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Investigation into a Potential Reduction of FMEA Efforts Using Action Priority

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Abstract
FMEAs have been prioritized using RPN; however, a new standard has introduced AP for prioritization. This study seeks to determine if the number of required improvement actions increases, decreases, or stays the same when using AP in place of RPN. Statistical software was used to simulate 10,000 combinations of severity, occurrence, and detection. Both AP and RPN were calculated for the 10,000 combinations. Statistical hypothesis testing was performed to determine if there was a difference between RPNs when sorted by AP and to determine if there was a difference in actions required using RPN or AP. There is a statistically significant difference between RPNs when sorted by high, medium, and low AP. Using an RPN threshold equal to or greater than 100 would result in no change in the number of actions required if prioritizing by high and medium, but would result in fewer actions required if only high is used.

Keywords
FMEA, Failure modes and effects analysis, Risk analysis, Failure prevention, Quality.

Introduction

An FMEA (Failure Modes and Effects Analysis) is a risk mitigation and reduction method (Houston, 2004) that is used to identify the ways in which a failure can happen (Mahanti, 2005) as well as to identify risks and prioritize actions to reduce the risks (Davis, 2017). FMEAs are performed to identify failures early, so that they can be prevented from happening later (Jing, 2014) by implementing actions to prevent or detect the failures (Flori, 2012).

FMEAs can be performed when creating a new product or process or when modifying an existing product or process, as well as when the usage or operating environment changes (Coleman, 2018). Use of an FMEA can reduce warranty costs and product recalls (Reid, 2005).

A PFMEA (Process Failure Modes and Effects Analysis) is performed for a process and a DFMEA (Design Failure Modes and Effects Analysis) is performed for a design concept (Stamatis, 2003). There is also a system FMEA, which is used to assess an entire system (Netherton, 2010) and an FMEA can also be used for assessing the failure of production equipment (Cotnareanu, 1999).

A DFMEA is created before the PFMEA to assess the design and the PFMEA follows the DFMEA to assess a process (Swift & Flynn, 1989). DFMEAs help to design in increased reliability of products (Kreiner, 2015) and may be performed to assess a complete system, subassemblies from a system, or single components (Reid, 2009).

The concept of an FMEA has been around since 1949 and has remained mostly unchanged (Watson, 2012). Originally described in a United States military standard, the concept spread through industry with Ford Motor Company bringing FMEAs to the automotive industry in the 1970s (Smith, 2005) and now FMEAs are used for medical products (Rodríguez-Pérez & Peña-Rodríguez, 2012), in health care facilities (Reiling et al., 2003) and are also performed as part of the Six Sigma approach to quality improvement (Hahn et al., 2000). Some industries, such as the automotive industry, require the use of an FMEA (Jing, 2019b).

There are various standards for FMEAs that have been released by organizations such as AIAG (Automotive Industry Action Group) (AIAG, 2008), VDA (Verband der Autombilindustrie) (VDA, 2003), and

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SAE (Society of Automotive Engineers) (SAE, 2009) and it is difficult for organizations when customers require FMEAs according to different industry standards (Munro et al., 2015).

North American automotive industry customers required conformance with AIAG's *FMEA Manual Forth Edition* (AIAG, 2008) and German customers required conformance with VDA's *Qualitätsmanagement in der Automobilindustrie: Sicherung der Qualität während der Produktrealisierung Methoden und Verfahren – System FMEA* (Translated into English as: Quality Management in the Automotive Industry: Quality Assurance During Product Implementation, Methods and Procedures – FMEA System) (VDA, 2003).

The original VDA FMEA methodology was more complicated than the AIAG methodology. The VDA approach linked components, assemblies, and complete systems in one FMEA using an FMEA software program. However, both an AIAG and VDA style FMEA would look comparable when viewed in an FMEA form sheet due to the connections being in the software program. Although a VDA style FMEA provides a thorough analysis of a system, it was difficult to implement in an organization because an experienced FMEA moderator was needed due to the complexity involved with using the necessary software (Barsalou, 2020). The VDA approach differed significantly from the AIAG approach, resulting in organizations needing to create separate FMEAs for different customers.

This problem was remedied with the 2019 release of *AIAG/VDA FMEA Handbook* (AIAG/VDA, 2019), which integrated aspects of a VDA style FMEA that was typically done in software into the FMEA form sheet. Previously, VDA style FMEAs created structure trees in software to graphically display the structure of a product or process, function trees to link functions between levels in a product or process, and a failure net to link the failure cause, failure mode, and failure effect (VDA, 2003). In contrast, AIAG style DFMEAs used a boundary diagram to analyze the structure of a product and a p-diagram (parameter diagram) to analyze a product's functions and a flow chart to analyze the operations in a process (AIAG, 2008).

An FMEA can have hundreds of line items; therefore, a prioritization is needed (Faltin and Opitz, 2017) and an RPN (Risk Priority Number) is calculated by multiplying the severity rating times the occurrence rating times the detection rating (Kumar et al., 2011). An RPN has a minimum possible value of 1 and a maximum possible value of 1,000 (Vandenbrande, 1998).

The highest RPNs are addressed first due to resource limitations (Zhou, 2016) with improvements stopping before the lowest RPNs are addressed when there is no more time or resources available for additional improvements. However, a major disadvantage of RPN is that severity, occurrence, and detection all have equal weight resulting in the same degree of importance (Li, 2020), which places equal importance on all three values (Sharma, 2007) and a failure effect with almost unnoticeable consequences may be addressed before a failure effect that could threatened life or limb if the later has a good prevention or detection action.

An FMEA has traditionally used RPN to prioritize risks to reduce (Tanik, 2010) and as an alternative to RPN, the AIAG/VDA FMEA Handbook introduced the use of AP (Action Priority) for prioritization of actions. An AP places a heavier emphasis on the severity rating, some emphasis on the occurrence rating, and the least emphasis on a detection rating (AIAG/VDA, 2019).

A severity of 10, occurrence of 6, and detection of 2 has an RPN of 120 and so does a severity of 2, occurrence of 6, and a detection of 10. The former has a severity rating indicating a threat to life or limb together with an excellent detection action and the later has a severity rating indicating a problem that is almost unnoticeable by customers together with a very poor detection action or no detection action. The former would have an AP of H and the later would have an AP of L, even though the RPN is the same for both (Barsalou, 2021). In this example, AP differs from RPN due to use of a table that places the most emphasis on severity, followed by occurrence, and the least emphasis on detection (Cox and Watson-Hemphill, 2022).

The *AIAG/VDA FMEA Handbook* (AIAG/VDA, 2019) is not the only standard that now uses AP. There is also (SAE's *Surface Vehicle Standard J1739* (2021), which is much like an older traditional FMEA form sheet, but with the option to use either RPN or AP (SAE, 2021).

The reduction of risk is important; however, resources are finite and not every risk identified by an FMEA will be addressed. This paper seeks to determine if use of an AP in place of an RPN results in needing to take less actions while still addressing the most pressing risks.

Literature review

FMEAs should be started early; an FMEA started for a process after the process is already running will not provide the same value as one that iden-

tified potential problems before they happened (Dietmüller and Spitler, 2009). However, prior to starting an FMEA, planning and preparation is needed and this begins with forming an FMEA team. The teams should be a multidisciplinary team with team members from different roles and different departments (Maisano, 2020). In addition to regular team members, relevant SMEs (Subject Matter Experts) must also be consulted when performing a DFMEA (Bossert, 2020). For example, a material expert may be needed when a new type of material is being used or a machinist may be needed if the team lacks the necessary knowledge of a machining operation.

Older FMEAs should be consulted when starting a new FMEA; however, the ratings should be adapted to the new product or process and not simply taken over as-is (Faltin and Opitz, 2017). Existing information, such as data from a database of field failures for comparable products should also be considered when starting an FMEA (2014).

Scoping actions are also performed during the planning and preparation for an FMEA. This includes actions such as reviewing technical drawings, lessons learned, and customer and legal requirements. Often, generic FMEA may already exist for a process. These are called foundation FMEAs, family FMEAs, or FMEA templates and these can be taken and updated based on the actual process being assessed by the FMEA (AIAG/VDA, 2019). Major advantages of templates include not needing to start from zero each time a new FMEA is needed and the templates can contain lessons learned from previous problems in comparable processes.

The exact layout and content of an FMEA form sheet may vary between organizations (Bigley, 2017). However, each FMEA form sheet has a header that is filled out during planning and preparation and the header of an FMEA should list the names of the person responsible for the FMEA as well as the names of the FMEA team members (McCain, 2006).

A process flow diagram must be created to analyze the process under evaluation when performing a PFMEA (AIAG/VDA, 20019). A process flow diagram is essentially a flow chart, which is used to graphically depict the steps in a process with labeled text boxes identifying process steps and arrows indicating the direction of the process (Tague, 2005).

For DFMEAs, a boundary diagram and p-diagram (parameter diagram) are used for preparation. A boundary diagram consists of blocks with component or assembly names and arrows depicting physical contact between components or assemblies as well as the flow of material such as oil. The boundary diagram is used for understanding the structure of a system as well as the limits of the system and interactions both inside and outside of the system. A p-diagram is used to identify a system's inputs, ideal outputs, and error states as well as the functions and requirements of a system. A p-diagram also lists noise factors such as variation between parts, interactions with other systems, changes over time, the system's operating environment, and the customer's usage of the system; all of which could contribute to failures of the system (AIAG, 2008).

The relevant process step being evaluated must be listed in a PFMEA and a DFMEA lists the name of the component, assembly, or system being evaluated (Kubiak, 2014). The new style *AIAG/VDA FMEA Handbook* PFMEA form sheets now include the 4M type of the process work element (AIAG/VDA, 2019). The 4M refers to four of the six Ms used in an Ishikawa diagram (Babula et al., 2015) consisting of material, operator (man), environment (Milieu), and machine. The additional Ms form an Ishikawa diagram, method and measurement (ReVelle, 2004), may be used if an organization chooses too. The PFMEA form sheet also lists the process step that is being evaluated as well as the number of the work station. The name of the overall process is also listed in the form sheet (AIAG/VDA, 2019).

The item under consideration's function should be listed in the FMEA form sheet. A function could be "Weld the hinge bracket onto the armature" (Pan and Kolarik, p. 18 1992) or a requirement to maintain a specific temperature (Pyzdek, 1993).

When using the *AIAG/VDA FMEA Handbook* for a PFMEA, a function analysis is conducted to detail the function of the process work element and process characteristic, function of the process step, and function of the overall processes. The function of the process work element is what exactly must be done by the characteristic classified under the 4Ms and is where the failure cause happens. The function of the process step describes exactly what happens during the operation and is where the failure mode is located. The function of the processes is what the overall press must achieve and is where the failure effect happens. Here, the function of a component, assembly, or the complete system is also listed (AIAG/VDA, 2019).

For DFMEAs per the *AIAG/VDA FMEA Handbook*, the form sheet lists the focus element, which is what is being evaluated and where the failure happens, as well as the next higher level and the next lower level. The next higher level is an assembly or complete system and is where the failure effect happens. The next lower level is either a component when the focus element is an assembly, or a characteristic when the focus element is a component. The

next lower level is where the failure cause happens (AIAG/VDA, 2019).

An FMEA lists failure causes, failure modes, and failure effects. The failure cause is something going wrong that results in the failure mode, such as a part that has a fracture (Ramachandran et al., 2020), material that has been poorly handled or stored, problems with workmanship (Prashar, 2018), the wrong current setting in a welding machine (Anderson & Kovach, 2014), or a design that has insufficient spacing between two electronic components that cause a short circuit (Hatty and Owens, 1994). Potential sources of failure causes also include customer misuse of a product (Taormina, 2019). An Ishikawa diagram should be used when brainstorming failure causes and failure modes (Netherton, 2010).

The failure mode is a consequence of the failure cause and describes what goes wrong at the process operation for a PFMEA or the component, assembly, or system for a DFMEA. The failure mode should consist of a noun and a verb to ensure people understand what is being referred to and what is happening (Netherton, 2010). An example of a failure mode is "particle contamination" (Hatty and Owens, 1994, p. 177) or a headlight switch that sticks in the on position when activated in cold conditions (Davis, 2017). Other examples of a failure mode are an item that is oversized, undersized, out of perpendicularity, out of tolerance (Pan and Kolark, p. 18 1992), or an item with corrosion or wear (Vinodh & Santhosh, 2012). A weakness of FMEAs is that complicated failure modes are not considered such as when the failure mode is the result of multiple events occurring together (Nanda, 2010).

The failure effect results from the failure mode (Stamatis, 2003). One failure mode may have multiple failure effects and failure effects should be listed for the consequence of the failure at the plant where it happened, at the customer, and at the end user. An unacceptable scrap rate may be a failure effect in an FMEA (Das and Gupta, 2012). Other examples of failure effects are too much moisture in a quenching process (Deshpande et al., 2004) or an unacceptably high waiting time in a workflow process (Trimarki, 2016).

Exactly what is a failure cause, failure mode, or failure effect can vary depending on where one looks in the chain of failures. For example, something may be a failure cause, failure mode, or failure effect depending on where in the chain of causality it is, with failures above being failure effects and failures below being a failure cause (Jing, 2019a).

The severity of the failure effect is the impact of the failure mode (Miguel and Cauchick, 2008) and must be rated on a scale of one to ten, with ten being the worst and one being the least bad. One example of a severity rating of 10 is when a person may be endangered without warning and a severity rating of 1 is when there is only a minor inconvenience or the effect is not noticed (Vinodh & Santhosh, 2012).

Tables are used in rating severity and organizations may have their own table. Alternatively, there are also severity tables in *AIAG/VDA FMEA Handbook* (AIAG, 2019), SAE J1739 (SAE, 2021), *VDA Band 4* (VDA, 2003), and *FMEA Manual Fourth Edition* (AIAG, 2008).

The risk analysis follows the failure analysis. First, the current prevention and detection actions are defined and the detection and prevention actions are the actions that are currently in place.

The prevention actions are to prevent the occurrence of the failure cause. Prevention actions include actions such as setting up a machine per predefined instructions or a Poke Yoke fixture to ensure the failure cause cannot happen. The occurrence of the failure cause is determined using tables (Dillibabu & Krishnaiah, 2006) where a low value may indicate that the failure cause cannot happen and a high value indicates that the failure cause happens often (Vinodh & Santhosh, 2012).

Detection actions include 100% inspection, random sampling, Statistical Process Control (SPC), and Poke Yoke devices to ensure that an out of specification part cannot be passed to the next operation in the processes. A visual inspection of a finished part is an example of a PFMEA detection action (Prashar, 2018). The detection rating rates the ability to detect either the failure cause or the failure mode (Sangode and Metre, 2011) and the detection rating is determined using a scale of 1 to 10 using tables (Anderson and Kovach, 2014) with low values indicating a low chance of the failure cause or failure mod being detected o and high values indicating a high chance of detecting the failure cause or failure mode if they occur (Mahanti, 2014).

Once identified, the most serious risks in an FMEA are addressed with improvements (Carlson, 2014). Traditionally, FMEAs used RPN to prioritize improvement actions by multiplying severity, occurrence, and detection to derive the RPN (Johnson et al., 2006) with the highest RPNs addressed first (Vinodh & Santhosh, 2012); for example, by identifying the highest RPNs using a Pareto chart (Liu et al., 2018), which graphically depicts frequencies of occurrences (Alsyouf et al., 2018).

FMEAs should not have a threshold value for RPNs (Netherton, 2010). But, some customers do mandate an RPN threshold value with all RPNs above the

threshold requiring an improvement to reduce the RPN below the threshold; however, this should be avoided (Reid, 2009).

The disadvantage of the RPN approach is that severity, occurrence, and detection all have equal weights and a low severity problem may be addressed before one with a much higher severity. For example, a severity of 2, occurrence of 5, and detection of 10 results in an RPN of 100. A severity of 10, occurrence of 5, and a detection of 2 also results in an RPN of 100 (Borror, 2009).

To compensate for this, an organization can prioritize based on criticality, which is derived by multiplying only severity and occurrence (Pyzdek, 1993). This results in problems with a high severity and high occurrence being addressed first, but severity and occurrence still have equal weight and detection is not even considered.

The *AIAG/VDA FMEA Handbook* uses AP to prioritize actions for improvement based on a table available in the book that give the most weight to severity, some weight to occurrence, and the least amount of weight to detection (AIAG/VDA, 2019). Using RPN, two problems with same RPN would have the same priority even when one has a high severity rating and the other with a high detection rating (Borror, 2009). With AP, the one with the higher severity rating would be addressed first (AIAG/VDA, 2019).

The AP prioritization table is available in both *AIAG/VDA FMEA Handbook* (AIAG/VDA, 2019) and *SAE J1739* (SAE, 2021). For example, a severity of 8, occurrence of 1, and detection of 5 would have an RPN of 40 based on multiplying the three numbers. For AP, a table would be consulted. First severity would be located in a row for severity 7–8 in the table, then an occurrence of 1 would be located in a row for occurrence of 1, and then detection would be located in a row for detection values between 1 and 10, indicating an AP of L. Alternatively, a severity of 9, occurrence of 3, and detection of 7 would have an RPN of 189 and an AP of high based on a severity in the row for severity of 9–10, an occurrence in the row for an occurrence of 2–3, and the row for a detection between 7 and 10 (AIAG/VDA, 2019).

Tables are available for deriving AP; however, the tables run across multiple pages and require having a copy of the standards available when using the table. An alternative is to create a matrix based on the AP table. Such a matrix would make it possible to quickly derive an AP using only one small matrix showing combinations of severity, occurrence, and detection with the appropriate APs (Barsalou, 2021). An example of an AP matrix is shown in Figure 1.

An AP uses ratings consisting of high, medium, and low. A high AP requires an improvement action to reduce the AP, or a strong justification documented in the form sheet explaining why current actions are believed to be sufficient. A medium AP should have either an action or a justification in the form sheet explaining why current actions are sufficient. A low rating does not require an improvement action; however, an organization may still choose to implement additional actions, even if the actions have no impact on AP (AIAG/VDA, 2019).

When using an RPN, higher RPNs indicated a higher degree of risk (Welborn, 2007). In contrast to the level of risk identified by an RPN (Jiang & Chen, 2015), AP identifies the prioritization of actions and not the actual level of risk (AIAG/VDA, 2019).

An FMEA form sheet also has a column for special characteristics. Special characteristics are characteristics that require special attention due to the impact if anything goes wrong with them. For example, they may impact health and safety or form, fit, and function. As such, they are candidates for special control actions to ensure that they are always within specification (SAE, 2021).

Once actions are prioritized, new actions are identified for prevention actions, detection actions, or both prevention and detection actions. A person

		Severity Rating														
		1	2–3		4–6				7–8				9–10			
Ocurrence Rating	8–10	Low	Low	Medium	Medium	Medium	High	High	High	High	High	High	High	High	High	High
	6–7	Low	Low	Low	Low	Medium	Medium	Medium	High	High	High	High	High	High	High	High
	4–5	Low	Low	Low	Low	Low	Low	Medium	Medium	Medium	Medium	High	Medium	High	High	High
	2–3	Low	Low	Low	Low	Low	Low	Low	Low	Low	Medium	Medium	Low	Low	Medium	High
	1	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
		1–10	1 -4	5–10	1	2–4	5–6	7–10	1	2–4	5–6	7–10	1	2–4	5–6	7–10
		Detection Rating														

Fig. 1. AP matrix based on Barsalou, 2021

must be assigned responsibility for implementing improvements to reduce prevention or detection ratings (Ramu, 2009) and a due date is given.

The severity rating is difficult to change as improved prevention or detection actions have no impact on the severity of the failure effect, which is the impact of the failure cause happening. A failure effect can be reduced; however, a new concept is needed that results in a situation where the failure effect can't happen even if a failure occurs. This is demonstrated by a university that used an FMEA to assess new housing. One possible failure mode was high renovation costs with a severity of 7, occurrence of 8, detection of 10 and an RPN of 560. An improvement was implemented. In this case, it was a concept change to use interior rooms that could have the layouts easily changed, resulting in a severity reduction to 3 and a new RPN of 210 (Johnson et al., 2006).

The status of the action should also be listed. Once completed, the implemented actions are listed in a column for completed actions and the completion date is listed in a separate column. The rating for the improved occurrence or detection action is then reevaluated and a new AP is derived and listed when AP is used. New actions are then identified if the new AP is considered unacceptable. In addition, new detection and prevention actions can be identified and implemented even if there is no impact on the AP (AIAG/VDA, 2019). Alternatively, the RPN is recalculated once improvement actions are in place (Johnson, 2016).

The final step in performing an FMEA is the documentation and reporting of results. For example, customers and managers may be presented with a summary of key risks and activities (AIAG/VDA, 2019).

An FMEA is a living document (Pollock, 2005) and an FMEA may still be updated after it is initially completed (Ramu, 2009) as new information becomes available (Shahin, 2004) such as when a product or process is changed after the completion of an FMEA due to the introduction of actions to avoid failures (Liebesman, 2014) such as after a customer warranty claim or a customer complaint (Reid, 2004). When an FMEA is revised, revision dates should be listed indicating when the FMEA was updated (McCain, 2006).

Materials and methods

Minitab Statistical Software® was used to list 10,000 severity, occurrence, and detection ratings. This was done by using the software to generate numbers 1 through 10 and repeating the pattern 1,000 times each for severity, occurrence and detection. Then new columns were labeled Severity_Random, Occurrence_Random, and Detection_Random. Each of the new columns were populated using a random normal distribution generator to generate 10,000 values with a mean of 100 and a standard deviation of 10 (see Figure 2).

	C1	C2	C3	C4	C5	C6
	Severity_Random	Severity	Occurrence_Random	Occurrence	Detection_Random	Detection
1	91,259	1	104,768	1	92,023	1
2	85,660	2	92,304	2	99,388	2
3	102,316	3	88,109	3	92,223	3
4	103,366	4	102,426	4	104,213	4
5	90,062	5	91,793	5	94,560	5
6	115,051	6	71,623	6	98,543	6
7	106,216	7	87,548	7	107,102	7
8	98,897	8	108,755	8	110,988	8
9	121,323	9	97,057	9	98,611	9
10	102,134	10	105,562	10	117,500	10
11	111,523	1	103,155	1	109,086	1
12	99,480	2	103,913	2	97,971	2
13	93,536	3	102,143	3	91,655	3
14	103,996	4	93,505	4	87,970	4
15	81,902	5	111,067	5	85,626	5
16	94,912	6	96,279	6	86,246	6
17	94,617	7	109,700	7	93,882	7
18	111,100	8	115,508	8	104,077	8
19	107,444	9	118,146	9	93,954	9
20	101,339	10	89,107	10	94,147	10

Fig. 2. First 20 rows of unsorted random values

The severity_random and severity columns were sorted by severity_random to randomize the order of the simulated severity ratings. The same procedure was repeated to randomize simulated occurrence and detection ratings. The RPN was then determined by using the statistical software program to multiply severity, occurrence and detection (see Figure 3).

	C1	C2	C3	C4	C5	C6	C7
	Severity_Random	Severity	Occurrence_Random	Occurrence	Detection_Random	Detection	RPN
1	63,798	8	57,994	3	59,968	4	96
2	66,108	6	65,342	5	60,910	9	270
3	68,680	4	66,427	1	61,028	8	32
4	68,996	1	67,585	4	63,386	2	8
5	69,346	1	67,792	3	63,471	3	9
6	69,495	10	67,877	7	63,934	5	350
7	69,744	8	68,443	4	64,099	3	96
8	69,745	10	68,635	2	64,751	3	60
9	69,823	2	69,084	10	66,294	3	60
10	69,825	5	69,606	10	67,302	6	300
11	69,908	2	69,949	2	67,452	5	20
12	69,986	7	70,010	7	67,728	7	343
13	69,993	7	70,262	3	67,805	7	147
14	70,274	8	70,912	3	68,223	8	192
15	70,349	7	70,937	8	68,413	6	336
16	70,739	9	71,100	5	68,467	1	45
17	71,556	7	71,215	10	68,931	7	490
18	71,569	5	71,298	8	69,287	2	80
19	71,722	3	71,341	4	69,343	7	84
20	71,771	7	71,361	1	69,377	7	49

Fig. 3. First 20 rows of sorted random values

The severity, occurrence, and RPN were then transferred to a spreadsheet formatted to automatically calculate an AP as shown in Figure 4.

	A	B	C	D	E
1	**Severity**	**Occurence**	**Detection**	**RPN**	**AP**
2	**8**	**3**	**4**	**96**	**L**
3	**6**	**5**	**9**	**270**	**M**
4	**4**	**1**	**8**	**32**	**L**
5	**1**	**4**	**2**	**8**	**L**
6	**1**	**3**	**3**	**9**	**L**
7	**10**	**7**	**5**	**350**	**H**
8	**8**	**4**	**3**	**96**	**M**
9	**10**	**2**	**3**	**60**	**L**
10	**2**	**10**	**3**	**60**	**L**
11	**5**	**10**	**6**	**300**	**H**
12	**2**	**2**	**5**	**20**	**L**
13	**7**	**7**	**7**	**343**	**H**
14	**7**	**3**	**7**	**147**	**M**
15	**8**	**3**	**8**	**192**	**M**
16	**7**	**8**	**6**	**336**	**H**
17	**9**	**5**	**1**	**45**	**M**
18	**7**	**10**	**7**	**490**	**H**
19	**5**	**8**	**2**	**80**	**M**
20	**3**	**4**	**7**	**84**	**L**

Fig. 4. First 20 rows of a spreadsheet for determining AP

The results were then copied back to the statistical software program as shown in Figure 5.

↓	C1	C2	C3	C4	C5-T
	Severity	Occurrence	Detection	RPN	AP
1	8	3	4	96	L
2	6	5	9	270	M
3	4	1	8	32	L
4	1	4	2	8	L
5	1	3	3	9	L
6	10	7	5	350	H
7	8	4	3	96	M
8	10	2	3	60	L
9	2	10	3	60	L
10	5	10	6	300	H
11	2	2	5	20	L
12	7	7	7	343	H
13	7	3	7	147	M
14	8	3	8	192	M
15	7	8	6	336	H
16	9	5	1	45	M
17	7	10	7	490	H
18	5	8	2	80	M
19	3	4	7	84	L
20	7	1	7	49	L

Fig. 5. First 20 rows of severity, occurrence, detection, RPN, and AP in statistical software

The data was generated using multiple iterations of the values 1 to ten and they did not follow any statistical distribution. The RPNs were generated by multiplying three columns of data with values framing from one to 10. This means $10 \times 10 \times 10$ would generate an RPN of 1,000, but the values $9 \times 10 \times 10$ would only result in an RPN of 900. Statistical software was used to perform an individual distribution identification and the results shown in Figure 6 indicate that the data did not follow any of the evaluated distributions.

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	550.239	<0.005	
Box-Cox Transformation	14.774	<0.005	
Lognormal	49.278	<0.005	
3-Parameter Lognormal	34.361	*	0.000
Exponential	26.166	<0.003	
2-Parameter Exponential	27.329	<0.010	0.000
Weibull	20.574	<0.010	
3-Parameter Weibull	15.506	<0.005	0.000
Smallest Extreme Value	940.582	<0.010	
Gamma	25.407	<0.005	
3-Parameter Gamma	19.286	*	0.000
Logistic	402.559	<0.005	
Loglogistic	47.784	<0.005	
3-Parameter Loglogistic	48.655	*	0.049

Fig. 6. Individual distribution identification

Figure 7 depicts probability plots for various statistical distributions. The data depicted do not conform to any of the evaluated distributions.

There was much overlap of RPNs between high, medium, and low APs. Low AP values overlapped with 2,044 high values and 1,926 medium values also overlapped with high values. Medium and low values had 1,803 occurrences of overlapping.

The high degree of overlapping can be seen in the boxplots of RPN by AP in Figure 8. A boxplot is a graphical technique that displays half the data within a box with a line indicating the location of the median value and lines indicating a quarter of the values above and below the box, with asterisks indicating the presence of statistical outliers (Tague, 2005), which are values that stand out from the rest of the data (Allen and Seaman, 2007).

The RPNs under high AP had higher values than RPNs under low and medium and low had the lowest RPNs. However, there was overlap between all groups, so an ANOVA was performed to determine if there was a statistically significant difference in the means of the groups.

An ANOVA is a statistical method used to determine if there is a statistically significant difference between three or more means (Lawson & Erjavec, 2001). The resulting ANOVA shown in Figure 9 has a p-value less than 0.05; therefore, there is a statistically significant difference in one or more means.

The statistical software program crated the interval plot in Figure 10, which depicts the means and a 95% confidence interval around the means. None of the confidence intervals overlap; therefore, all three means are statistically different.

The RPNs were then stacked in individual columns based on the AP using a function of the statistical

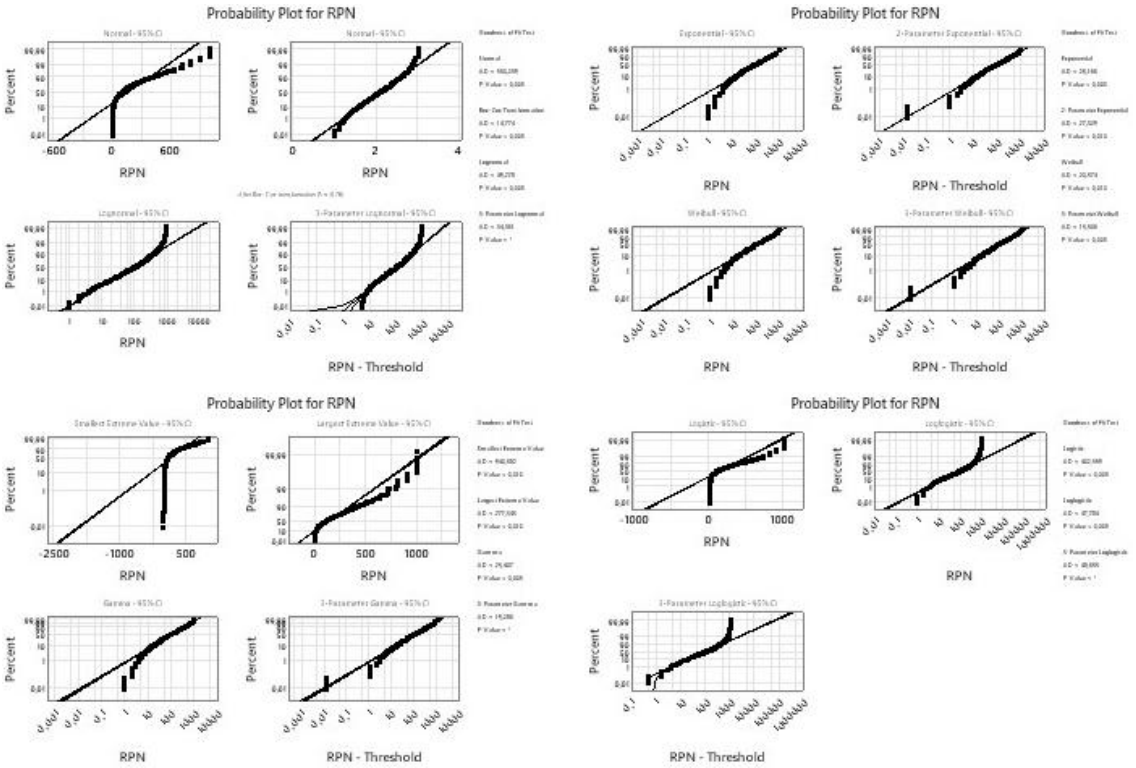

Fig. 7. Probability plots for individual distribution identification

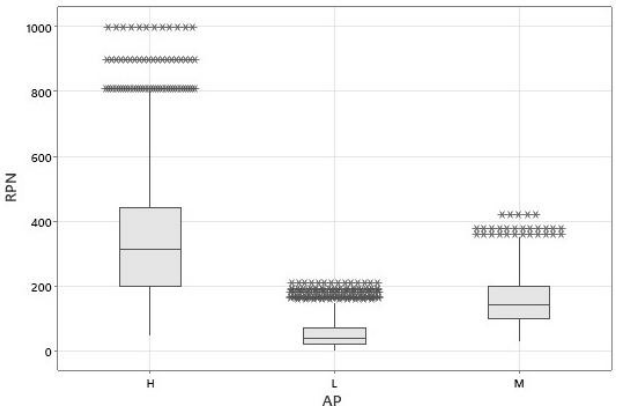

Fig. 8. Box plot of RPNs by AP

One-way ANOVA: RPN versus AP Method

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Factor	3	H; L; M

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	158604415	79302208	6085.43	0.000
Error	9997	130275822	13031		
Total	9999	288880237			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
114.156	54.90%	54.89%	54.87%

Means

Factor	N	Mean	StDev	95% CI
H	3199	340.45	186.03	(336.49; 344.41)
L	4725	52.381	40.777	(49.126; 55.637)
M	2076	154.96	75.24	(150.05; 159.87)

Pooled StDev = 114.156

Fig. 9. ANOVA of RPN versus AP

software program for unstacking and stacking data. A calculation function was then used to identify RPNs over 100 using the formula RPN_Low $\geq 100 = 1$ with a 1 appearing in a new column if the RPN was equal to or greater than 100. The same procedure was repeated for medium and high APs.

Cutoff scores or threshold values are to be avoided (Anleitner, 2011); however, a threshold value was needed for the study to have some form of criteria for determining when an action is needed or not. Stamatis (2003) recommends a value of 100; therefore, the number 100 was selected as a compromise value for study purposes.

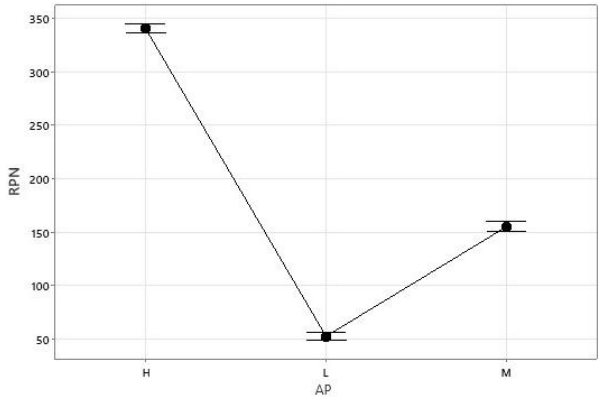

Fig. 10. Interval plot of means using pooled standard deviation with 95% confidence interval

The total number of occurrences was then determined and is shown in Table 1. There were 5,141 RPNs equal to or greater than 100 and 4,859 RPNs less than 100. There were 3,199 ratings with an AP of high, 2,055 with an AP of medium, and 4,746 with a low AP.

Table 1
Occurrences equal to or greater than 100 and less than 100

	High AP	Medium AP	Low AP
RPN $\geq$ 100	2 950 (92.2%)	1 566 (75.4%)	625 (13.2%)
RPN $\leq$ 100	249 (7.8%)	510 (24.8%)	4 100 (86.4%)

The number of required actions was then determined by looking at only high APs, high AP and medium APs, and RPNs equal to or greater than 100 as shown in Table 2. Both high AP and high and medium APs were assessed as high APs must have an action and medium APs may have an action and an organization may implement actions for both.

Table 2
Number of required actions

	Only High AP	High and Medium AP	RPN $\geq$ 100
Actions needed	3 199	5 275	5 141

Only using actions based on a high AP would result in fewer required actions than looking at RPN and a two sample hypothesis test of proportions was performed to determine if the difference is statistically significant (Lawson and Erjavec, 2001). The results shown in Figure 11 have a p-value less than 0.05; therefore, there is a statistically significant difference between the proportions.

Test and CI for Two Proportions Method

p_1: proportion where Sample 1 = Event
p_2: proportion where Sample 2 = Event
Difference: $p_1 - p_2$

Descriptive Statistics

Sample	N	Event	Sample p
Sample 1	10000	3199	0.319900
Sample 2	10000	5141	0.514100

Estimation for Difference

Difference	95% CI for Difference
–0.1942	(–0.207599; –0.180801)

CI based on normal approximation

Test

Null hypothesis	H_0: $p_1 - p_2 = 0$
Alternative hypothesis	H_1: $p_1 - p_2 \neq 0$

Method	Z-Value	P-Value
Normal approximation	–28.41	0.000
Fisher's exact		0.000

Fig. 11. Test of two proportions for high AP versus RPN equal to or greater than 100

There were more actions required for the combination of high and medium APs than RPNs equal to or greater than 100 and a second hypothesis test of two proportions was performed to determine if the there was a statistically significant difference. The results in Figure 12 have p-values greater than 0.05; therefore, there is no evidence of a statistically significant difference.

Test and CI for Two Proportions Method

p_1: proportion where Sample 1 = Event
p_2: proportion where Sample 2 = Event
Difference: $p_1 - p_2$

Descriptive Statistics

Sample	N	Event	Sample p
Sample 1	10000	5254	0.525400
Sample 2	10000	5141	0.514100

Estimation for Difference

Difference	95% CI for Difference
0.0113	(–0.002547; 0.025147)

CI based on normal approximation

Test

Null hypothesis	H_0: $p_1 - p_2 = 0$
Alternative hypothesis	H_1: $p_1 - p_2 \neq 0$

Method	Z-Value	P-Value
Normal approximation	1.60	0.110
Fisher's exact		0.113

Fig. 12. Test of two proportions for high and medium AP versus RPN equal to or greater than 100

Discussion and conclusions

The use of an RPN value in FMEAs is common in industry, yet an RPN gives equal weighting to severity, occurrence, and detection ratings; however, severity should be considered first (Ningcong et al., 2011) and this has been addressed by the use of AP (AIAG/VDA, 2019) and this study showed that fewer improvement actions need to be implemented if an organization only prioritizes APs of high when compared to an RPN equal to or greater than 100. There is statistically no difference in the number of actions if an organization uses both high and medium APs to prioritize actions.

There was much overlap in RPNs between high, medium and low APs and this can be seen in the individual value plot shown in Figure 13. Although there is much overlap, prioritizing based on AP and not RPN would result in taking actions for cases where there was a higher severity combined with a higher occurrence. The low AP still had RPNs that were high, but the severity would be low in such cases and either the occurrence or detection rating must also be low to have a low AP.

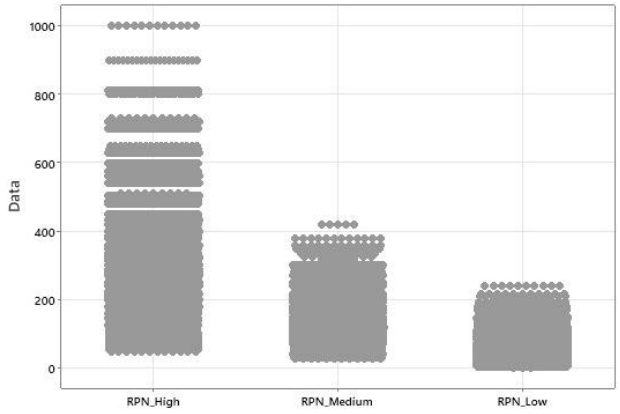

Fig. 13. Individual value plot of RPN by AP ratings

Although there was much overlap the RPN for an AP of medium cannot exceed 420 and an RPN for a low AP cannot exceed 210. However, there is not a one-to-one comparison between AN AP and an RPN. An RPN of 100 could be an AP of high with a severity of 10, occurrence of 5, and detection of 2, or an AP of medium with a severity of 2. Occurrence of 10, and detection of 5, or an AP of L with a severity of 5, occurrence of 2, and a detection of 10. Although the RPNs are the same, order in which the risks should be prioritized differ, with AP putting an emphasis on bad consequences that happen often due to the emphasis on severity and then occurrence.

Using only RPN, an organization would have to implement many actions for what would be a low AP due to lower severity and occurrence ratings that can drive up an RPN. Using AP in place of RPN can reduce the number of actions required while ensuring that the actions that are identified, are identified where the highest priority is based on a severe consequence combined with a higher chance of the failure cause happening. Therefore, although implementing actions for both high and medium APs would not result in fewer actions than prioritizing based on RPN, the actions would still be ones that addressed the failures with the most severe consequences.

The study used simulated severity, occurrence, and detection ratings and an RPN threshold value of 100. However, the threshold was to only to have criteria by which to perform the study and actual FMEAs should never use a threshold value (Netherton, 2010).

The distribution of severity occurrence and detection ratings will vary within organizations, with more high APs when the organization has more severe failure consequences resulting in higher severity ratings combined with high occurrence ratings and more low AP ratings if most failure effects are not noticeable combined with strong prevention actions.

Harpster describes an FMEAs as "a powerful tool when properly used" (Harpster, p. 24, 1999). Using an AP in place of RPN and only taking action for high APs can reduce efforts while simultaneously concentrating on the items that have the most impact on severity and occurrence and will provide the most impact if improved, making the powerful tool even more powerful.

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