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Risk management in automotive manufacturing process based on FMEA and grey relational analysis: A case study

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ABSTRACT

Risk management is an important issue in manufacturing companies in today's competitive market. Failure modes and effects analysis (FMEA) method is a risk management tool to stabilize production and enhance market competitiveness by using risk priority numbers (RPN). Although the traditional FMEA approach is an effectively and commonly used method, it has some shortcomings such as assumption of equal importance of the factors, severity, occurrence and detectability, and not following the ordered weighted rule. Thus, in order to improve RPN, an integrated method combining grey relational analysis (GRA) with FMEA is used in this study. The purpose of this paper is to contribute to risk management activities by proposing solutions to assembly line problems in an automotive manufacturing company by using combined GRA and FMEA method. In the proposed method, the priorities of production failures were determined by GRA approach and these failures were minimized by using FMEA technique. The study results indicated the actions that lead to enhancement in the product. The implementation of corrective/preventive activities resulted in 96 % improvement in door seal cuts problem caused by the door step assembly. Door seal cuts problem caused by instrument panel assembly and the noisy door window problem are solved completely.

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1. Introduction

Before a new product is introduced to a market, the manufacturing companies probably face many problems in the stages of design, plan, production and delivery. It is very critical to detect and solve these problems, before the product reaches a customer. Some failures are easy to detect while some of them remain hidden. The whole process should be evaluated carefully and the appropriate quality control techniques should be used in order to find out these hidden failures. One of the most effective methods to determine the failures in any process is Failure Mode and Effects Analysis (FMEA).

FMEA can be expressed as a specific methodology in order to evaluate a process, system, service or design for possible ways in which failure can occur [1]. Risks, problems, concerns or errors are different type of failures. Failure mode can be described as a product failing to perform its desired function, described by the expectations of the customers. Failure emerges from the deviation from standards in the conditions of machine, method, material and workforce, affecting the quality of a product or a process. The FMEA analysis follows a well-defined sequence of steps that includes (1) failure mode, (2) failure effects, (3) causes, (4) detectability, (5) corrective or preventive actions and (6) rationale for acceptance [2]. Today, with the increasing competition in the market, any deficiency and deviation in product performance result in market share loss. Although the traditional FMEA employing risk priority numbers (RPN) is an efficient and effective tool to stabilize production and enhance market competitiveness, it has been criticized for the following shortcomings: its (1) high duplication rate, (2) not following the ordered weighted rule, (3) assumption of equal importance of severity (S), occurrence (O), and detectability (D) and (4) failure to consider the direct and indirect relationships between the modes and the causes of failure [3].

In this study, an integrated method combining FMEA and Grey Relational Analysis (GRA) is used in order to overcome the shortcomings of traditional FMEA method. GRA is used to determine the priorities of production failures in an automotive manufacturing company. The two failures, door seal cut and noisy window problems, have been minimized by using FMEA methodology.

2. Literature review

FMEA methodology is widely used to manage risk in industries such as manufacturing, automotive, and aerospace. Vinodh and Santhosh [4] reported an application of design FMEA to an automotive leaf spring manufacturing organization in India. Implementation of fuzzy developed FMEA method to aircraft landing system, which is one of the important potential failure mode in aerospace industry, has shown the strength of the method in managing risk [5]. Chang [6] combined generalized multi-attribute FMEA and multi-attribute FMEA to improve LCD manufacturing process in a company in Taiwan. Segismundo and Miguel [7] proposed a methodological approach to effective risk management in new product development in a Brazilian automaker company by using FMEA technique. Banduka *et al.* [8] integrated lean approach with process FMEA in automotive industry. Liu *et al.* introduced a risk priority model by combining hesitant 2-tuple linguistic term sets and an extended QUALIFLEX method and FMEA methodology for handling a health care risk analysis problem [9, 10]. Barkovic *et al.* used FMEA method in improvement of newspaper production system quality [11].

GRA has been used by managers to make decisions under uncertainty in many different areas since 1982. Feng and Wang [12] measured the financial performance of airway companies with the help of GRA. Hsu and Wen [13] proposed a design to deal with the traffic and flight frequency in airways using GRA. In the study of Lin and Lin, one of the techniques used for optimization of wire erosion system was grey relation analysis method [14]. Wang *et al.* [15] proposed a hybrid methodology using grey relational analysis and experimental design to solve several multi-criteria decision making problems such as, a flexible manufacturing system, a rapid prototyping process and an automated inspection system. Palanikumar et.al. [16] optimized the results of polymer material process with grey relation analysis method. Rajeswari and Amirthagadeswaran [17] used grey relational approach to improve machinability properties of end milling process. Wang [18] developed a model for measuring the performance of logistic companies via grey relational analysis method. Ramesh *et al.* [19] proposed an effective model to investigate turning of magnesium alloy by using grey relational analysis method.

A combination of FMEA and GRA techniques are used by authors in order to eliminate the shortcomings of FMEA. Pillay and Wang [2] used an integrated method combining FMEA and grey theory to investigate the system failures in fuzzy environment for an ocean-going fishing vessel in their study. Baghery *et al.* [20] implemented process FMEA method combining with DEA (data envelopment analysis) and GRA in an automotive company producing auto parts for Samand, Peugeot 405 and Peugeot 206.

3. Materials and methods

In this study a combined methodology of failure modes and effect analysis and grey relational analysis is used. The priorities of production failures were determined by GRA approach and failures were minimized by using FMEA technique.

3.1 FMEA method

FMEA was first developed as an assessment tool to improve the evaluation of the reliability of military systems and weapons in the US army in the late 1940s. This method was also used for Apollo space missions in the 1960s by the National Aeronautics and Space Administration (NASA) [3]. In the late 1970s FMEA was used by Ford Motor Company in automotive production processes [6]. Because these applications resulted in satisfactory improvements in the Ford Company, the method has been widely used in automotive industry as a risk assessment tool. Today FMEA is applied successfully to industries such as aircraft, automotive, medicine, semiconductors and food industry. In the FMEA approach, for each of the failures identified (whether known or potential), an estimate is made of its occurrence (O), severity (S) and detection (D) [1]. Occurrence is the probability of occurrence of the failure and its cause. Detection is an evaluation process to find potential failures in the product. Severity is an expression of importance and emergency of potential system default mode. FMEA technique evaluates the risk of failure by using RPNs. The RPN value is found by taking the product of S, O, and D on a scale from 1 to 10. Higher RPN value indicates a higher priority.

3.2 Grey relational analysis

Grey relational analysis is a multi-criteria decision making method used by decision makers to take the right decision under circumstances with limited and uncertain data [21]. GRA approach explores system behavior using relational analysis and model constructions [2]. The grey system provides solutions to problems where the information is incomplete, limited or characterized by random uncertainty. The grey theory has become a popular technique providing multidisciplinary approaches in recent twenty years. The grey relational analysis was first developed by Julong Deng in 1982 [22]. The model includes three types of information points: white, grey or black. The main goal is to transfer black points in the system to the grey points. Grey relation analysis consists of six basic steps. These steps are explained below [19, 23, 24]:

Step 1: Construct a norm matrix X. It is assumed that there are n data sequences including m criteria:

$$X = \begin{bmatrix} x_1(1) & x_1(2) & \dots & x_1(m) \\ x_2(1) & x_2(2) & \dots & x_2(m) \\ \dots & \dots & \dots & \dots \\ x_n(1) & x_n(2) & \dots & x_n(m) \end{bmatrix} \quad (1)$$

where $x_i(j)$ is the entity in the i-th data sequence corresponding to the j-th criterion.

Step 2: Since multi-criteria decision making (MCDM) problems may contain a variation of different criteria, the solution needs normalization. Normalization process based on properties of three types of criteria, larger the better, smaller the better, and nominal the best:

$$x'_i(j) = \frac{x_i(j) - min_{j=1}^{n}[x_i(j)]}{max_{i=1}^{n}[x_i(j)] - min_{j=1}^{n}[x_i(j)]}; \text{ larger the better} \quad (2)$$

$$x'_i(j) = \frac{max_{i=1}^{n}[x_i(j)] - x_i(j)}{max_{i=1}^{n}[x_i(j)] - min_{j=1}^{n}[x_i(j)]}; \text{ smaller the better} \quad (3)$$

$$x'_i(j) = 1 - \frac{|x_i(j) - x_{obj}(j)|}{max\,\{max_{i=1}^{n}[x_i(j)] - x_{obj}(j),\, x_{obj}(j) - min_{j=1}^{n}[x_i(j)]\}}; \text{ nominal the best} \quad (4)$$

$x_{obj}(j)$ is the target value for the criterion j, and $min_{i=1}^{n}[x_i(j)] \le x_{obj}(j) \le max_{i=1}^{n}[x_i(j)]$.

Step 3: Normalize the data set and generate a reference sequence based on Eq. 2 to Eq. 4. Normalized matrix is expressed as X':

$$X' = \begin{bmatrix} x_1'(1) & x_1'(2) & \dots & x_1'(m) \\ x_2'(1) & x_2'(2) & \dots & x_2'(m) \\ \dots & \dots & \dots & \dots \\ x_n'(1) & x_n'(2) & \dots & x_n'(m) \end{bmatrix} \tag{5}$$

Step 4: Calculate absolute value table. The difference between a normalized entity and its reference value is calculated. The difference is shown as $\Delta_{0i}(j)$.

$$\Delta_{0i}(j) = |x_0'(j) - x_i'(j)| \tag{6}$$

$$\Delta = \begin{bmatrix} \Delta_{01}(1) & \Delta_{01}(2) & \dots & \Delta_{01}(m) \\ \Delta_{02}(1) & \Delta_{02}(2) & \dots & \Delta_{02}(m) \\ \dots & \dots & \dots & \dots \\ \Delta_{0n}(1) & \Delta_{0n}(2) & \dots & \Delta_{0n}(m) \end{bmatrix} \tag{7}$$

Step 5: Compute grey relational coefficient $\gamma_{0i}(j)$, applying following grey relational equation:

$$\gamma_{0i}(j) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(j) + \zeta\Delta_{max}} \tag{8}$$

where $\Delta_{max} = max_{i=1}^{n} max_{j=1}^{m} \Delta_{0i}(j)$, $\Delta_{min} = min_{i=1}^{n} min_{j=1}^{m} \Delta_{0i}(j)$, and $\Delta_{0i}(j)$ and $\zeta \in [0,1]$. ζ is the distinguishing index and in most cases it takes the value of 0.5 offering moderate distinguishing effect.

Step 6: Compute the grey relational degree. Grey relational degree which indicates the magnitude of correlation or similarity. The overall grey relational degree (Γ_{0i}) is calculated by taking average value of grey relational coefficients by using the following equation:

$$\Gamma_{0i}(j) = \sum_{j=1}^{m} \gamma_{0i}(j) w(j) \tag{9}$$

where $w(j)$ refers to the weight of the j-th criterion. The sum of the weights of all criteria must equal to 1.

3.3 Integration of grey theory and FMEA method

The traditional FMEA method cannot assign the possibility of occurrence of failure, its detectability and severity comply with the real world. The integration of grey theory to FMEA allows engineers and decision makers to assign relative weights depending on research and production strategies. In decision making problems, the factor series with the highest grey relation degree gives the best alternative. The greater the relation degree means the smaller effect of failure source in FMEA application. For this reason, the increasing relative degree shows the decrease in risk priority of potential sources which have to be improved.

4. Case study

The case study was held in a car manufacturing company in the Turkish automotive industry. The aim of the study was to solve the assembly line problems. The company mainly faced two types of problems. The first one was the car door seal problem and the second one was the noisy car window problem.

4.1 Formulation of problems and causes

The car door seal problem can be explained as a tear or cut in the seal of the car doors. The door seal serves as a barrier protecting the inner car against dust and water from the outside. If the seal is damaged and if this damage cannot be detected through quality control processes, it may cause severe customer complaints. The noisy car window problem is the annoying noise and shaking problem when the window glass moves up and down.

The factory has used Pareto analysis to find out the failures in manufacturing and their occurrence probability. The numbers about the occurrence probability, the causes of failures and the failure detection points are given in Table 1. The line point in the table represents the problems detected through the control points of the assembly line itself. Final point is the point of a detailed control of the car just before it leaves the assembly line. Pre-quality point is a control point for repaired cars before quality control. After quality control of the products, five of them are very carefully controlled in detail at a quality control point. The company's expert team has determined two important production problems and the most probable causes by using FMAE technique. The resulting causes are listed below:

Causes for car door seal cut or tear problem are summarized below:

Step:	Tear or cut in the car door seal during the door step assembly
IP:	Tear or cut in the car door seal during instrument panel assembly
Door lock:	Tear or cut in the car door seal during door lock assembly
Seat:	Tear or cut in the car door seal during car seat assembly
Operator:	Damaging of the car door seal by operator during placement of the seal

Causes for noisy window problem are as follows:

Rivet position:	The effect of the position of the rivet of window mechanism
Fixing equipment:	The incompatibility between window mechanism and fixing equipment
Hole position:	The effect of the position of the rivet hole

Table 1 Problems and causes

Failure	Cause	Detection Point					
		Line	Final	Pre-quality	Quality	Detailed quality	Customer
Cut/tear in door seal	Step	0	4	0	5	0	2
	IP	0	5	0	2	0	0
	Door lock	0	2	0	2	0	0
	Seat	0	0	0	2	0	0
	Operator	0	0	0	2	0	0
		Line	Final	Pre-quality	Quality	Detailed quality	Customer
Noisy window	Rivet position	0	88	0	9	0	0
	Fixing equipment	0	108	0	20	0	0
	Hole position	0	190	0	20	0	0

4.2 Probability of occurrence, detectability, severity

Occurrence (O):

Occurrence is the probability of failure occurrence and its cause. The precautions for detecting the failures are not taken into consideration in this step. Only the methods determined for preventing failure are considered. If the process is under statistical process control, the evolution depends on the statistical data. Otherwise, intangible data from judgments are used for evolution. In the factory, the occurrence and the detection points of failures are expressed by Pareto analysis and then transferred to a "1-10" scale. In the table, the O column describes the occurrence of probability between the values 1 and 10.

Table 2 Calculation of O values based on Pareto analysis

Failure	Cause	Detection Point						
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	O
Cut/tear in door seal	Step	0	54	0	55	0	12	10
	IP	0	25	0	32	0	0	7
	Door lock	0	12	0	0	0	0	3
	Seat	0	0	0	12	0	0	3
	Operator	0	0	0	12	0	0	3
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	O
Noisy window	Rivet position	0	88	0	9	0	0	7
	Fixing equipment	0	190	0	20	0	0	10
	Hole position	0	109	0	20	0	0	9

Detectability (D):

Detection is an evaluation process to find the potential failures in a product, before it leaves the assembly line. The failure should be accepted as it has occurred and the criteria for failure detection should be detected before the product has been introduced to a consumer. In the factory, according to results from Pareto analysis, the failures are scored for their detection points to calculate D values. The scale used in the calculation of D value is below:

Line point:	1-2
Final point:	3-4
Pre-quality:	5-6
Quality:	7-8
Detailed quality:	9
Customer:	10

Since all the failures are detected more than once in different points, D values are calculated by the weighed matrix (Table 3) and based on QLS Pareto analysis (Table 4).

Table 3 Weighted D values

Failure	Cause	Detection Point						
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	D
Cut/tear in door seal	Step	0	54X4	0	55X8	0	12X10	776
	IP	0	25X4	0	32X8	0	0	356
	Door lock	0	12X4	0	0	0	0	48
	Seat	0	0	0	12X8	0	0	96
	Operator	0	0	0	12X8	0	0	96
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	D
Noisy window	Rivet position	0	88X4	0	9X8	0	0	424
	Fixing equipment	0	190X4	0	20X8	0	0	920
	Hole position	0	109X4	0	20X8	0	0	596

Table 4 Calculation of D values based on QLS Pareto analysis

Failure	Cause	Detection Point						
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	D
Cut/tear in door seal	Step	0	54X4	0	55X8	0	12X10	6
	IP	0	25X4	0	32X8	0	0	6
	Door lock	0	12X4	0	0	0	0	4
	Seat	0	0	0	12X8	0	0	8
	Operator	0	0	0	12X8	0	0	86
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	D
Noisy window	Rivet position	0	88X4	0	9X8	0	0	4
	Fixing equipment	0	190X4	0	20X8	0	0	4
	Hole position	0	109X4	0	20X8	0	0	5

Severity (S):

Severity is an expression of importance and urgency of a potential system default mode. The only evaluation criterion for severity is the effect of a failure. The severity degrees are defined according to the degree of the effects on product, system, customer and legal obligations. The failure scale matrix of the factory's quality system is used directly in this study (Table 5). The severity values are calculated with the help of this table. Table 6 gives the S values determined by the company's experts using quality leadership system (QLS) Pareto analysis.

Table 5 Failure increase matrix for severity calculations

Failure Severity (Quality Standards)	Pick Level	Increase Level				
		Line team leader	Team leader	Area manager	Quality assurance manager	Factory manager
Blitz (10-9) Failure effects auto/driver control, customer safety and legal conditions.	Cause or Quality					
	1	X	X	X		
	3				X	X
	Sampling					
	1	X	X	X	X	
	3					X
A (8-7) Failure is very annoying and customer files a complaint to vendor/service.	Cause or Quality					
	1	X	X	X		
	3				X	
	Sampling					
	1	X	X	X	X	
	3					X
B (6-5) Failure is annoying, causing customer unsatisfaction and complaints of guarantee.	Cause or Quality					
	5	X	X			
	8			X		
	10				X	X
	Sampling					
	2	X	X	X		
	4				X	X
C (4-3) Failure is detected by educated/critical customers and it needs long time improvements.	Cause or Quality					
	10	X	X			
	15			X		
	Sampling					
	4	X	X	X		
	6				X	

Table 6 Severity calculation based on QLS Pareto values

Failure	Cause	Detection Point						
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	S
Cut/tear in door seal	Step	0	54	0	55	0	12	7
	IP	0	25	0	32	0	0	7
	Door lock	0	12	0	0	0	0	7
	Seat	0	0	0	12	0	0	7
	Operator	0	0	0	12	0	0	7
		Line	Final	Pre-quality	Quality	Detailed quality	Customer	S
Noisy window	Rivet position	0	88	0	9	0	0	6
	Fixing equipment	0	190	0	20	0	0	6
	Hole position	0	109	0	20	0	0	6

4.3 Calculation of risk priority number (RPN)

RPN is calculated by multiplication of O, D and S values. RPN shows the relative importance of failure causes. The resulting rank of RPN values help the decision makers to decide which cause should be improved first. The highest the RPN value means the first rate. The ranking according to RPN is shown in Table 7.

Table 7 Risk priority numbers

Failure	Cause	O	D	S	RPN	Rank
Cut/tear in door seal	Step	10	6	7	420	1
	IP	7	6	7	294	2
	Door lock	3	4	7	84	6
	Seat	3	8	7	168	5
	Operator	3	8	7	168	5
Noisy window	Rivet position	7	4	6	168	5
	Fixing equipment	10	4	6	240	4
	Hole position	9	5	6	270	3

4.4 Calculation of grey relational coefficient

The RPN in Table 7 are transferred to grey RPN values and reordered by using grey relational analysis. Then the difference matrix is constructed by using Eq. 8:

$$\begin{bmatrix} x_1(1) & x_1(2) & x_1(3) \\ x_2(1) & x_2(2) & x_2(3) \\ x_3(1) & x_3(2) & x_3(3) \\ x_4(1) & x_4(2) & x_4(3) \\ x_5(1) & x_5(2) & x_5(3) \\ x_6(1) & x_6(2) & x_6(3) \\ x_7(1) & x_7(2) & x_7(3) \\ x_8(1) & x_8(2) & x_8(3) \end{bmatrix} = \begin{bmatrix} 10 & 6 & 7 \\ 7 & 6 & 7 \\ 3 & 4 & 7 \\ 3 & 8 & 7 \\ 3 & 8 & 7 \\ 7 & 4 & 6 \\ 10 & 4 & 6 \\ 9 & 5 & 6 \end{bmatrix}$$

$$\begin{bmatrix} \Delta_1(1) & \Delta_1(2) & \Delta_1(3) \\ \Delta_2(1) & \Delta_2(2) & \Delta_2(3) \\ \Delta_3(1) & \Delta_3(2) & \Delta_3(3) \\ \Delta_4(1) & \Delta_4(2) & \Delta_4(3) \\ \Delta_5(1) & \Delta_5(2) & \Delta_5(3) \\ \Delta_6(1) & \Delta_6(2) & \Delta_6(3) \\ \Delta_7(1) & \Delta_7(2) & \Delta_7(3) \\ \Delta_8(1) & \Delta_8(2) & \Delta_8(3) \end{bmatrix} = \begin{bmatrix} 9 & 5 & 6 \\ 6 & 5 & 6 \\ 2 & 3 & 6 \\ 2 & 7 & 6 \\ 2 & 7 & 6 \\ 6 & 3 & 5 \\ 9 & 3 & 5 \\ 8 & 4 & 5 \end{bmatrix}$$

According to difference matrix, $\Delta_{\min} = 2$, $\Delta_{\max} = 9$ and ζ is assumed as 0.5 value. After calculation of difference matrix, grey relational coefficients are calculated by using Eq. 8.

$$\gamma_{0i}(j) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(j) + \zeta\Delta_{max}} = \frac{2 + 0.5 \cdot 9}{9 + 0.5 \cdot 9} = 0.481$$

The following matrix is constructed by using grey relational coefficients:

$$\begin{bmatrix} \gamma_1(1) & \gamma_1(2) & \gamma_1(3) \\ \gamma_2(1) & \gamma_2(2) & \gamma_2(3) \\ \gamma_3(1) & \gamma_3(2) & \gamma_3(3) \\ \gamma_4(1) & \gamma_4(2) & \gamma_4(3) \\ \gamma_5(1) & \gamma_5(2) & \gamma_5(3) \\ \gamma_6(1) & \gamma_6(2) & \gamma_6(3) \\ \gamma_7(1) & \gamma_7(2) & \gamma_7(3) \\ \gamma_8(1) & \gamma_8(2) & \gamma_8(3) \end{bmatrix} = \begin{bmatrix} 0.481 & 0.684 & 0.619 \\ 0.619 & 0.684 & 0.619 \\ 1.000 & 0.867 & 0.619 \\ 1.000 & 0.565 & 0.619 \\ 1.000 & 0.565 & 0.619 \\ 0.714 & 1.000 & 0.789 \\ 0.556 & 1.000 & 0.789 \\ 0.600 & 0.882 & 0.789 \end{bmatrix}$$

The last step is to calculate the Grey RPN to determine the priorities. Table 8 shows the weights of cost based priorities.

Table 8 Cost based weights

	W_O	W_D	W_S
Cost	2.6 €	1.3 €	2.6 €
Weight	0.4	0.2	0.4

Grey relational degrees are found by the formula in Eq. 8. The grey relational degree of the first failure level is calculated as 0.577 by using Eq. 9.

$$\Gamma_{0i}(j) = \sum_{j=1}^{m} \gamma_{0i}(j) w(j) = 0.481 \cdot 0.4 + 0.684 \cdot 0.2 + 0.619 \cdot 0.4 = 0.577$$

The weighted grey RPN values are found as follows:

$$\text{Weighted Grey RPN} = \begin{bmatrix} 0.577 \\ 0.632 \\ 0.821 \\ 0.761 \\ 0.761 \\ 0.823 \\ 0.759 \\ 0.742 \end{bmatrix}$$

The RPN and Grey RPN values are listed comparatively in Table 9. As shown in the table, the weight of rivet position differs from one method to the other. According to the ranking in Table 9, the most important problem is the door seal cuts caused by step assembly. The second important problem is the seal cuts caused by instrument panel assembly. The third one is the noise problem of the window caused by the position of the hole. The least important problem is defined as noisy window problem caused by rivet hole position. The priority of decision makers is to initiate improvement on these most urgent problems.

Table 9 The comparison of FMEA RPN and grey RPN

Failure	Cause	O	D	S	FMEA RPN	Rank	Grey RPN	Rank
Cut/tear in door seal	Step	10	6	7	420	1	0.577	1
	IP	7	6	7	294	2	0.632	2
	Door lock	3	4	7	84	6	0.821	6
	Seat	3	8	7	168	5	0.761	5
	Operator	3	8	7	168	5	0.761	5
Noisy window	Rivet position	7	4	6	168	5	0.823	7
	Fixing equipment	10	4	6	240	4	0.759	4
	Hole position	9	5	6	270	3	0.742	3

4.5 Results and discussion

The solutions are developed according to the resulting grey RPN ranks. After improvements better results in the quality metrics are obtained.

- The solution for door seal cuts problem causing from door step assembly:

  Since a door seal prevents water and dust leakages, a tear or cut in the door seal causes customer complaints. There are five basic causes for the door seal problems. Based on Table 9, the most important reason for this problem is tear or cut in door seal during step assembly process. When the door step assembly process was inspected in detail, it was determined that the sharp corners of the step caused cuts in the seal during assembly of the step by an operator. As a part of corrective or preventive activities, all the areas of seal to where the step corners hit were detected. Magnetic protectors were made. The operators have begun to use these protectors in relevant areas during assembly. One month later, quality records indicated an important decrease in seal cuts by the rate of 96 %.

- The solution for door seal cuts problem causing from instrument panel assembly:

  Cut or tear in door seal during assembly of instrument panel gets the second rank in priority. The sharp-edged frame of the instrument panels was identified as the cause for this problem. The corrective and preventive activities were developed as effective solutions to the problem. As a result of corrective or preventive activities, the potential tangible areas of seal were determined. Magnetic protectors were designed to protect the surfaces which are likely to be damaged. The operators have begun to use these protectors in relevant areas during assembly. One month later, quality records indicated that cuts and tears in door seal caused by instrument panel assembly were prevented by the ratio of 100 %.

- The solution for noisy window glass problem causing from hole position:

  Noisy window glass is a problem which causes a disturbing noise and jolt in the vehicle, while the window is moving up and down. According to Pareto analysis, the most important reason with the third lowest degree in priority level is the rivet hole position. Riveting process in window installation were inspected in detail and it was detected that the distance between mechanism and the rivet hole was too small (2 mm). This short distance caused the mechanism parts to hit the rivet which resulted in a disturbing noise and jolt in windows. As a result of corrective/preventive activities, the position of rivet hole was moved to a 3 mm lower position. Therefore the distance became 5 mm which was sufficient for preventing the hitting of window mechanism parts. The preventive activities have resulted in 100 % improvement in the noise problem in one month.

The quality reports indicated that 2 operators have spent 48 working hours in a month to deal with quality problems before improvements. After implementation of grey FMEA technique, this time was reduced to 2 hours which means saving cost by 2300 Euro in a month and 27600 Euro in a year.

5. Conclusion

FMEA is widely used as an efficient decision-making tool to control the stability of the manufacturing process and to improve product and system performance by decreasing failure rate. Although the traditional FMEA, employing risk priority numbers, stabilize production and increase the market competitiveness, it has some limitations such as failing to evaluate the relative relationship of each weight of those parameters. In this study the limitations of FMEA are overcome by using an integrated method of grey theory and FMEA. First, the possible causes of failure and their detection points are determined by FMEA. Second, the priorities of the factors (causes) are determined by using grey RPN values. According to the results of case application in an automotive manufacturing factory, a 96 % improvement was achieved for a door seal cuts problem caused by the door step assembly. A further door seal cuts problem caused by the instrument panel assembly was solved completely. As a third improvement, the noisy door window problem, caused by riveting hole position, is prevented by 100 %.

The main advantage of the integrated GRA and FMEA method in this study is the flexibility of assigning weight to each factor in FMEA, providing an effective and consistent methodology to identify weak parts in the component studied. This integrated approach is convenient to deal with risk assessment problems under circumstances where the information is incomplete or uncertain. The processing of linguistic information based on expert knowledge and experience enables a realistic, practical and flexible way to express judgments.

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