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A hybrid model for learning from failures

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ABSTRACT

In this paper we propose the usage of a hybrid of techniques as complementary tools in decision analysis for learning from failures and the reason behind systems failure. We demonstrate the applicability of these tools through an aviation case study, where an accident investigation report was obtained from the Directorate of Accident Investigation in the Ministry of Transport and Communications in Botswana to provide as a basis for the application of the model. The report included all the factual information required to carry out the investigation using the hybrid of FTA, RBD, AHP, HoQ and the DMG tools.

We discuss the steps followed in applying the tools in the process of learning from failure. It also shows the importance of such tools in accident investigations by showing the importance of prioritising the available options in order of their importance to the accident under investigation.

Most of the available research in learning from failure focuses mostly on the direct causal factors of the failure event. Here we provide a holistic approach to learning from failure by focusing on both direct and indirect causes of a failure event through the use of Reliability Engineering tools, Multi Criteria Decision Making tools and House of Quality.

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1. Introduction

In many organisations failure is always the cause of conflicts as they have inherited a blame and lack of trust culture (Cox, Jones, & Collinson, 2006; and Jefcott, Pidgeon, Weyman, & Walls, 2006). Even though this is the case, some organisations view failure as an opportunity to obtain lessons for continual improvement hence a chance of gaining competitive advantage over their nearest rivals.

Failure can be defined in many different ways of which the use is influenced by the context it is used on. Torell and Avelar (2010) described failure in two distinct ways as the inability of a product or system to perform its required function and also as the inability of a component to perform its required function without hindering the function of the product as a whole.

The ability to learn from failures helps organizations, engineers and designers to put in place measures to avert the same inadequacies from re-occurring. Labib (2015) explains that for clear understanding of the causes of a failure, there is a major need to analyse four factors, which are; human, design, organizational and socio-cultural factors.

By doing so Labib and Read (2015) suggested that four main benefits could be obtained that include easy identification of root causes of the failure and the associated reasons. The other benefit is that such analysis of failure can help to institute long term plans to prevent similar events from re-occurring and can also act as an early warning signal just prior to the event in order for defensive actions to be taken. They also suggested that it helps decision makers with information on priorities for resource allocation for both recovery and prevention.

Labib and Read (2015) proposed categorising of causal factors as either direct cause or contributing factors when dealing with natural disasters. This approach can also be useful when dealing with failures associated with multi-disciplinary environments such as in aviation where there is an interaction of many specialties such as operations, maintenance, air traffic control, meteorology, airport services, fire fighting etc.

When dealing with failure engineers tend to tackle only the direct causes of a failure event hence putting less or almost no effort on averting indirect causes of a failure incident. As a result these indirect causes remain unsolved hence continuing hidden in the system, with a chance of causing further failure in the future.

It is the purpose of this paper to present a hybrid model for learning from failures where both the direct causes and indirect causes of failure are investigated. This model utilises the reliability engineering tools of Fault Tree Analysis (FTA), Reliability Block

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Diagrams (RBD) and Fault Modes, Effects and Criticality Analysis (FMECA); Multi-criteria Decision Analysis techniques of Analytic Hierarchical Process (AHP) and Decision Making Grid (DMG); and House of Quality (HoQ). To explain the usefulness and application of the model a case study is used.

The next section provides a detailed literature review on how different researchers use the above-mentioned technique to learn from failure. This is followed by a brief summary of the failure event that will be used as the case study for the application of the proposed model with the subsequent section focusing on the framework itself and its application on the case study. Finally section five gives the conclusion of the report underlining the weakness and the strength of the proposed approach.

2. Theoretical frameworks

There is a number of research work carried out by scholars and industry experts in order to come up with models of learning from failures. These literature works act as a starting point for further research in this important area and also as a guide for the model proposed in this paper.

Classification of hybrid models and modelling of operational research tools can be traced back to the work of Shanthikumar and Sargent (1983), who suggested that hybrid approaches can manifest itself in two ways; either through the models and their solution procedures, or through the use of the solution procedure of independent types of models. The former option they called it 'hybrid model', whereas the latter they termed it as 'hybrid modelling'. In our approach we will focus on the former option where an output of one type of modelling can be an input to the other. In terms of types and usage of operational research (OR) models, Shanthikumar and Sargent (1983) suggested that modelling is used in five ways (i) in analysis, where modelling is used to obtain an output for a given system and input, (ii) in optimization, where the model and its solution procedure are used to find the values of the decision variables to optimize an objective function, (iii) in synthesis, where a model is developed to convert a set of inputs into a set of desired outputs, (iv) in gaining insight into a system's behaviour by developing a model of it and using its solution procedure to explore its behaviour, and (v) in the comparison of alternative systems, where modelling of various alternative systems are carried out to determine the "best" one. In our work we are interested here in two types of synthesis, and gaining insight through learning lessons from failures.

Morgan, Belton, and Howick (2016) and Morgan, Howick, & Belton, 2017 developed a good review about use of hybrid OR techniques, where they concluded that mixing OR modelling methods raises many philosophical issues and that there are arguments that suggest benefits and potential problems of mixing OR methods in general. However, they argue that real-world problem situations are highly complex and multidimensional, and potentially may benefit from different paradigms to focus on different aspects of a situation. Howick, Ackermann, Walls, Quigley, and Houghton (2017) used a case study to illustrate how one can learn from mixing OR methods and specifically they focused on the value or impact of such integration of methods. However, most of the survey literature about case studies of mixing methods tend to be applied to a hybrid f two or maximum three methods, whereas in our case we develop a framework that utilises multiple methods and we highlight the benefit of using each one.

Love, Lopez, and Edwards (2013) developed a learning framework that can be used to mitigate design errors and potential failures and accidents in the construction industry. Their framework acknowledges the fundamental pathogenic influences that contribute to errors and failures. As such it suggests that a group of approaches should be implemented simultaneously at a project, organisational and people level in order to lessen errors and failures.

Failure to do this, according to Love et al (2013) would depend on time until the next major failure is experienced. They continue by explaining that reviewing past experiences is the first step in learning from failures but the much bigger step is taking action. This is because taking action involves a major change in both behaviour and culture.

When analysing the Fukushima accident, Zubair, Park, Heo, Hassan, and Aamir (2015) noticed that there exist basic precursors of nuclear accidents that are inherently difficult to quantify with vague priorities. So, to overcome these shortfalls they proposed a model, which combined the AHP and the Bayesian Belief Network (BBN). These helped them to accomplish sensitivity analysis and prior probabilities into posterior probabilities of precursors. As such they found out that design is the most important precursor though the chance of an accident is also dependent on other factors such as culture and plant specific conditions, which can affect the distribution of prior probability. For a review of AHP in terms of its methodological variation, please see Ishizaka and Labib (2011a, b).

In their research, Ishizaka and Labib (2014) studied the Bhopal disaster and proposed a model for learning from failure. In their model they demonstrated that the FTA can be improved in Crisis Tree Analysis (CTA) in order to map a crisis with the introduction of the revolving gate as opposed to the AND and OR gate that are used in an FTA. The CTA caters for amplified impact of the input event to the final event.

They also suggested that the RBD could also map crisis with hyper-blocks as the complement of the revolving gate. Their model also utilises the AHP method to measure the criticality of the basic events. Through the use of their model more realistic and sound decisions can be made unlike when using each technique in isolation.

In a bid to show that the use of FTA and RBD can systematically help in solving complex industrial failures, Yunusa-Kaltungo, Kermani, and Labib (2017) applied these techniques to investigate a chronic rotary kiln refractory brick failure in a fully integrated cement plant. They compared the efficiency of these methods to the one that was being used in the plant that is based on Root Cause Analysis (RCA). The results obtained indicated that the investigative method that was used in the plant that is based on RCA failed to prevent future occurrences. Through the usage of FTA and RBD the investigative team obtained a holistic understanding of the failure causing factors and their interrelations hence helping in avoiding repetition in the future. Both FTA and RBD have been used in a complimentary manner (Bhattacharjya & Deleris, 2012).

Labib (2015) emphasized the importance of the FTA and RBD techniques in creating a framework for learning from failures. He used these techniques to analyse the Bhopal disaster and he concluded that they could be used to serve as both knowledge retention and decision support tools. According to Labib (2015) they can provide practitioners with guidelines to follow the root cause of the problem, equips them with the tool box leading to more effective decision making practices, process safety and environment protection.

Morgan et al. (2016) presented insights on using hybrid models by mixing OR methods of system dynamics and discrete-event simulation within a real world project. They presented the model development process, the role of each modelling method and the benefits of using such hybrid models in project design. In their work, they have shown that by using hybrid models in complementary, each model add value to the other resulting in an all-round solution to the problem.

On the other hand, Labib and Read (2015) proposed a hybrid model for learning from failure that utilises both the reliability engineering tools and the multi criteria decision analysis tools. They used the reliability tools of FMECA, FTA and RBD in their model. They used this model to study the Hurricane Katrina disaster. The FTA is the starting point of their model creating inputs for FMECA and RBD. The output for the FMECA, FTA and RBD act as inputs to the MCDA method of AHP which produces the outputs helping the user to make either selection decisions or resource allocation decisions.

All the models proposed in the above studied literature have been applied on major disasters as such one can wonder if they can be of ultimate importance in minor failures. They also concentrate more on the direct cause of the failure with less emphasis on indirect factors. These outlines the importance of the proposed model as it will focus on both direct and indirect causes of a failure with the use of a case study in which no lives were lost. It also tries to appreciate the benefits of using hybrid models by using techniques in complementary.

3. ZS-CME serious incident

ZS-CME is a bombardier CRJ-100 series aircraft that is registered by the South African civil Aviation Authority under the ownership of CemAir. This aircraft suffered main landing gear wheel disintegration upon landing during its scheduled flight from Cape Town to Gaborone.

This incident was investigated as a means to derive lessons and gather facts as to what happened, how it happened, when it happened, where and why it happened by the directorate of accident investigation in the ministry of transport and communications in Botswana. The purpose of this investigation was to obtain facts in order to prevent similar incidents from occurring in the future.

According to ICAO annex 13, aircraft wheel disintegration are not classified as accidents but circumstances surrounding the ZS-CME incident made it to be have classified as a serious incident rather than just an incident (Moakofi, 2016). The below sections give a clear synopsis of what really happened.

3.1. Synopsis of the incident

On August 31, 2015 ZS-CME operated by Air Botswana under a lease agreement on a scheduled service as BOT 332 experienced starboard outer wheel disintegration upon landing at Sir Seretse Khama International Airport (SSKIA) in Gaborone. The aircraft departed Cape Town International Airport (CTIA) earlier that day where it was reported to have experienced excessive vibration during the take-off roll but the flight crew misjudged as minor and continued with the flight.

Two seconds after touch down it was reported that the crew, air traffic control (ATC) and even the fire fighters heard a loud bang sound. Even though the crew had no idea what was the problem they taxied the aircraft for almost 1.3 km in order to clear the runway for the service that was landing behind them while increasing the inherent risk to passengers. All passengers and crew disembarked safely as it was noticed the aircraft was tilting to the right as the wheel has disintegrated destroying the right main landing gear and ripping off the inner flap hence creating a fire hazard as the wings contained fuel.

3.2. Investigation findings

The worrying issues were the prolonged period the fire and rescue services (FRS) took to heed help to the occupants in the aircraft and the unavailability of aircraft engineers to attend the incident. These prompted the investigators to dig deep to see what could have caused this delays and the unavailability of engineers.

As a result, they found out that the Public Address (PA) system that would have made it possible for the ATC to communicate effectively with FRS was unserviceable which meant the relay of information from the ATC to the FRS was ineffective as it has to pass through a third person before the information can reach its destination.

The other startling discovery was that since the aircraft was operated by Air Botswana under a lease agreement, CemAir did not provide the ground support engineers at the airport even though the lease agreement stated that, “the lessor shall supply duly qualified ground engineers/technicians who shall be available in the operations area to carry out daily line maintenance and minor engine and airframe inspections on the aircraft as required, as per included costs” (Moakofi, 2016). It was evident the lessee had paid for such services because they had no engineers appropriately trained on the type of the aircraft because they had no such type on their fleet. It is reported that the maintenance crew arrived later on from Johannesburg.

Since the incident resulted in debris all over the runway it was also noticed that the airport had no serviceable runway sweeper regardless of the threat foreign object debris on the runway pose to safe air travel. The measures put in place to act as an alternative are not only time consuming but also ineffective as compared to the use of a runway sweeper. See Davidson and Labib (2003) on the impact of debris of rubber from the wheel on the runway of the Concorde accident.

The direct causes of the incident upon investigation where found to be originated from a major maintenance work that was carried out some two and half months prior to the incident. It was evident that during maintenance work there occurred an incorrect installation of brake lines to the inboard/outboard swivel assembly ports. This would result in a faulty operation of the anti-skid system producing a pro-skid condition which when activated would increase load on the landing gear instead of reducing it. This cross wiring of brake lines can be attributed to design errors in the aircraft landing gear system which made it possible.

Investigators found out that the aircraft manufacturer became aware of the design error and offered a service bulletin (SB), which according to Moakofi (2016) it was not evident whether the SB was affected, as the aircraft records from their previous owner, an American company, were inadequate to tell. The effective date of the SB was 26 December 2014 and operators where required to have complied within 6600 flying hours from the effective date but not later than March 2017.

Moakofi (2016) also found out that during the take-off roll in CTIA the aircraft experienced severe vibration that could have been an indication of fault initiation. The crew then decided to continue with the flight as they considered the vibration to be minor. Even though Moakofi (2016) did not mention anything about the vibration limits of the aircraft it can be argued that the pilot decision was informed by what the indicators told them or maybe they acted in negligence. The indicators might have given them inadequate information that could have left the crew indecisive about what measure to take.

4. Proposed model

The proposed model is an extension of the model proposed by Labib and Read (2015) that encompasses reliability engineering tools of FTA, FMECA and RBD and the MCDM tool of AHP. As an extension to this model the new model will make use of a simplified HoQ matrix and a modified MCDM technique of DMG. The overview of the proposed model is shown in Fig. (1).

The FMECA tool is not explained in this paper but its application in the proposed model is the same as explained in Labib and Read (2015), and for a review of its variations please see

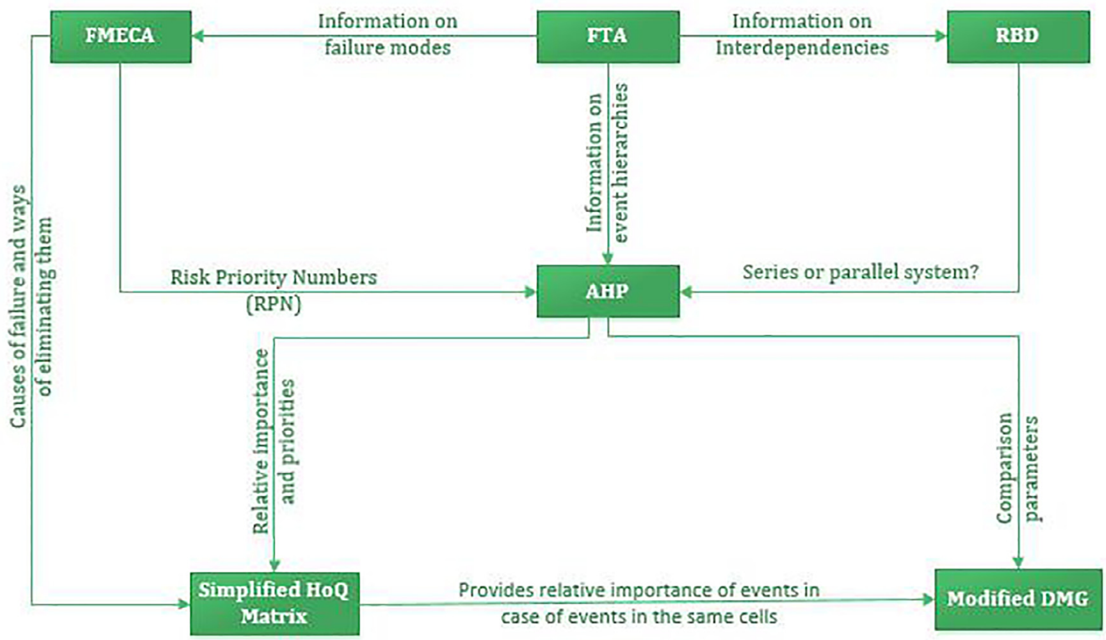

Fig. 1. The model overview and interface of techniques.

Liu, Liu, and Liu (2013). It is the authors' view that the use of FMECA will provide risk priority numbers that will show the criticality of the basic events to the AHP. This combat the importance of other basic events to the failure hence resulting in devising a solution to the critical causal factors only. As a result the events that are not deemed critical remain unsolved and hidden in the system resulting in them causing failures in the future.

In the following, the criteria for application of the proposed hybrid model for learning from failure are summarised. The details about each of the tools used are given in the subsequent subsections.

Step 1: Develop an FTA for the root causes of the failure event, expand by mapping the FTA into an RBD and use them to derive an equivalent RBD model.
Step 2: With the information on root causes from the FTA formulate a FMECA study.
Step 3: Using the risk priority numbers from the FMECA, hierarchical model from the FTA and information on parallel and series structures from the RBD, complete the AHP.
Step 4: Use causes of failure and ways of eliminating them from the FMECA, and the relative importance and priority numbers from the AHP to formulate a House of Quality matrix.
Step 5: Obtain comparison parameters from the AHP model to create a DMG and use relative importance weights from the HoQ matrix in case of events belonging to the same cell of the grid to make decisions on which to prioritise more within the same cell.

4.1. Fault Tree Analysis (FTA) and the Reliability Block Diagrams (RBD)

The FTA shows how basic events interact leading to the overall failure under study. At the top of the FTA is the undesirable failure that is under study, which in our case study is the ZS-CME serious incident, with different failures connected underneath until the basic events are reached. Basic events are the root causes of such failures that lead to the overall failure under investigation. The use of logic AND- and OR- gates show the relationship between the basic events and the failures. The AND- gate shows that the system is parallel and the OR-gate indicates series systems. Fig. (2) shows the FTA for the ZS-CME serious incident.

It is from the FMECA that we obtain information on failure modes to be used on the formulation of the FTA. We also obtain information on how basic events are related towards causing the failure under investigation helping in formulating the reliability block diagram of the system. The FTA also shows the hierarchy of events that took place towards the failure under investigation hence giving input information for the AHP tool.

In other words, the hierarchies in both FTA and AHP are already considering every element (contributing factor). However, we group these factors under the two categories of direct and indirect causes.

The justification for the usage of the two AND- gates that leads to the ZS-CME serious incident is because the analysis is made after the incident has taken place, which means all the events that fall under those branches had a part to play towards the incident. The occurrence of either event 1 or event 2 would have resulted in failure on the operational side hence the justification for the OR-gate.

Occurrence of unclear maintenance records had a negative effect on the maintenance works carried out on the aircraft leading to maintenance faults. The same applies to the failure by the aircraft design team to avoid interconnectivity of components in their design, an aspect that played a vital role in the occurrence of the incident. These events on their own would have resulted in errors in the maintenance of the aircraft hence the usage of the OR- gate.

As for the indirect causes of the incident, each event would have had an effect without the influence of another event. This means that event 6 would result in the outcome of the incident without event 7 or event 8. The same applies to the two other indirect causes hence the reasoning behind the OR- gate.

The RBD designed from the interdependency information obtained from the FTA is shown in Fig. (3). It can be noted that from this diagram the indirect causes of the incident form a series system, a finding that should be a main cause for worry. Failure

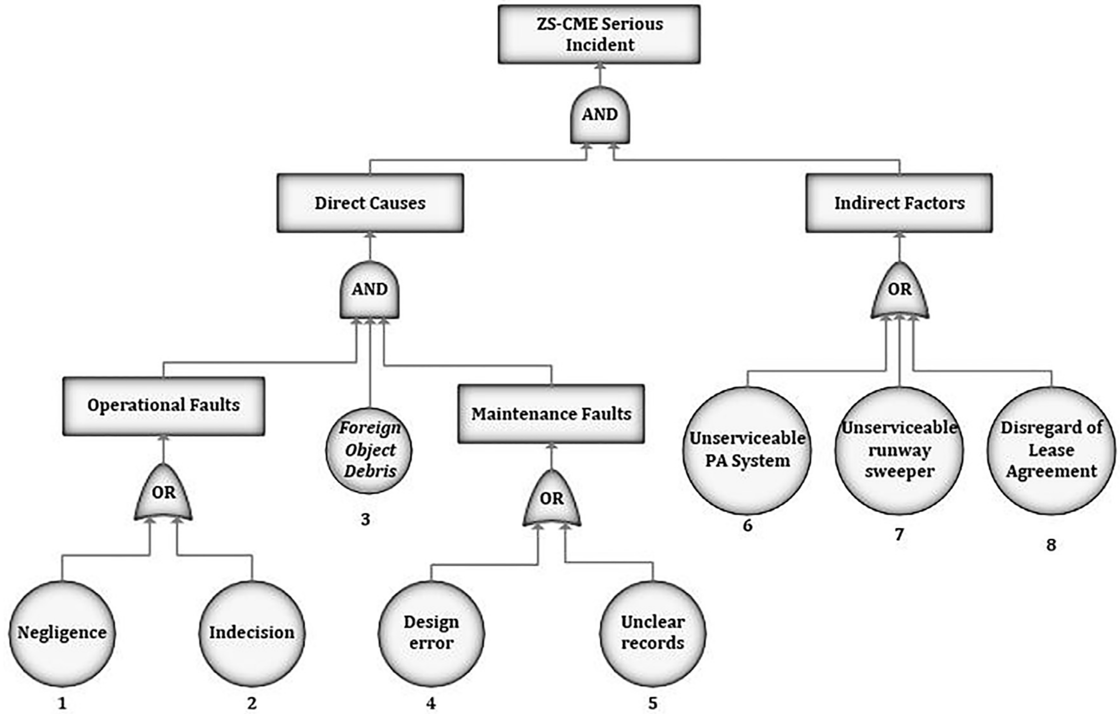

Fig. 2. The Fault Tree analysis (FTA) of the ZS-CME serious incident.

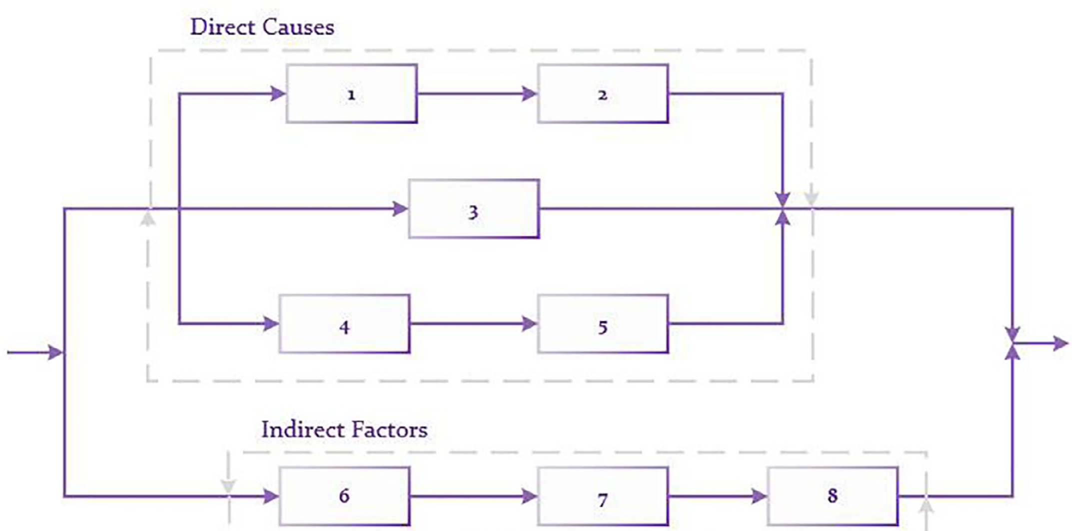

Fig. 3. The Reliability Block Diagram (RBD) of the ZS-CME serious incident.

of either event 6, 7 or 8 results in a complete breakdown of the whole branch of the RBD leaving reliance only on the direct causes branch. This shows that the indirect causes should never be taken lightly when analysing such a failure.

The minimum cut set for this system would be a failure of one event in the indirect causes branch of the RBD (6, 7 or 8) and failure of three events from the direct causes. The three events from the direct causes branch could be event 3 and either event 1 or event 2 and either event 4 or event 5. Shown below is the derivation of the minimum cut set of this system.

Cut set = (6 + 7 + 8). (4 + 5). (3). (1 + 2) which implies that the minimum cut sets are;

Minimum cut sets are 1.3.4.6; 1.3.4.7; 1.3.4.8; 1.3.5.6; 1.3.5.7; 1.3.5.8; 2.3.4.6; 2.3.4.7; 2.3.4.8; 2.3.5.6; 2.3.5.7 and 2.3.5.8

From the minimum cut sets we can also notice the importance of event 3. Its occurrence weakens all other sets.

4.2. Analytical Hierarchy Process (AHP)

The MCDM technique of AHP helps in assessing the relative weights of multiple options against given criteria in an intuitive manner (Parthiban, Zubar, & Garge, 2012). From the FTA we get the hierarchical information to be used on the AHP with the sec-

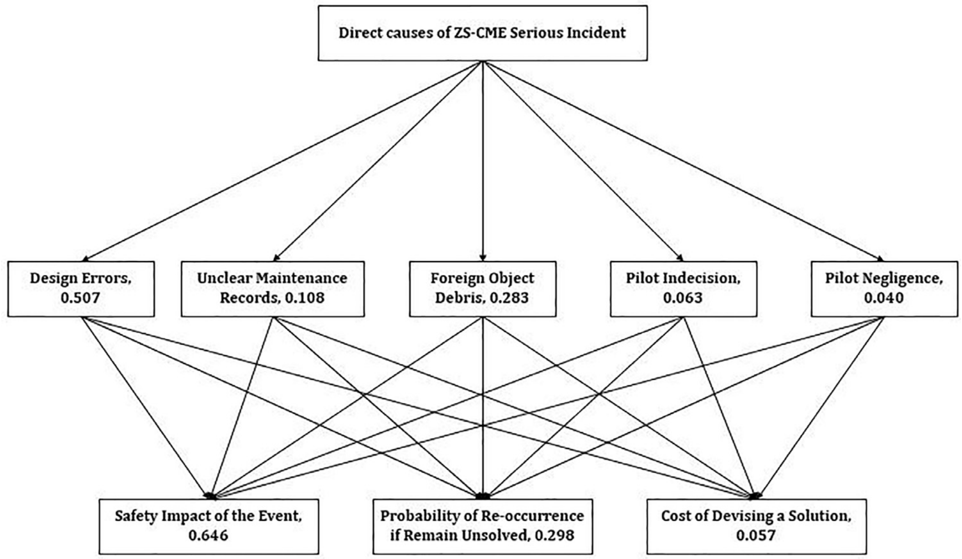

Fig. 4. AHP structure for the direct causes of the ZS-CME serious Incident.

ond level being the criteria and the basic events being the sub criteria.

The alternatives will be other common factors to consider when trying to solve the basic events and these will include the *probability* of re-occurrence when the basic event remains unsolved, the *safety impact* (severity) caused by the basic event and the *cost* incurred when trying to devise a solution. These three common factors are considered as decision variables since any decision taken will tend to focus on mitigation against risk in the form of both probability of re-occurrence and severity, as well as the required resource allocation in terms of cost incurred.

Using the AHP, to create the evaluation criteria, basic events are compared and given weights that will give the information on their priorities when trying to put in place measures that will help to avoid the similar failure from occurring in the future. This is done using the methodology that was explained by Saaty (2008) where a matrix is formed by comparing each basic event against the other basic events from the FTA and giving a score between 1 and 9 with 1 indicating that the events are equally important and 9 indicating that one event is absolutely more important than the other. The scores depend on the authors' judgement of the criteria. However the authors were informed by secondary data based on information included in the investigations reports of the accident.

The formed matrix is then normalised by making the sum of all values in a column equal to one. We then get the weight of each evaluation criteria by adding the values in each row and obtaining the average. To ensure that both the direct causes and the indirect causes of the failure are considered as seen from the RBD they are both important, two AHP models are created one for the direct and the other for the indirect causes. Fig. (4) shows the AHP for the direct causes of the failure with weights of both criteria and alternatives indicated. As for indirect causes, the model is shown in Fig. (5).

In order to come up with the weights for alternatives, we create a matrix by comparing the alternatives (safety impact of the basic, Probability of reoccurrence if it remains unsolved, cost of devising a solution) to each other with respect to each basic event and give a score of 1– 9. Then this matrix will undergo a normalisation process described above for the evaluation criteria and the average of values in a row obtained.

Finally to obtain the weights of alternatives the matrix of alternatives with respect to the basic event is multiplied with the matrix of criteria. Table 1 and 2 shows the pairwise comparison of the main criteria with respect to the goal and the pairwise comparison matrix of the alternatives with respect to event 4 respectively.

In order to explain how the priorities (weights) are derived once the comparisons matrices are completed, we use the traditional AHP eigenvalue method as described in Appendix A.

From the AHP structure for direct causes we can notice that devising a solution for event 4(design errors) have to be given the highest priority followed by event 3, event 5, event 2 and event 1 respectively. Also from the alternatives we can deduce that it is important to consider the safety impacts of each criterion before we can consider the probability of re-occurrence and the cost of developing a solution. Probability of re-occurrence has a higher priority than the cost of devising a solution. This information will be very important in the formulation of the modified decision making grid.

The weakness of the AHP include too much dependency on judgement of the person who is using it as such it can be subjective an aspect that can be eliminated by having a group of experts stating their views on what a score to give to a certain criteria with respect to the goal or an alternative with respect to a criteria. The strength includes simplifying of the users decision-making process by expertly comparing criteria with respect to the goal and alternatives with respect to criteria.

4.3. Simple House of Quality (HoQ) matrix

According to Kuei (2002) HoQ is a structured and systematic approach designed to translate customer needs into appropriate company business objectives. The HoQ matrix is made up of six major sections that show how the customer specifications are translated into the designer's language. A full HoQ matrix is shown on Fig. (6).

As shown in Fig. (6) the formulation of a HoQ matrix start with customer requirements being defined and given the relative importance weights as suggested by the customers, which are the rows, or the 'Whats' (i.e. what the customers wants) in the HoQ matrix). The next step is to come up with what designers can achieve to satisfy such requirements, which are the columns, or the 'Hows' (ie how can the customer requirements be fulfilled). This is followed by the customer's perception of where the company is as compared to competitors. At the centre of the matrix is the inter-

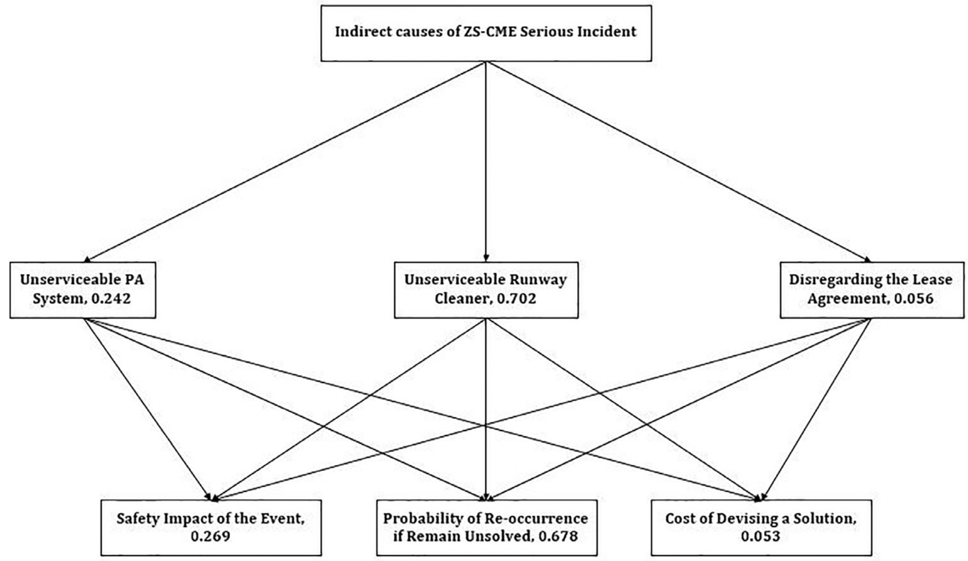

Fig. 5. AHP structure for the indirect causes of the failure.

Table 1
Pairwise comparison of the main criteria with respect to the direct causes of the failure.

	Design errors	Unclear maintenance records	FOD	Pilot indecision	Pilot negligence	Weights
Design errors	1	7	3	8	8	0.507
Unclear maintenance records	1/7	1	1/5	4	3	0.108
FOD	1/3	5	1	7	6	0.283
Pilot indecision	1/8	1/4	1/7	1	3	0.063
Pilot negligence	1/8	1/3	1/6	1/3	1	0.040

Table 2
Pairwise comparison of alternatives with respect to Event 4 (design error).

	Safety impact of the event	Probability of *Re*-occurrence if unsolved	Cost of devising a solution	Weights
Safety impact of the event	1	5	9	0.723
Probability of *Re*-occurrence if unsolved	1\5	1	5	0.216
Cost of devising a solution	1\9	1\5	1	0.061

relationship matrix, which shows how the customer needs relate to the engineering characteristics.

At the roof of the matrix is a depiction of how the engineering characteristics affect each other. As such the roof of the matrix presents an opportunity for engineers to specify the various engineering features that have to be improved collateral (Hauser & Clausing, 1988). The final aspect of the HoQ matrix is the technical assessment and target for each engineering characteristic for the betterment of the product.

Hauser and Clausing (1988) described the HoQ as a kind of conceptual map that provides the means for inter functional planning; which means it can be used as a diagrammatic representation. It is as such, that in the proposed model a simple HoQ matrix is employed in order to provide a visual representation of the causal factors of the failure and the ways of eliminating or reducing the severity of such factors.

The causal factors will occupy the part of the matrix where customer needs are defined and the engineering characteristics section will be occupied with ways of eliminating the causal factors to the failure under investigation. The weights obtained for the criteria's in the AHP will be transferred to the relative importance section.

It must be noted that both direct and indirect causes to the failure are treated as having equal importance as such each have its section in the matrix. A simplified HoQ matrix for the failure being investigated is shown in Fig. (7). In Fig. (7), we simply map the 'Whats' (rows) in the HoQ model against the 'Hows' (columns). Not that the 'Hows' are potential solutions that in our view can address each of the rows in varying degrees as captured by the X's in the relationship matrix in the middle of the grid, which is a simplified version of HoQ model. Note that the top of the matrix was generated using the information obtained from Moakofi (2016).

4.4. Decision making grid (DMG)

The decision making grid is an MCDM technique which provides means of identifying which maintenance actions are viable for a system In order to provide optimised balance between cost and performance risks. Labib developed this concept in 1996 by combining the rule-based approach with the AHP for MCDM (Labib, Williams, & Connor, 1998).

It acts as a map where using multiple criteria the worst performing machines can be classed (Labib, 1998). This grouping of machines aid in the implementation of appropriate actions that will improve their performance, hence moving them to the region of low downtime and low frequency. The objective is to improve the performance of the machines so that they move to the low frequency and low downtime cell of the DMG. Fig. (8) shows the DMG as proposed by Labib (1998).

The machines that are classed in the cell for high frequency and high downtime are considered to be the worst performing ones. So, to ensure the improvement in performance for such machines

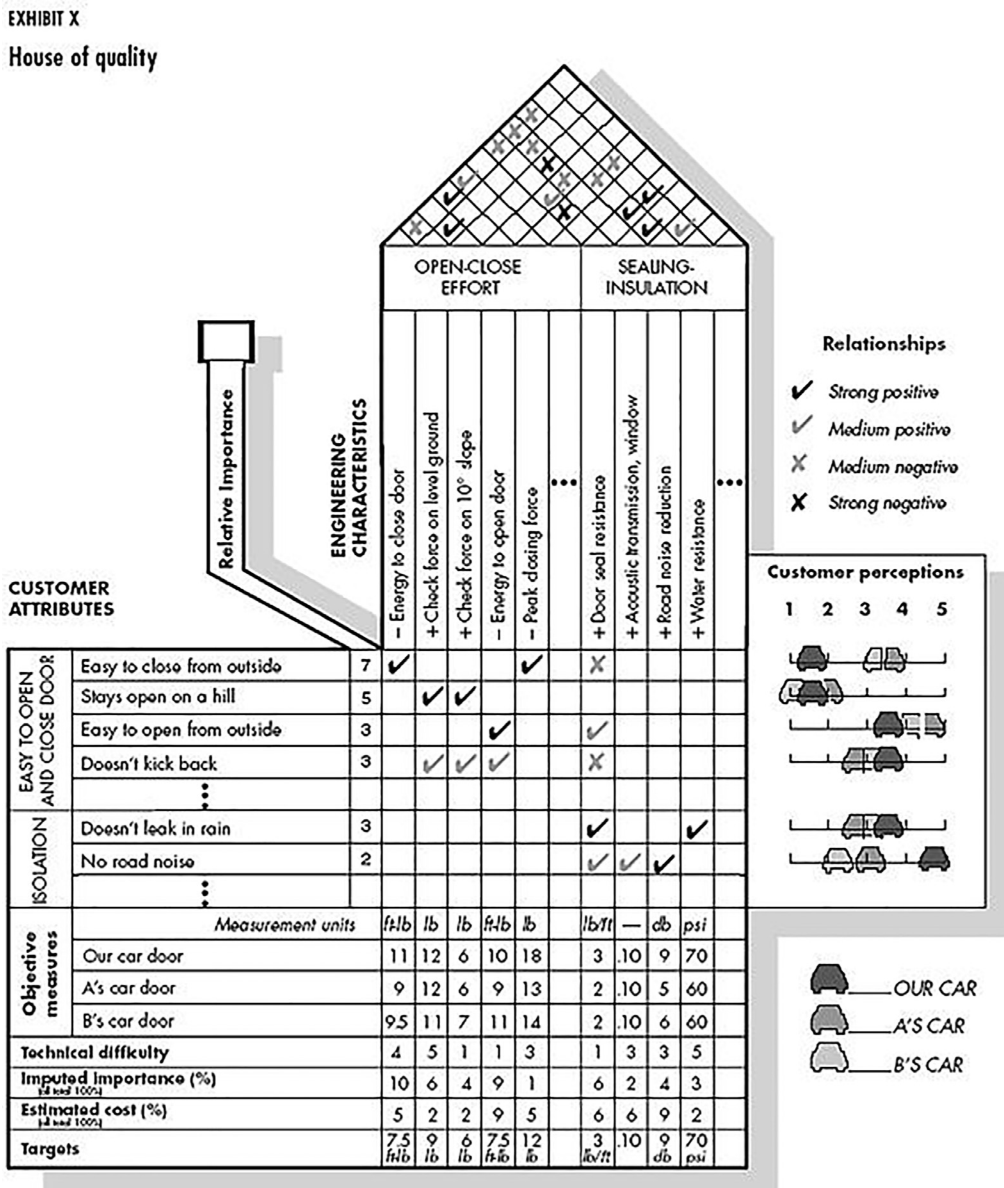

Fig. 6. A full HoQ Matrix (Hauser & Clausing, 1988).

a design out maintenance strategy is used. For machines that are classed in the low frequency high downtime cell, the rightful strategy to implement is the condition-based maintenance.

If a machine is put in the low downtime and high frequency, the rule that applies is autonomous maintenance or Skill Level Upgrade (SLU). This implies that operators are trained to perform the maintenance associated with such machine, as the tasks are relatively easy. Whereas, if a machine is put in the low frequency and high downtime, the rule that applies is Condition-Based Maintenance (CBM). This implies that there is need to monitor condition of a major type of problem that seldom occurs. As for the ones allocated to a low frequency and low downtime cell, an 'Operate To Failure - OTF' strategy has to be implemented. For the remaining cells of the DMG, the usage of the Total Preventive Maintenance (TPM) strategy needs to be continued. Finally a high frequency, high downtime implies a Design Out Maintenance (DOM) strategy since the whole machine needs to be reconfigured.

Traditionally, the DMG model that compares frequency and downtime have been used in helping decision makers and policy developers in selecting the rightful maintenance strategies for their critical assets. This technique has recently been extended to help in learning from failures. Aslam-Zainudeen and Labib (2011) stated that the technique has also been used in crisis management.

In this paper we modify the DMG to use it in ensuring that all the causal factors of a failure are solved and preventive measures are put in place as to avoid them to aid in the formulation of another failure in the future. From the AHP developed in the earlier section we obtain information on which two alternatives we need to pay attention to in order to ensure that the basic events don't result in another failure in the future.

The two alternatives that received higher rankings in the AHP models provided earlier are the safety impact of the basic events and the Probability of re-occurrence. As such we are going to develop a DMG with increasing safety impact on the x-axis and the probability of re-occurrence in the y-axis. Each axis would then be divided into three levels (low, medium and High) to form a grid of nine sections as shown in Fig. (9).

	Relative Importance	Develop A new design for MLG of C100 series	Carry out Pilot Training	Develop a minimum equipment list for airport services	Ensure serious penalties for breach of contract especially in aviation services	Ensure up-to-date maintenance records accompany the aircraft when procuring a pre-used aircraft	Ensure operators knows the importance of aircraft records
Pilot Indecision	0.063		x				
Pilot Negligence	0.040		x				
Foreign Object Debris	0.283			x			
Design Errors	0.507	x					
Unclear Records	0.108					x	x
Unserviceable PA System	0.242			x			
Unserviceable Runway sweeper	0.702			x			
Contract Disregard	0.056				x		

Fig. 7. The simplified HoQ matrix.

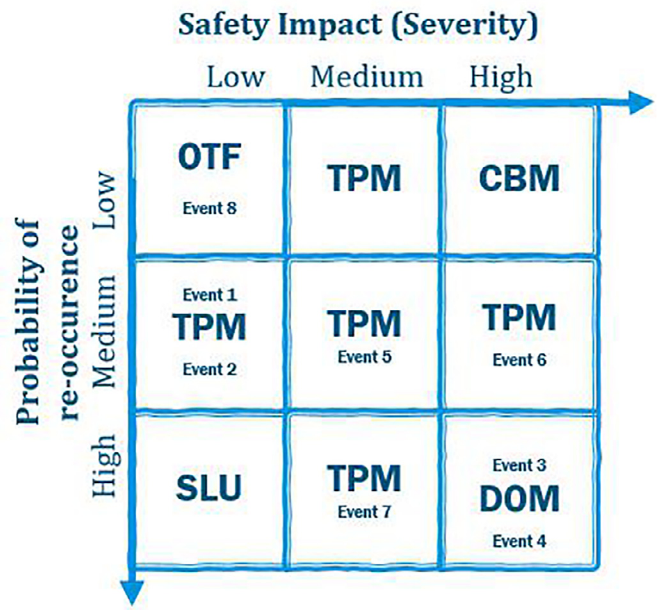

Fig. 9. The modified DMG model.

Therefore, in order to summarise how in Fig. (9), the results of previous methods can feed into this grid, we do this in two ways, one is to determine the new set of axes used (compare original grid in Fig. (8) to the modified one in Fig. (9)). The second way is through plotting the different basic events from Fig. (2) and their ranking with respect to the two axes as shown in Figs. (4 and 5) into the grid. As for how the borders have been set, this judgement is based in the variation in the values, but can also be formalised using different methods. For more details about different methods to set the borders in DMG, please see Seecharan, Labib, and Jardine (2018).

Using personal judgement each basic event is allocated to the most appropriate cell of the grid. Each of these cells indicates the priority that should be given to the allocated event. For example the basic event that is allocated to the high safety impact high probability of re-occurrence cell must be given higher priority as compared to the events in other cells.

The objective of this DMG is to ensure that preventive measures for the basic events that are in the High-high cell in the matrix are put in place so that they move to the cells that are of lower safety impact and lower probability of re-occurrence as compared to their initial allocated cell. The order of ensuring that all basic events are tackled is to start with event allocated to the high safety impact high probability of re-occurrence (high-high) cell then high-medium, medium-high, medium-medium, high-low, low-high, low-medium and low-low respectively.

As the output of the proposed model each basic event that resulted in the occurrence of the incident under study are prioritized and preventive measure put in place to ensure that their influences

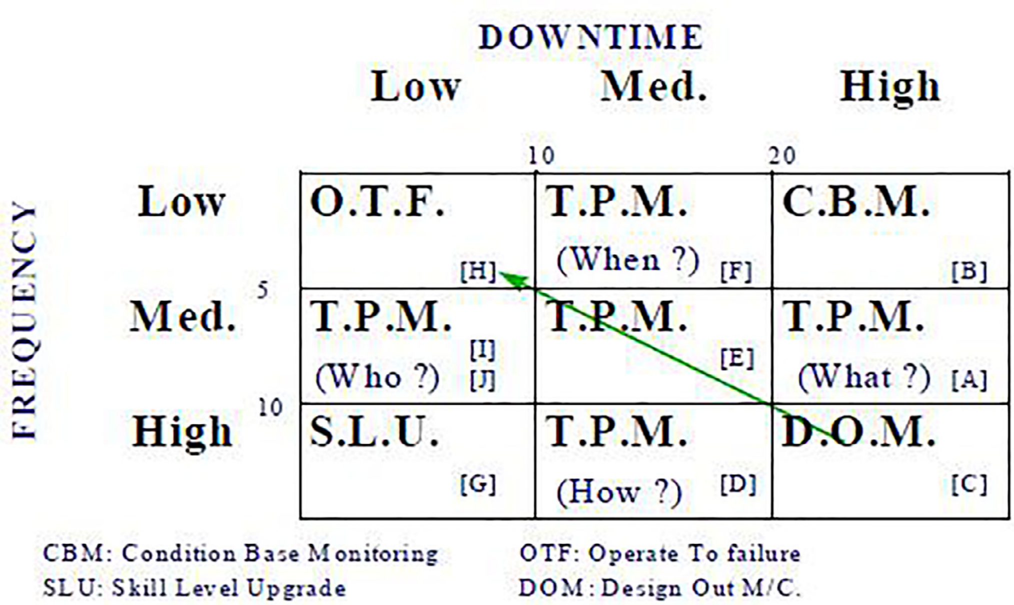

Fig. 8. DMG (Labib, 1998).

even on the future are eliminated. These priorities indicates the level of response, at which the solutions need to be implemented, as such could be compared to the maintenance strategies proposed in the original DMG model by Labib (1998).

In the proposed model, DOM has the same meaning as 'immediate response'. This means that event 3 and 4 would require being resolved immediately. The level of response required in resolving the causal factors reduces with the decrease in either the safety impact or the probability of re-occurrence, with the factors located in OTF cell being the last one to resolve. Event 7 is solved before event 6 because from the AHP model for indirect causes the rating for Probability for reoccurrence is higher than that of safety impact and this is the opposite for direct causal factors.

The strengths of this feature of the proposed model is that all the causal factors to the failure are taken and put in one place and solutions developed one at a time ensuring that the ones that are of high safety impact and have high chance of re-occurring if left unattended are given attention first before dealing with the remaining ones. This helps to ensure that no causal factors to a failure are left hidden in the system an issue that can spark a re-occurrence in the future.

The weakness of this feature is that basic events that lie in the same cell of the grid but at different extremes are treated the same hence in actual facts they have different states. The example being event 3 and 4. As a solution to this weakness, the proposed model utilises the HoQ matrix that feeds information on relative importance of events to the simplified DMG hence priorities. As such, we can tell that event 4 have to be given higher priority than event 3 even though the two are in the same cell of the DMG. This can also be solved by the application of fuzzy logic as proposed by Aslam-Zainudeen and Labib (2011).

5. Conclusions

The proposed hybrid model is an extension of the model by Labib and Read (2015). The ZS-CME serious incident has been investigated using the proposed model which showed that the causal factors number 3 and 4 should be given high priority when devising preventive measures as they fall in the high safety Impact and high probability of re-occurrence cell in the modified DMG. The results from the HoQ indicates that even though event 3 and 4 are given the same priority in the DMG event 4 should be given the utmost priority as it has a high value of relative importance.

For Indirect causes, the modified DMG shows that event 7 needs more priority as compared to event 6 because it falls under the high probability of re-occurrence region as compared to high safety Impact region. This is so because the AHP model for indirect causes of the failure have awarded a high weight to probability of re-occurrence rather than safety impact, as it is the case with direct causes.

The novelty of the proposed model came from the fact that HoQ and DMG are used to show the priorities that need to be given to each of the causal factors of the failure and comparing their results. This comparison cancels out the weakness of the DMG that is associated with events in the same cell but on the opposite extremes hence eliminating the need for fuzzy logic. The other strength that is associated with the proposed model is that it leaves no stone unturned in the event of a failure as was seen by taking consideration of both the direct and indirect causal factors of the failure.

The weakness of the proposed model comes with too much dependency on personal judgement. This does not only bring bias to the failure investigation but also inconsistencies. The authors believe that the inconsistencies and bias can be eliminated by the use of a group of people in situations where personal judgements are required hence resulting in the use of collective judgement of the group. However, group decision making has its own assumptions and challenges which are beyond the scope of this paper. For example, individual decision makers in the group can be either assumed to be equally weighted, or a method needs to be derived to allocate weights to each decision maker (Chakhar, Ishizaka, Labib, & Saad, 2016; Ishizaka & Labib, 2011b). In addition, there is a challenge in finding a suitable group that can represent all the stakeholders in the decision making process (Poplawska, Labib, Reed, & Ishizaka, 2015).

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Appendix A

In order to briefly describe the traditional AHP eigenvalue method , we start from the case of a consistent matrix with known priorities p_i.

If the matrix is perfectly consistent, the transitivity rule (1) holds for all comparisons a_{ij}:

$$a_{ij} = a_{ik} \cdot a_{kj} \tag{1}$$

In this case, the comparisons of the alternative i and j is given by p_i/p_j. If, we multiply it with the priority vector $\vec{p}$, we obtain:

p_1/p_1	p_1/p_2	...	p_1/p_n
p_2/p_1	p_2/p_2	...	p_2/p_n
...	...	...	...
p_n/p_1	p_n/p_2	...	p_n/p_n

$$\begin{bmatrix} p_1 \\ p_2 \\ \dots \\ p_n \end{bmatrix} = n \begin{bmatrix} p_1 \\ p_2 \\ \dots \\ p_n \end{bmatrix}$$

or grouped:

$$\mathbf{A}\vec{p} = n\vec{p} \tag{2}$$

where $\vec{p}$: vector of the priorities
n: dimension of the matrix
$\mathbf{A}$: comparison matrix

Eq. (2) is the formulation of an eigenvector problem. The calculated priorities are exact for a consistent matrix. When slight inconsistencies are introduced, priorities should vary only slightly according to the perturbation theory (Saaty, 2003).

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