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Modifying risk priority number in failure modes and effects analysis

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ABSTRACT

Failure modes and effects analysis *(FMEA)* greatly facilitates the efforts of industrial manufacturers in prioritizing failures that require corrective actions to continuously improve product quality. However, the conventional approach fails to provide satisfactory results in some practical applications. Therefore, this paper presents a modified scheme of risk priority number *(RPN)* used in *FMEA* by considering quality cost as an additional determinant to signify the priority level for each failure mode. Effectiveness of the modified *RPN* scheme is evaluated on a manufacturing chain of aluminium cans used for beer and soft drinks. Analysis results indicate that the modified scheme outperforms *RPN* in reducing the percentage of defective products, i.e. from 14% before the test to 4% by the modified number compared with 6% by the traditional one.

1. Introduction

Failure modes and effects analysis (FMEA) has been considered as an effective analysis tool widely used in several developed countries such as Japan, USA, and Europe (Chen, 2007; Hung et al., 1999) in different industries, such as automobile, electronics, households, energy plants, telecommunications (Onodera, 1997), pharmacy (Bonnabry et al., 2005), health care services (Benjamin, 2003; Montesi and Lechi, 2009), e-commerce (Linton, 2003), product design (Davidson and Lib, 2003; Hsiao, 2002), etc., because it provides both qualitative and quantitative measures to identify failures and their effects towards the quality of products/service (Chen, 2007). Particularly, *FMEA* evaluates failure modes and their possible causes in a scale of 10 for three different aspects, including: Severity rating (*S*), Occurrence rating (*O*), and Detection rating (*D*) based on the guidelines in Table 1.

From the above ratings, a so-called Risk Priority Number (*RPN*) for a certain cause is determined by Eq. 1. A cause with higher *RPN* should be priorly treated; i.e. corrective actions to either eliminate or reduce failures should start with the highest-prioritized causes. As such, *FMEA* is an effective tool in prioritizing failures that require corrective actions to improve product quality (Sawhney et al., 2010; Daily, 2004).

$$RPN = S \times O \times D \quad (1)$$

However, conventional *FMEA* fails to provide sufficient discrimination power in some circumstances because it appoints the same weight for all of the ratings (Sawhney et al., 2010; Zambrano et al., 2007; Cox et al., 2007; Cox, 2008); meaning that they have similar impacts on the *RPN*. As a matter of fact, *S* and *O* are two major affecting factors that should be more prioritized (O'Connor, 2011). For examples, let's consider a failure mode with three different causes A, B, and C whose ratings are respectively given as (S_A=8, O_A=5, D_A=4), (S_B=10, O_B=4, D_B=4), and (S_C=5, O_C=4, D_C=8); and their *RPNs* thus are all equal to 160. In this case, if only *RPN* is taken into consideration regardless of the ratings of severity, occurrence, and detection, none of the causes should be prioritized, leading to dispersion and inefficient utilization of limited resources, or even some causes that have profoundly negative impacts may fail to attract special attention (Sawhney et al., 2010). Hence, if each of the rating components is investigated, a better decision can be made. Specifically, though A occurs more frequently than B, B should be more priorly investigated than A because B is more severe than A. In the same token, though B and C have the same occurrence rating of 4 and the detection of C is really low (8/10), B still needs more prioritized in practice because C is less severe than B. From these analyses, we conclude that corrective actions should be priorly made for B. And obviously, the traditional *RPN* fails to provide such a decision in the investigated circumstance due to its low discrimination power.

To overcome the above shortcoming in lean manufacturing systems, Sawhney et al. (2010)

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proposed an alternative index called Risk Assessment Value (RAV) determined by Eq. 2.

Table 1: Rating scale guidelines

Rating value	Severity	Occurrence	Detection
1	insignificant	extremely unlikely	absolutely certain to detect
	↓	↓	↓
10	catastrophic	inevitable	no control exists

They believed that efficient detection and control of failure play important role in minimizing failure occurrence and failure severity (Karthik et al., 2015). Benchmarking the performance between RPN and RAV, Kirthik et al. (2015) pointed that RAV provides better priority orders. However, with our above-mentioned example, the RAV of A, B, and C are respectively obtained as $RAV_A = 10$, $RAV_B=10$, and $RAV_C=2.5$; hence, between A and B, which one should be prioritized is still unknown. This indicates that though RAV performs better than RPN, it still fails to provide sufficient supremacy in making final decision in such cases.

$$RAV = O \times S \times / D \quad (2)$$

Meanwhile, Gilchrist (1993) and Kmenta and Ishii (2004) suggested using a so-called "Expected cost" to present S whereas using probability to measure the O and D. Nonetheless, in practice, the expected cost should be considered in line with technical issues: production techniques that cause the failure and failure detection techniques. Moreover, different industries have different failures which are classified as repairable and irreparable, i.e. their costs are varied. More importantly, once failures are not fully detected and eliminated before getting to consumers, accompanied warranty cost, compensation cost for problems occurred in using the faulty products/services would arise; and even the invisible cost for business fame/brand would seriously affect the performance of the whole organization. These costs, hereinafter, are referred in a more general term as "Quality cost". Consequently, to remedy the above drawbacks, this paper proposes integrating the quality cost as an additional factor into the conventional RPN formula to enhance its discrimination power in analyzing failure modes and their effects. Our proposed formula is called "Modified Risk Priority Number" ($MRPN$).

The rest of this paper is organized as the following. Section 2 presents primary definitions commonly used in $FMEA$ while $MRPN$ is constructed in Section 3. Section 4 discusses a case study at a company producing aluminum cans for beer and soft drink industry to demonstrate the practical applicability of our proposed $MRPN$.

2. Primary definitions

2.1. Failure modes

Failures are any errors or defects, especially ones that affect the potential or actual customers. "Failure modes" means the ways that failures arise. Key inputs and production process play critical role in the quality of product/service. Thus, fully identify possible failures at each stage of the process is always expected so that manufacturers/ service providers can implement suitable actions to either eliminate or reduce their negative impacts, minimize production cost, and satisfy customer demands.

2.2. Effects

Effects of a failure refer to the consequences caused by the failure to the quality of a product/service. They can be evaluated with the satisfaction level or perception of customers who are either external customers or internal customers who are the users in the next stages of the process.

2.3. Cause

Cause is the source of variations and failures. Hence, to improve the quality of product/service, it is the best that possible causes should be fully identified so that we can have proper solutions to effectively deal with them. One of the commonly used tools is the Cause-Effect Diagram, also called Fishbone Diagram.

2.4. Control system

It is actually a system of facilities and control methods to prevent or detect failures in all phases of production process before faulty products/services are delivered to customers. Such systems can obviously abate profitless costs and time as well as other inextricable issues that may occur in the future. Therefore, an effective quality control system is always a permanent desire of every manufacturer/service provider. Depending on particular industry and their level of applying science – technology, the control systems can be either done manually or operated automatically with modern equipment.

3. Proposed modified risk priority number

This section presents the development of our proposed modified risk priority number ($MRPN$). Assume that there are n identified failure modes existing in a production process. For j^{th} mode ($j=1, 2, ..., n$), the following denotations are used.

•P_O^j: occurrence probability of the j^{th} mode (given by experts);

•P_D^j: detection probability of the j^{th} mode (given by experts);

•S_T^j: severity level of the j^{th} mode from technical perspective (in service industry, S_T^j is actually the timing of the process); evaluated in a traditional scale of 10;

•S_I^j: severity level from economic perspective in internally dealing with the j^{th} mode; thus, it closely relates to a so-called "internal failure costs";

•S_E^j: severity level from economic perspective in externally dealing with the j^{th} mode; i.e. the level of external costs occurred after non-detected faulty product/service is delivered to external customers; thus, it closely relates to a so-called "external failure costs".

Then, a new index $MRPN_j$ of the j^{th} failure mode is determined by:

$$MRPN_j = P_O^j \times S_T^j \times \left[\frac{max\{P_D^1, P_D^2, \ldots, P_D^n\}}{P_D^j} \times S_I^j + (1 - P_D^j) \times S_E^j\right] \quad (3)$$

Eq. 3 with the quantity of $(1 - P_D^j)$ obviously considers the effects of a failure when it is not detected by the control system. Besides, *MRPN* and the conventional *RPN* have some similar characteristics; for example, the lower detection probability in *MRPN* (i.e. P_D^jsmaller) is respectively to the higher of *D* in *RPN*, which is shown in $\frac{max\{P_D^1, P_D^2, \ldots, P_D^n\}}{P_D^j}$ in Eq. 3. Moreover, $(1 - P_D^j)$ lso reflects the impacts of external failure costs on the amplitude of *MRPN*; specifically, if the probability of detecting failures is low, the chance of a faulty product/service delivered to customers is certainly high, resulting in higher *MRPN*; meaning that the j^{th} failure mode would be more prioritized. The values of S_T, S_I, and S_E are evaluated as the following.

3.1. Evaluation of severity of failures from technical perspective ST

The severity level of technical failures *(S_T)* is determined based on key requirements about technology, aesthetics, fundamental characteristics and specified standards. Basically, the failures may be resulted from input materials, production process, control methods, labor, facilities, and even from the impacts of working environment. Hence, for each failure (potential or detected), we need to carefully identify its major causes so that we can evaluate the remedy possibility in terms of technology, process, facilities, control methods and labor forces, etc. It is also critical to evaluate its negative impacts on the next stages in the production process, product quality and customer perception. Thus, the severity S_T in *MRPN* is actually the severity level *S* in the traditional *RPN*. Table 2 illustrates an example of the evaluation of the technical severity S_T used for compact fluorescent tube manufactured in Company P mentioned in Section 4.

Table 2: Evaluation of severity level ST from technical perspective

Severity	Impact level	Evaluation criteria
10	Extremely serious, unpredictable	Technical failures can't be detected from production process; e.g. cracked circle, cracked tipping, cracked stress-bending, etc.
9	Extremely serious, predictable	Technical failures only detected after checking finished products; e.g. cracked head, kaput bulb, lessened luminosity, etc.
8	Serious	Technical failures only detected after completing production; e.g. wrong dimensions, deficient loading pressure/electric current/voltage/color transfusion/ initial light band, etc.
7	High	Technical failures need long time to be remedied; e.g. mock-marked weld, cracked weld-point, blackened/ stained electrodes, etc.
6	Quite high	Failures affecting next stages; e.g. mouth-contorted weld, semi-product dimensions, high tipping, etc.
5	Significant	Failures affecting finished product beauty; e.g. flaked fluorescent, arch rib, bubbled coating, etc.
4	Quite significant	Failures due to equipment can be immediately remedied; e.g. greasy tube, chipped bend, scratched neck, redundant/deficient mercury, etc.
3	Low	Failures due to operational failures.
2	Very low	Normal failures only affect the cost of materials; e.g. dirty wash/bend, fluorescent slip, bubbled bend, etc.
1	Extremely low	Almost no impact on product quality.

3.2. Evaluation of severity of failures from economic perspective SI and SE

As mentioned above, quality cost closely related to quality assurance of semi-products and finished products in all stages of production process from inputs to outputs and using period by customers. The quality cost can be divided into four groups: (1) Prevention costs; (2) Appraisal costs; (3) Internal failure costs; and (4) External failure costs (Montgomery, 2013). Among them, the first two groups are controllable while the last two ones directly relate to production process which accounts for a significant part of the total cost of an organization. So, this paper investigates the last two groups as a key component in our proposed *MRPN*.

3.3. Internal failure cost (IFC)

IFC are actually the costs occurred due to the quality incompliance of any component, part, material, product, and/or related service provided that defective products are detected before being delivered to customer. IFC takes a value of 0 if no defective product is found prior to delivery. Particularly, it consists of the following components: scrap; rework; retest; failure analysis; downtime; and yield losses, etc.

3.4. External failure cost (EFC)

EFC includes all costs occurred due to the failures detected after products are delivered to customers. It takes a value of 0 when all products meet specified requirements. EFC consists of the following components: field servicing and handling complaints; recalls, returns, replacements; warranty; other indirect costs because defective products/services lead to the dissatisfaction of customers and their negative impression about the products/services and the manufacturers/providers; consequently, damage customer good-will, lose sales due to bad reputation, etc.

Therefore, for every failure mode, we need to carefully and fully identify associated IFC and EFC so that we can have proper solutions for quality improvement. IFC and EFC can be respectively converted into S_I and S_E with the following procedure. Assume that we have n failure modes in the production process of a product. Let IFC_j and $EFC_j (j = \overline{1,n})$ respectively denote the internal and external failure costs of the j^{th} mode. S_I^j and S_E^j are then determined by:

$$S_I^j = \frac{IFC_j}{FC_{min}}; \quad S_E^j = \frac{EFC_j}{FC_{min}}; \qquad (4)$$

where $FC_{min} = min\{IFC_1, \dots, IFC_n, EFC_1, \dots, EFC_n\}$

The determination of S_I^j and S_E^j shown in Eq. 4 obviously not only overcomes the shortcomings of the RPN in conventional $FMEA$ approach and the RAV proposed by Sawhney et al. (2010) but also considers the severity level of two prominent quality costs namely IFC and EFC of the same failure mode; i.e. for a failure whose S_E is higher than S_I, we can conclude that the inspection for defects should be especially concerned in the final stage of quality control to minimize defective products delivered to customers because its external cost is higher than that if internally detected; or, if S_I is higher than S_E, we need to carefully investigate and eliminate the causes for the failures in each stage of the production process.

4. Practical application

In order to evaluate the applicability of the proposed $MRPN$, we conduct a practical study at Company P specializing in producing aluminum cans used in beer and soft drink industry, located in Dong Nai province, Vietnam. Basically, the company usually has a critical problem in delivery schedule because their defective cans account for about 14% of total manufactured products. Such high percentage of defective cans certainly reduces the annual performance of the company. To deal with this problem and minimize the number of defective products, we set up an $FMEA$ team consisting of 15 members who are administrators, top engineers, leaders of related departments, and group leaders. The team focuses on analyzing production process and identifying major failure modes in each production stage as shown in Table 3.

Table 3: Evaluation of severity level ST from technical perspective

Production stage/phase	Failure modes
Oil coating	Superfluous oil, insufficient oil
Cup banging	Irregular thickness, scratched/ rumpled body, rumpled bottom
Cup refining	Holed/ rumpled/ torn cup
Edge cutting	Irregular cut, swarf agglutination, uneven/ unusual height
Cup washing and desiccating	Oily cup, spotted body and bottom
Vanish coating	Uneven coat, overlapped coat, inside-cup vanish
Printing	Incorrect tone, unexpected printing stroke, blurred colour
Lacquer coating and IBO desiccating	Uneven coat
Can-neck bending	Rumpled can-neck, deformed/rough edge

With the $FMEA$ approach, the team determines the occurrence rate of each mode (P_O), detection rate (P_D), the severity levels of failures from technical and economic perspectives (S_T, S_I, S_E). Consequently, the $MRPN$ for each failure mode can be easily obtained. Finally, the team agrees to take corrective actions against four modes that have the highest RPN and $MRPN$ as shown in Table 4.

Table 4 clearly shows that the risk priority orders for the four failure modes are significantly different. Specifically, the traditional RPN results in a descending order as: (1) Holed/torn cup at the cup refining stage; (2) Rumpled cup at the cup banging stage; (3) Spotted cup at the cup washing and desiccating stage; and (4) Rumpled can-neck, deformed/rough edge at the cup-neck bending stage. Meanwhile, the proposed $MRPN$ results in a descending order as: (1) Holed/torn cup at the cup refining stage; (2) Rumpled can-neck, deformed/rough edge at the cup-neck bending stage; (3) Rumpled cup at the cup banging stage; (4) Spotted cup at the cup washing and desiccating stage. Thus, both *RPN* and *MRPN* indexes signify "holed/torn cup at the refining stage" as the most serious failure to be first considered. However, the other three modes are differently ordered; so, actual corrective actions between the two indexes can be accordingly different and may lead to different results. Different actions for the four modes are suggested as demonstrated in Table 5.

Table 4: Four major failure modes with the highest RPN and MRPN

Stage	Cup banging	Cup refining	Cup washing and desiccating	Can-neck bending
Failure mode	Rumpled	Holed, torn	Spotted	Rumpled, deformed/ rough
Causes	Improper pressure of banging piston; loose mold	Incorrect operation parameters, distracting workers	Substandard washing liquid, carelessly cleansing of rust	Swarf agglutinated shackle
Current control	After the stage; manual check	After the stage; manual check	After the stage; manual check	After the stage; manual check
O	9	10	6	5
D	4	4	7	5
S	8	8	5	7
RPN	288	320	210	175
P_O	0.08	0.12	0.07	0.06
S_T	8	8	5	7
P_D	0.95	0.96	0.85	0.92
S_I	12	15	16	18
S_E	21	26	20	22
MRPN	8.43	15.40	7.37	8.63

Table 5: Some specific corrective actions

Stage	Mode	Corrective actions	Group
Cup banging	Rumpled cup	Guide workers to carefully adjust operational parameters about the pressure of banging piston and check the tightness of molds before each production shift. Besides, they need to make sure that molds and shackles are precisely positioned and their attrition is in control.	1
Cup refining	Holed/ torn cup	Guide workers to carefully adjust operational parameters. Temporarily assign supervisors to monitor the workers' concentration level in operating the facilities; in long run, monitoring cameras should be set up.	2
Cup washing and desiccating	Spotted cup	Clearly set up the checking standards for washing liquid, washing tanks and hygienic state of aluminum cups before desiccating; provide workers with proper checking equipment and regularly replace washing liquid.	3
Can-neck bending	Rumpled can-neck, deformed/ rough edge	Ask sanitation workers to carefully wash shackles before and after each production shift. In each shift, workers need to regularly check the agglutination of swarf on the shackles. Especially, the shackles must be correctly positioned.	4

To evaluate the performance of our proposed *MRPN* in comparison with the traditional *RPN*, our *FMEA* team chose two production lines with the same production conditions (facilities and worker's ability); and each line focused on three most prioritized solutions, meaning that the first line implemented the solution groups 1, 2, and 3 while the second worked with solution groups 1, 2, and 4. With the proposed solutions, the two investigated lines concurrently produced trial lots in two consecutive working weeks. We then checked all of the produced cans of each line separately; and found that the defective products in the first and the second lines are respectively 6% and 4% of the total manufactured cans. These figures indicate that the priority order obtained from our proposed *MRPN* outperforms that from the conventional *RPN*.

5. Conclusion

FMEA approach has been widely applied in analyzing failure modes and their effects towards product/service quality as it can help manufacturers/ service providers to identify failures/ defects of their products/services, their severity levels as well as their negative impacts on related stakeholders and their business performance. However, the traditional approach with the *RPN* consisting of three components, namely occurrence rating, detection rating and severity level, reveals certain disadvantages in prioritizing failures to be solved. Thus, this paper proposes an advanced index by modifying the conventional *RPN* with associated quality cost and the capability of failure detection system because the capability intimately relates to the possibility of defective products/services delivered to customers, i.e. such capability can either establish or damage the quality reputation of an organization. The performance of our modified index *MRPN* was tested in an empirical case at a company specializing in producing aluminum cans used in beer and soft drink industry. We found that the percentage of defective cans has been significantly reduced from about 14% before the trial period to 4% with the *MRPN* or 6% with the traditional *RPN* after the trial. Hence, *MRPN* outperforms *RPN* in identifying priority order to deal with detected failures. However, we suggest further investigation of the *MRPN* in different business sectors, industries and benchmark with other existing indexes before we can firmly ascertain its remarkable performance.

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