approach described above is applied for the remaining RA tools, i.e. FTA, DFTA, BN and DBN. It is of course intuitive that the aforementioned tools follow the same risk assessment process described in Figure 1. As such, the same selection decision elements apply to all the tools, thou varying in terms of importance. For instance, the data collection schemes (failure/cost databases), statistical models, software tools and personnel skills (e.g. statistician) ought to be in place prior to selecting the BN. On the other hand, analysis/decision support tools (e.g. P&ID) together with personnel skills (i.e. multi-disciplinary teams) may suffice for selecting FMEA technique.

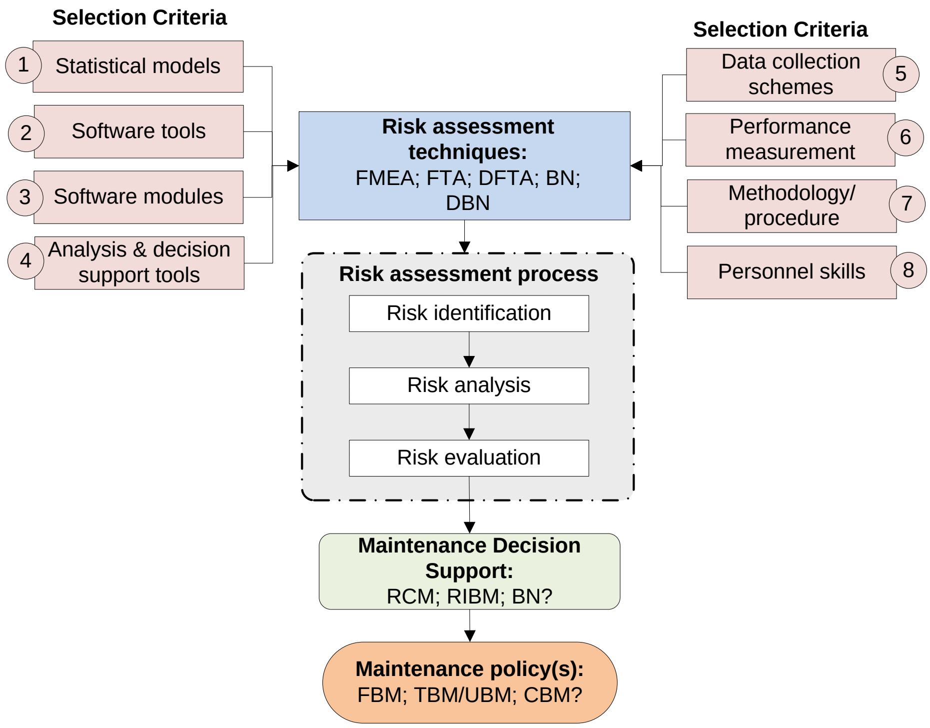

Figure 1: A summary of linkage between the selection decision criteria and risk assessment

Table 1 presents a summary of 33 generic selection decision elements clustered into 8 decision criteria derived from literature review. The decision criteria are denoted SC1 to SC8 as illustrated in Table 1. From the review, the decision criteria such as “risk analysis and decision support tools” consist of five decision elements while some, e.g. the “methodology/procedure” consists of three decision elements. The “methodology/procedure” cluster details the decision structure linked to the specific RA tool, e.g. FMEA is linked to RCM, with FTA likewise linked to RBIM.

Depending on the specific RA tool, it is intuitive that the decision elements vary in importance. As such, each decision element clearly has varying priority weights. For this reason, a MCDM approach is considered suitable for defining the selection problem. Moreover, the decision elements are clearly inter-dependent. For instance, elements in the decision cluster “risk analysis and decision support tools” are dependent on the cluster “personnel skills”. As such, the ANP methodology is considered as a plausible approach for formulating the decision problem.

	Decision Criteria	Decision elements	Tools	Author
SC 1	Software tools	(1) Computerized maintenance management software (CMMS); (2) Enterprise asset management (EAM); (3) Enterprise resource planning (ERP); (4) Dedicated risk assessment software, e.g. xFMEA™, Hugin™, ISOGRAPH™.	FMEA/FTA/BN	Barber et.al. [2010]; Echeverry and Leverette [2004]; Äepin and Čepin [2002]; Khakzad et.al [2013]; Jones et al. [2010]; Langseth and Portinale [2007]; Braaksma et. al. [2012].
SC 2	Software modules	(1) Maintenance budget control; (2) Decision support, e.g. Monte Carlo simulation; (3) Report generation (4) Configuration management	FMEA/FTA/BN	Braaksma et. al. [2012]; Barber et.al. [2010]; Rausand [1998]; Celeux et.al [2006]; Khan [2004].
SC 3	Risk analysis and decision support tools	(1) Process description diagrams, e.g. piping and instrumentation diagram (P&ID), functional diagrams; (2) Operating and maintenance records, e.g. maintenance records, OEM manuals, failure function matrix; (3) Analytic logical techniques: e.g. fault tree, event tree, reliability block diagram, Markov diagram, directed acyclic graph; (4) Probability paper, e.g. Weibull probability paper; (5) Conditional probability tables, questionnaires for deducing conditional & marginal probabilities.	FMEA/FTA/BN	Barber et.al. [2010]; Echeverry and Leverette [2004]; Moubray [2001]; Braaksma [2012]; Khan [2004]; Volkanovski et al. [2009]; Äepin and Čepin [2002]; Jones et.al [2010]; Langseth and Portinale [2007]; Weber and Jouffe [2003].
SC 4	Data collection schemes	(1) Reliability databases; (2) Maintainability data e.g. repair data, rework data; (3) Operation/maintenance cost database; (4) Design modification, e.g. re-design, retro-fitting. (5) Inspection, safety, or environmental damage database.	FMEA/FTA/BN	Barber et.al. [2010]; Echeverry and Leverette [2004]; Moubray [2001]; Braaksma [2012]; Khan [2004]; Volkanovski et.al. [2009]; Äepin and Čepin [2002]; Jones et.al. [2010]; Celeux et.al. [2006]; Portinale et.al. [2010]; Weber and Jouffe [2003].
SC 5	Statistical models	(1) Failure functions, e.g. Weibull, gamma, exponential; (2) Maintenance optimization models, e.g. inspection/maintenance interval optimization; (3) Damage/deterioration models, e.g. corrosion or wear; (4) Maintainability models, e.g. perfect repair, imperfect repair; (5) Bayesian inference algorithms (Markov chain - Monte Carlo, M-Hastings).	FMEA/FTA/BN	Echeverry and Leverette [2004]; Braaksma [2012]; Crocker and Kumar [2000]; Khan [2004]; Äepin and Čepin [2002]; Langseth and Portinale [2007]; Jones et.al. [2010]; Weber and Jouffe [2003].
SC 6	Performance measurement	(1) Functional analysis statements (operational/maintenance performance standards); (2) Operational/maintenance indicators; (3) System loss indicators.	FMEA/FT/BN	Echeverry and Leverette [2004]; Khan [2004]; Moubray [2001] Khakzad et.al. [2013]; Portinale et.al. [2010].
SC 7	Methodology /procedure	(1) Reliability centered maintenance (RCM); (2) Risk based inspection and maintenance; (3) Bayesian inferential statistics.	FMEA/FTA/BN	Echeverry and Leverette [2004]; Moubray [2001]; Khan [2003]; Volkanovski et.al. [2009]; Portinale et.al. [2010].
SC 8	Personnel skills	(1) Facilitators/statisticians; (2) Multi-disciplinary teams; (3) Expert elicitation techniques; (4) Knowledge/skills matrix (i.e. skills on functional analysis, statistical analysis, failure reliability analysis).	FMEA/FTA/BN	Echeverry and Leverette [2004]; Moubray [2001]; Braaksma [2012]; Celeux et.al. [2006]; Langseth and Portinale [2007].

Table 1: Summary of selection decision criteria and respective elements

3.2 Developing the Conceptual ANP model

The ANP methodology, first proposed by Thomas Saaty is a MCDM approach considered suitable for complex decision making [Saaty, 2001]. For reasons of brevity, this article only demonstrates the applicability of the ANP approach for the RA tool selection problem. As such detailed description of the ANP approach is omitted with the interested reader referred to the work of Saaty [2001]. Essentially, the decision problem is formulated through the ANP network structure incorporating relationships between decision clusters.

The ANP model defined in Figure 2 is developed by the authors for illustrative purposes and consists of eight decision clusters namely SC1 to SC8. Moreover, two types of influences are depicted, i.e. the outer and inner influence. The outer influence compares the influence of elements in one cluster against those of a different decision cluster given a control criterion .e.g. comparing SC 3 to SC 4. The control criterion in this case implies selecting one of the RA tool, e.g. FMEA. On the other hand, the inner influence compares the influence of elements within a given decision cluster, e.g. comparing of elements within the decision cluster SC3. This implies that for each alternative, i.e. RA technique, a different ANP network is developed. For ease in representation, the outer dependence is represented by straight arrows while loops represent the inner dependence.

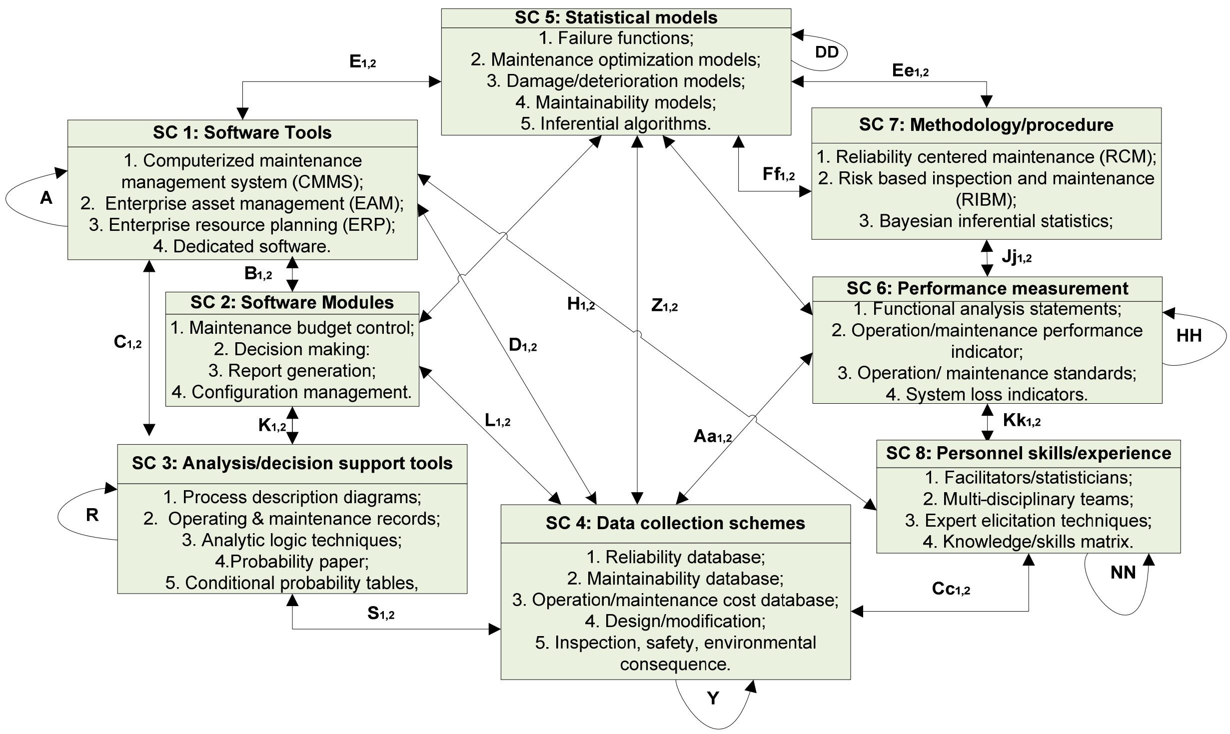

Figure 2: The conceptual ANP model

Ideally, the ANP network structure is developed based on expert judgment and requires an intuitive understanding of the decision problem [Saaty, 2001]. Here, the decision problem is characterized by three aspects namely the goal, control criterion and alternatives. Thus the overall goal considered in this article is prioritizing the decision elements and criteria necessary for selecting a specific RA tool(s). The selection model is developed separately on the basis of the priority weights derived through the ANP methodology. A detailed discussion of the selection model is presented in Section 3.4. It is also important to mention here that the ANP structure depicted in Figure 2 is illustrative for FMEA selection, but ideally, varies depending on the RA tool under consideration.

Indeed, depending on the decision makers, some of the decision clusters or elements in the clusters may be omitted or added to the ANP structure. For instance, the decision clusters "software tools" and "software modules" may be omitted from the network structure when formulating the FMEA selection problem. This may apply to a case where the organization intends to implement the convectional RPN approach.

3.3 Assigning Priorities through Pairwise Comparison

In this step, the domain experts apply the reciprocal pairwise comparison to the decision clusters and respective elements. The judgment is often made in qualitative terms and expressed numerically as per the Saaty scale [Saaty, 2001]. The priority weights derived from the reciprocal pairwise comparison are entered on the ANP supermatrix consisting of cluster matrices. For each cluster matrix, a reciprocal pairwise comparison is considered with respect to a control criterion. As such, the control criterion for each matrix varies depending on the relationships defined in the ANP network.

Table 2 illustrates an example for the ANP supermatrix derived from the model depicted in Figure 2. Here, the control criterion for the decision problem is selecting the FMEA risk assessment technique. In the supermatrix (Table 2), the decision clusters are entered on the first column at the extreme left and at top of the table, illustrated by abbreviations (i.e. SC1 to SC 8). Each variable in the supermatrix represents an individual cluster matrix. For instance, the cluster matrix 'R' depicts the reciprocal pairwise comparison for decision elements in the "analysis/decision support tools" decision cluster and illustrated in Table 3. Moreover, Table 3 illustrates an example of inner dependency amongst elements in a decision cluster.

On the other hand, variables represented with subscripts, illustrate outer dependence between two decision clusters with respect to the control criterion. For instance B_1 illustrates the outer dependence for elements in the "software modules" with respect to elements of the decision cluster "software tools". Table 4 illustrates the outer dependence of the decision clusters SC1 to SC8 with respect to selecting the FMEA technique. The dependencies, illustrated using variables are also depicted in Figure 2.

Selection criteria	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**	**SC7**	**SC8**
Software tools	A	B_2	C_2	D_2	E_2			H_2
Software modules	B_1		K_2	L_2				
Analysis/decision support tools	C_1	K_1	R	S_2				
Data collection schemes	D_1	L_1	S_1	Y	Z_2	Aa_2		Cc_2
Statistical models	E_1			Z_1	DD	Ee_2	Ff_2	
Performance measurement				Aa_1	Ee_1	HH	Jj_2	Kk_2
Methodology/procedure					Ff_1	Jj_1		
Personnel skills	H_1			Cc_1		Kk_1		NN

Table 2: The supermatrix for FMEA risk assessment tool

It is worth noting that in Table 3, two decision elements, the analytic logic techniques (ALT) and conditional probability tables (CPT) are dropped from the pairwise comparison with respect to FMEA. The reason for the emission is due to the fact that ALT tools such as fault trees, and the CPT are not considered essential for the conventional FMEA approach where the RPN is computed. The CPT is primarily applies to the BN tool where inferential statistics apply. However, the probability paper is considered essential for quantitative FMEA approaches where the occurrence (O) metric is substituted with failure distribution functions, e.g. Weibull function. This illustrates the flexibility of the ANP network structure illustrated in Figure 2 where the structure is easily customized depending on the decision problem at hand.

FMEA	PDD	O&M-R	PP	Priorities	CR
Process description diagrams (PDD)	1	2	6	0,478	
Operation and maintenance records (O&M-R)	1/2	1	7	0,452	0,073
Probability paper (PP)	1/6	1/7	1	0,070	

Table 3: Pairwise comparison for elements in the analysis and decision support tools cluster

The priorities illustrated in Table 3 and 4 are in each case derived from the reciprocal pairwise comparison and describe the relative importance of the decision (element/cluster) with respect selecting the FMEA. The scores depicted in Table 3 and Table 4 are assigned by the authors for illustrative purposes. Moreover, the assigned scores for pairwise comparison are evaluated for consistency, i.e. using the consistency ratios. Thus consistency ratios exceeding a value of 0.1 imply inconsistent judgments.

Based on the priorities derived from the individual cluster matrices, and represented in Table 3 and 4, the un-weighted supermatrix is constructed. Here, the derived priorities are located on columns in the un-weighted supermatrix. Next, columns of the un-weighted supermatrix are normalized thus transforming to the weighted supermatrix. Here, each column of the supermatrix sums up to 1. Finally, the weighted supermatrix is raised to powers until convergence is achieved, thus resulting in the limit supermatrix where each column in the supermatrix is column stochastic. As such the limiting priority weights depicted in Table 5 are replicated in each column of the ANP supermatrix.

FMEA	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	Priorities	CR
Software tools	1	4	1/5	1/3	1/2	1/4	1/5	1/7	0,0472	
Software modules	1/4	1	1/5	1/4	1/2	1/3	1/6	1/6	0,0204	
Analysis/decision support tools	5	5	1	3	4	3	1/3	1/7	0,1529	
Data collection schemes	3	4	1/3	1	3	4	1/4	1/4	0,1127	0,10
Statistical models	2	2	1/4	1/3	1	1/2	1/7	1/8	0,0452	
Performance measurement	4	3	1/3	1/4	2	1	1/7	1/8	0,0772	
Methodology/procedure	5	6	3	4	7	7	1	1/2	0,2384	
Personnel skills	7	6	7	4	8	8	2	1	0,3060	

Table 4: Pairwise comparison for the decision clusters with respect to FMEA

Table 5 illustrates the values of the limit supermatrix for decision elements with respect to the FMEA. Since the limiting values are column stochastic, the values represent the priority weights for the decision elements with respect to selecting the FMEA technique. Moreover, the priority weights may be ranked according to their relative importance as illustrated on the last column of Table 5. Thus as per the scores assigned by the authors, it seems that investing in a dedicated FMEA software is the most important decision element (ranked 1st). On the other hand, incorporating the 'report generation' software module into existing FMEA software is the least important decision element (ranked 25th). Thus, the ANP methodology presents an intuitive approach through which the decision makers can identify the most important decision elements the organization requires to focus on prior to selecting a particular risk assessment technique. By adapting the approach discussed in this section, priority weights are thus derived for each RA tool and form the basis for developing the selection model discussed in the next section.

Decision cluster	Decision elements	ANP limit matrix	
		Weight	Ranking
Software tools	Computerised maintenance management system	0.03792	13
	Enterprise asset management	0.01523	22
	Enterprise resource planning	0.01325	23
	Dedicated FMEA software	0.07845	1
Software modules	Maintenance budget control	0.01997	18
	Decision making	0.04689	12
	Report generation	0.00794	26
	Configuration management	0.06086	4
Analysis/decision support tools	Process description diagrams	0.06405	6
	Operation and maintenance records	0.06851	3
	Probability paper	0.01075	25
Data collection schemes	Reliability database	0.05357	9
	Maintainability database	0.05714	7
	Operation/maintenance cost database	0.01786	20
	Safety/environmental consequence database	0.01743	21
Statistical models	Failure functions	0.05425	8
	Monte carlo analysis	0.04762	11
	Damage/deterioration model(s)	0.01832	19
Performance measurement	Functional analysis statement(s)	0.06708	5
	Operation & maintenance performance indicator(s)	0.02497	16
	Operation & maintenance performance standard(s)	0.02484	17
	System loss indicator(s)	0.02609	15
Personnel skills	Facilitator(s)	0.04822	10
	Multi-disciplinary team	0.07845	2
	Expert elicitation technique(s)	0.01125	24
	Knowledge/skills matrix	0.02913	14

Table 5: The limiting supermatrix for FMEA risk assessment tool

3.4 Risk assessment tool selection model

The selection model builds on the previous steps discussed in Section 3.3 and presents a plausible framework for selecting the most appropriate technique amongst several alternatives. Moreover, the model allows the organization to evaluate itself against the prioritized decision elements. Developing the selection model entails the following steps:

1) The decision elements for each RA tool are prioritized following the approach described in Section 3.3. Since the decision elements are generic, the same decision elements apply to all the RA tools considered in this article. However, the weights vary depending on the specific RA tool;
2) Next, each decision element (D_i) is assigned a relative score (S_i) ranging from '1' to '5'. The assigned score evaluates the preparedness of the organization relative a decision element. For instance an organization with well-organized *process description diagrams* would assign a high score (e.g. 5) compared to one where the same diagrams are not well organized (i.e. assigned a score of 1);
3) The assigned score (S) is multiplied with its relative limiting priority weight (W_{ij}) (see Table 5). Here, the product of the aforementioned metrics likewise varies from '1' to '5'. This approach is implemented for each of the risk assessment techniques (i.e. RT_1 to RT_5).
4) The values computed in Step 3 above are summed to obtain a weighted score. Here, the final score is influenced by the varying priority weights of the individual priority

weights. However the score assigned by the decision makers applies for all risk assessment techniques. This results in differentiated final weighted scores.

5) Select the most appropriate risk assessment tool based on the value of the weighted score. Here, the technique considered most appropriate is one having the highest weighted score.

Decision elements (D_i)	Assigned score (S_i)	ANP importance weighting (W)				
		RT_1	RT_2	RT_3	RT_4	RT_5
D_1	S_1	W_{11}	W_{21}	W_{31}	W_{41}	W_{51}
D_2	S_2	W_{12}	W_{22}	W_{32}	W_{42}	W_{52}
D_3	S_3	W_{13}	W_{23}	W_{33}	W_{43}	W_{53}
↓	↓	↓	↓	↓	↓	↓
D_n	S_n	W_{1n}	W_{2n}	W_{3n}	W_{2n}	W_{5n}
	Weighted score	$=\sum_{1}^{n} S_i \times W_{1i}$	$=\sum_{1}^{n} S_i \times W_{2i}$	$=\sum_{1}^{n} S \times W_{3i}$	$=\sum_{1}^{n} S \times W_{4i}$	$=\sum_{1}^{n} S \times W_{5i}$

Table 6: Audit and risk assessment tool selection model

4. Conclusion

This paper presents a methodology for selecting the most appropriate risk assessment technique/tool for decision making in the asset maintenance context. The methodology is based on the analytic network process (ANP). It addresses an important decision making concern where maintenance practitioners are often confronted with diverse risk assessment techniques. However selecting the most appropriate technique is not so straightforward. Yet, risk assessment techniques play a vital role in maintenance decision making given that the techniques aid in systematically identifying, analyzing, evaluating and mitigating asset failure risks. The proposed selection model is based on priority weights derived by domain experts knowledgeable on use of the different techniques. Moreover, the selection model allows decision makers assess their “as-is” situation against the decision elements against which a weighted score is computed. Based on the weighted score, the most appropriate technique is selected amongst several alternatives.

However some limitations of the proposed approach need to be emphasized. The approach largely depends on knowledge of domain experts well-versed with the RA tools considered in this study. However, some techniques, e.g. the Bayesian networks are largely academic and seldom applied by maintenance practitioners. Moreover, the ANP methodology is considered costly, in terms of time given the number of cluster matrices required in the exercise. Nevertheless, the proposed approach attempts to address an important gap in practice by proposing a structured framework for selecting appropriate assessment techniques. Moreover, the selection model accounts for organizational capabilities, defined through the decision elements. Proposed future work will focus on validating the proposed methodology through case studies where the suitability of the selection model is evaluated. Moreover, comparative analysis where two or more risk assessment tools are used in combination will be evaluated in future work.

References:

Äepin, M., Čepin, 2002. A dynamic fault tree. *Reliability Engineering & Systems Safety* 75, 83.

Barberá, L., González-Prida, V., Parra, C., Crespo, A., 2012. *Framework to assess RCM software tools*, ESREL Conference.
Braaksma, A.J.J., 2012. A quantitative method for Failure Mode and Effects Analysis. *International Journal of Production Research* 50, 6904.
Dey, P.K., Ogunlana, S.O., 2004. Selection and application of risk management tools and techniques for build-operate-transfer projects. *Industrial Management & Data Systems* 104, 334-346.
Echeverry, J.A., Leverette, J., 2004. *NAVAIR Reliability Centered Maintenance Compliance with SAE JA1011*. July.
IEC, I., 2009. ISO 31010: 2009-11. *Risk management–Risk assessment techniques*.
Jones, B., Jenkinson, I., Yang, Z., Wang, J., 2010. The use of Bayesian network modelling for maintenance planning in a manufacturing industry. *Reliability Engineering & System Safety* 95, 267-277.
KarimiAzari, A., Mousavi, N., Mousavi, S.F., Hosseini, S., 2011. Risk assessment model selection in construction industry. *Expert Systems with Applications* 38, 9105-9111.
Khan, F.I., 2004. Risk-based inspection and maintenance (RBIM): Multi-attribute decision-making with aggregative risk analysis. *Process Safety and Environmental Protection* 82, 398.
Koronios, A., Nastasie, D., Chanana, V., Haider, A., 2007. *Integration through standards–an overview of international standards for engineering asset management*, Fourth International Conference on Condition Monitoring, Harrogate, United Kingdom.
Langseth, H., Portinale, L., 2007. Bayesian networks in reliability. *Reliability Engineering & System Safety* 92, 92-108.
Liu, H.-C., Long, L., Nan, L., 2013. Risk evaluation approaches in failure mode and effects analysis: A literature review. *Expert Systems with Applications* 40, 828-838.
Marhavilas, P.K., 2011. Risk analysis and assessment methodologies in the work sites: On a review, classification and comparative study of the scientific literature of the period 2000 to 2009. *Journal of Loss Prevention in the Process Industries* 24, 477.
Moubray, J., 2001. *Reliability-centered maintenance*. Industrial Press Inc.
Nakajima, S., 1988. *Introduction to TPM: total productive maintenance*. Productivity Press.
Pintelon, L., VanPuyvelde, F., 2006. *Maintenance decision making*. Acco, Leuven, Belgium.
Saaty, T.L., 2001. Decision Making with Dependence and Feedback: The Analytic Network Process : *the Organization and Prioritization of Complexity*. Rws Publications.
Tixier, J., Dusserre, G., Salvi, O., Gaston, D., 2002. Review of 62 risk analysis methodologies of industrial plants. *Journal of Loss Prevention in the Process Industries* 15, 291-303.
Van Horenbeek, A., 2010. Maintenance optimization models and criteria. *International Journal of Systems Assurance Engineering and Management* 1, 189.
Van Horenbeek, A., 2014. Development of a maintenance performance measurement framework using the analytic network process (ANP) for maintenance performance indicator selection. *Omega : The International Journal of Management Science* 42, 33.
Volkanovski, A., Čepin, M., Mavko, B., 2009. Application of the fault tree analysis for assessment of power system reliability. *Reliability Engineering & System Safety* 94, 1116-1127.
Weber, P., Jouffe, L., 2003. *Reliability modelling with dynamic bayesian networks*, In 5th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes (SAFEPROCESS'03), Washington, DC, USA, pp. 57-62.