Strojniški vestnik - Journal of Mechanical Engineering 56(2010)3, StartPage-EndPage
UDC xxx.yyy.z
Paper received: 17.11.2008
Paper accepted: 08.03.2010

The Possibility for FMEA Method Improvement and its Implementation into Bus Life Cycle

Vladimir Popović[1,*] - Branko Vasić [1] - Miloš Petrović [2]
[1] University of Belgrade, Faculty of Mechanical Engineering, Republic of Serbia
[2] Institute for Research and Design in Commerce & Industry, Republic of Serbia

This paper shows the way FMEA method (Failure Modes and Effects Analysis), which is widely used in motor vehicles industry, can be improved and later used during certain stages of vehicle life cycle. This is illustrated by the example of bus superstructure development. A number of possibilities have been given for the advanced method application during the selection and performance of vehicle maintenance process. A great deal of attention has been paid to risk analysis and the implementation of this parameter into the FMEA method, at the same time insisting on the inconsistencies of the traditional method. The result of our efforts is a new and in our opinion, improved approach to vehicle failure analysis, which gives a new dimension to the entire process. It is evident that this problem is vital from the aspect of high cost of vehicle warranty as well.

Keywords: FMEA method, bus superstructure, risk analysis, new approach

0 INTRODUCTION

The fastest, cheapest and easiest way to build something is doing it properly the first time [1]. This engineer's credo has made it into popular literature, but it seems to be largely ignored in the world of failure analysis. There are many reasons why a product might fail. Knowing the potential causes of failures, as far as it is practicable, is fundamental to preventing them. A real analysis or prediction of possible failure modes of any system, represents a necessary basis of every project the purpose of which is to increase reliability, which especially applies to development of new systems. Nowadays, we mostly apply complex systems which perform a variety of different functions and which are comprised of a large number of subsystems. Competition, the pressure of schedules and deadlines, the cost of failures, the rapid evolution of new materials, methods and complex systems, the need to reduce the product costs, and safety considerations, all increase the risks of product development. Fig. 1 shows the pressures that lead to the overall perception of risk [2]. Reliability engineering, together with its methods, has developed in response to the need to control these risks.

In this paper we have tried to diminish the risk of failure together with the risk of making wrong decisions related to bus exploitation and maintenance, by modification of one of the key failure analysis methods (FMEA). The aim of the paper was to create a somewhat different approach to FMEA method, which is to provide a more efficient engineering, research and scientific approach to technical system failure analysis, as well as develop a new interdisciplinary approach which will put a different light on: determining all the parameters necessary for the process of system failure analysis, failure risk analysis, the connection of this method to technical system maintenance and information system, the complexity of system analysis, qualitative and quantitative approach to the method, etc.

1 FMEA METHOD AND ITS SHORTCOMINGS

One of the best tools for sorting out the above-mentioned problems, is FMEA method. FMEA is especially efficient if applied in the analysis of elements which cause the whole system failure. However, it can be very complicated in the case of complex systems (such as vehicles), which have multiple functions and are comprised of a number of components, since a variety of information on the system has to be considered [3]. This problem can be increased together with the number of work modes, and when maintenance problems are considered as well. The analysis of these effects requires a thorough understanding of characteristics and work capabilities of different system components.

*Corr. Author's Address: Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Republic of Serbia, vpopovic@mas.bg.ac.rs

FMEA is intended to act in a preventive sense - it is not a method which is carried out after a failure, with the purpose of satisfying the customer or the requirements of ISO/TS 16949 standard (QS 9000) or ISO 9001 series of standards. A thorough FMEA demands time and provision of necessary resources during the design and process development, when design and process changes can be implemented with least difficulty and financial means. Only after a product failure or financial crisis, which are the results of late production changes, we can see the price of not performing FMEA.

Risk priority number (*RPN*) is mainly the result of FMEA analysis. This number is the mathematical product of severity value (*S*), occurrence value (*O*) and detection value (*D*):

$$RPN = S * O * D. \qquad (1)$$

It is used to help in identifying the principal risks, and to show us the way for corrective activities. If we take a look at the Eq. (1), we will find that the *RPN* method for risk estimation is much too simple. The three above-mentioned values don't have equal significance one in relation the other when it comes to the risk. This distortion is the consequence of non-linear nature of individual scales of values. As a result, some variants of *S-O-D* product give *RPN* which is smaller than other combinations, but with more risk. The high value of severity requires a great deal of attention, especially when it is coupled with a high value of failure occurrence. The term criticality has been developed to focus the attention on these combinations.

Although most manufacturers use FMEA method as the strategy for risk prevention, the result of the majority of FMEA analyses is negligible or non-existing quality improvement [4] to [7]. Companies race to apply FMEA method with the purpose of complying to the requirements of quality system assessors or to alleviate the concern of the user. As the result of this, they often fail to notice the potential for improving a business system functioning which FMEA offers. The principal purpose of these analyses, namely the protection of users by reducing the possibility of all failure occurrence [8] and [9]:

- FMEA is applied more as an initiative for quality and compliance control, than as an initiative for quality improvement. → Product or system quality does not improve with each application of FMEA.
- There is no value criterion for FMEA. → The organization sees no connection between the quality strategy of the corporation and performing FMEA.
- The financial support of the leading company managers to FMEA analysis is changeable or weak. → The authority of FMEA team, the objectives and the sources are limited.
- A system aspect that includes the people, the process, technology, organization and performance is lacking in FMEA structure. → There is not enough effort in the development and empowering of FMEA process.
- The thinking principle "find and fix" dominates the principle "find out and prevent". → FMEA is applied only after its biggest potential for quality improvement is reduced.
- The engineers believe that management sees the documentation on unresolved projects and process shortcomings as their (engineering) personal weakness. → There is less willingness among engineers to detect early potential failure modes in the process of product development.

Although many companies take FMEA method as a technique of softening, that is reducing the risk, there have been many negative comments on its account. These shortcomings limit the impact of this method and, by no means, represent a stimulus for its application. Perhaps the most seriously documented criticisms of this method are the following [7] and [10]:

- FMEA process is tiring and time-consuming;
- There are few overlaps, actually even a gap, between design and process FMEA;
- The failures are incompletely represented by FMEA method;
- *RPN* is not a consistent measure of risk;
- s, disappears in all that complexity. A few limitations affect the success of FMEA method application in many companies [FMEA is performed much too late to have an effect on the project decisions;
- FMEA does not identify the current failures, that occur in real time.

2 SUBJECT OF ANALYSIS

As we have pointed out, in practice we need a considerable amount of energy, time and money to perform FMEA analysis of a complex system such as a motor vehicle [11]. As a result of this, a great deal of effort is made in finding the modified, rapid ways of this method implementation, bearing in mind not losing the point and the concept of the analysis [5], [7], [10], [12] and [13]. One of the ways of this method's more efficient application is FMEA process modification, by determining the impact and the frequency of each failure occurrence [7] and [13]. The impact of each failure can be quantified by different measuring units (we have used monetary units).

Table 1. *Number of failures of bus grid construction*

Failure mode	Number of failures
Front bracket	21
Front axle zone	3
Drive axle zone	2
Engine support zone	2
Support arm girder	16
Pneumatic support girder	7
Unallocated	17

In this paper we have analyzed a part of the vehicle fleet belonging to Public Transport Company "Belgrade", with a special emphasis on bus superstructure. The subject of our analysis have been 59 vehicles of the same manufacturer ("Ikarbus" - Belgrade). All the observed buses are between 8 and 9 years old. In the previous period, the general body overhauling was performed on 16 vehicles (or 27.12%). The vehicles were being observed for 6 months and during that time there were 102 body failures reported, 68 of which had to do with the grid construction itself. These 68 failures have been distributed in the manner presented in Table 1.

2.1 *RPN* and the Expected Cost (*EC*)

In Table 2 [13], we can see a parallel summary of *EC* (obtained by multiplication of failure occurrence probability (*OP*) and that failure cost) and *RPN* for six different failure modes which are given in Table 1. The values of failure occurrence and severity have been adopted in accordance with [6]. In calculating *RPN* in Table 2, we have started from the assumption that the value of failure detection is 1, that is, assumption that we are bound to detect the referent failures. This has been done lest this value should divert our attention from the central problem - the values of *S* and *O*.

This high *EC* is the result of vehicle fleet obsolesce, as well as the bad maintenance policy and the policy of these vehicles' use, which will also be further discussed in final considerations. With the purpose of overcoming this situation, we considered several solutions, which might lead to successful dealing with this bad situation. First of all, we tried decreasing the number of buses which would have to undergo overhauling. We developed several solutions for bus design which resulted in its prolonged life cycle. The changes we introduced were that of design profile and the material out of which it is made. We performed several laboratory tests, together with the calculation of mathematical models, using a number of program packages [14].

The next strategy we considered was the possibility of maintenance cost decrease, with other parameters unchanged. There is room for this possibility due to the fact that all kinds of overhauling performed on these buses, are carried out by the manufacturer himself, which makes quite a solid ground for this kind of strategy.

Table 2. *Total expected cost and RPN for different failure modes*

Failure mode	*OP* [per vehicle]	*EC* [per vehicle, in $]	**Total *EC* [$]**	*O*	*S*	***RPN***
Front bracket (A)	0.3088	1000	**308.8**	8	6	**48**
Front axle zone (B)	0.0441	2000	**88.2**	6	8	**48**
Drive axle zone (C)	0.0294	2000	**58.8**	6	8	**48**
Engine support zone (D)	0.0294	1500	**44.1**	6	6	**36**
Support arm girder (E)	0.2712	250	**67.8**	8	4	**32**
Pneumatic support girder (F)	0.1186	200	**23.72**	7	4	**28**

The third possibility for *EC* decrease that we considered on this occasion, is the increase of preventive maintenance range relative to the corrective maintenance of bus support structure. The ground for this kind of a solution is in the fact that, in such a large vehicle fleet, there was a very small amount of preventive maintenance. There are many methods which might help in making decisions about preventive maintenance of the body, of which we used ultrasound testing [14], which might decrease the amount of corrective maintenance by 85%.

Results obtained by the application of several strategies cannot be simply compared, since there is an additional cost per vehicle in case of application of any of these strategies for the expected cost decrease. Bearing in mind the situation in our industry and transport organizations, each of the proposed strategies would contribute to the decrease of total *EC* during the vehicle entire life cycle. Given that the last two strategies require small additional expenses, their application is much simpler in the present circumstances; however, changes in bus design give better results in the long run. Beside that, in further research we have to take into account the fact that all the buses together, due to the state of failure, were out of operation for up to 1185 days (or 11.04%).

3 COST AND LIFE CYCLE

Today's customers require products that are reliable, that perform their functions safely and that can be easily maintained during their useful period. Their decision to purchase is not only influenced by the product's initial cost (acquisition cost), but also by the product's expected operating and maintenance cost during their life cycle (ownership cost) [15] to [17]. In order to achieve customer satisfaction, the challenge for suppliers is to design products that are reliable and cost competitive by optimizing acquisition and ownership costs.

Life cycle costing is the process of economic analysis to assess the total cost of acquisition and ownership of a product. This analysis provides important inputs in the decision making process in the product design, development and use. Life cycle cost (*LCC*) analysis is most effectively applied in the product's early design phase to optimize the basic design approach. However, it should also be used during the subsequent phases of the life cycle to optimize other engineering decisions and facilitate efficient allocation of resources, which we have done in this paper.

Dependability of a product is a collective term which is used to describe the product's availability performance and its influencing factors, such as reliability performance, maintainability performance and maintenance support performance. Performance in all these areas can have a significant impact on the *LCC*. Costs associated with product safety, reliability, maintainability and maintenance support performance, which are not that apparent, but need to be accounted for in life cycle cost models, may include the following, as appropriate [15]:

- unavailability cost (including costs associated with loss of product function);
- warranty costs and costs for warranty-type agreements;
- liability costs.

Unavailability of product is influenced by its reliability, maintainability and maintenance support resources. The product may be unavailable because of a hardware or software failure or a human error, or because of preventive maintenance (which requires the product to be taken out of service). There are labor, materials and other support costs associated with these activities. The costs of unavailability may include [15]:

- cost of corrective maintenance;
- cost of preventive maintenance;
- the cost associated with the loss of product's function during the period of its unavailability.

The latter cost, sometimes also referred to as consequential costs, can be quite significant in the case of products performing critical functions where the penalties for loss of the product's function are very high. The penalties consist of either loss of income to the user through failure of the product to deliver its output, or additional costs arising from the user having to take actions to compensate for the loss of the product's output. Unavailability cost could also include costs related to the loss of image and prestige of the company or the loss of clients, caused by some specific failures. In most cases, these costs are difficult to assess.

4 NEW APPROACH

After a detailed analysis of the results shown in Table 2, as well as the corresponding comments and strategies given in Chapter 2.1, we have come to the conclusion that, despite the application of the expected cost, he haven't perceived all the significant parameters when it comes to failure cost (i.e. consequences), which are necessary for us to make universal decisions, with the purpose of making future steps. Bearing in mind the considerations given in Chapter 3, we have formed a new model of failure cost analysis, which, in a more precise way, takes into account certain factors that we didn't previously discuss. This new approach is a combination of the standard failure analysis method (FMEA), cost-benefit analysis, risk analysis, life-cycle cost and multi-criteria analysis. Furthermore, it is a tool for expressing the will of shareholders in the decision-making process. The results of the performed analyses are given in Table 3, in which case the following equations were used for calculating specific values [10], [13] and [18]:

*Labour cost (LC) = Occurrence probability * * Labour rate * No. of operators * * Unavailability time (UT)*, (2)

*Material cost (MC) = Occurrence probability * * Parts cost (PC)*, (3)

*Unavailability cost (UC) = Unavailability time * * Unavailability cost per hour*, (4)

Unavailability time = Detection time (DetT) + + Fixing time (FT) + Delay time (DelT). (5)

Unavailability cost is the one that accumulates when a failure inhibits the system main function, and prevents creation of value. Bearing in mind the situation in our market, while calculating the results in Table 3, we have used values of 50$ per hour (for direct cost) and 100$ per hour (direct cost + vehicle amortization). In order to simplify the analysis in Eq. (2), we have adopted that the labor rate and the number of operators are equal for all activities defined in Eq. (5). The labor cost is 20$ per hour, and the number of operators is two. In Table 3, we have given unavailability cost only for the unavailability cost value per hour, which is 50$. In Fig. 2, we have shown the interrelation of the three output costs, depending on the failure mode (taking into account the value of unavailability cost of 50$ per hour), while in Fig. 3 you can see the interrelation of these costs expressed proportionally. In Fig. 4, we have presented in parallel the *RPN*, the expected cost and the results obtained by the new approach, depending on the failure mode.

5 FINAL CONSIDERATIONS

We can say that the principal aim of any company is making profit for its owners. Therefore it is evident that the financial aspect should mainly be considered in line with engineering tools or *RPN*. FMEA method is focused on the delivery of quality products (services) to its users. The financial impact of various possible problems in the processes is not

Table 3. *LC, MC and UC for different failure modes*

Failure mode	Origin of failure	Effect of failure	*OP* [per vehicle]	*Det T* [h]	*FT* [h]	*DelT* [h]	*UT* [h]	*PC* [$]	***LC* [$]**	***MC* [$]**	***UC* [$]**
Front bracket (A)	Oper.	Bus is out of function	0.2941	3	72	4	79	500	**929.36**	**147.05**	**3950**
	Manuf.		0.0147						**46.45**	**7.35**	
Front axle zone (B)	Oper.		0.0441	4	96	4	104	700	**183.46**	**30.87**	**5200**
Drive axle zone (C)	Oper.		0.0294	4	96	4	104	800	**122.30**	**23.52**	**5200**
Engine support zone (D)	Oper.		0.0294	4	48	4	56	600	**65.86**	**17.64**	**2800**
Support arm girder (E)	Oper.		0.2059	2	16	1	19	200	**156.48**	**41.18**	**950**
	Assem.		0.0147						**11.17**	**2.94**	
	Manuf.		0.0147						**11.17**	**2.94**	
Pneumatic support girder (F)	Oper.		0.0882	1	8	1	10	100	**35.28**	**8.82**	**500**
	Assem.		0.0147						**5.88**	**1.47**	

directly considered, and therefore, it was necessary to create a method which would identify and give priorities to those failures that have the biggest (financial) impact on the operation. In this way, alternatives may be evaluated on the basis of maximum financial gain, and the voice of the company owner (shareholder) gets to be heard in decision making. Some of the results of the modified FMEA method are:

- more satisfaction for the user;
- improvement of development efficiency (time and cost);
- documenting, ranking by importance and communicating potential risks in an explicit way to team members, suppliers, management, clients;
- comprehensibility – the possibility for a systematic assessment of the ratio between the cause and the consequences of specific failures, as well as pointing to failure modes that have especially undesirable effects on system functioning.

In this paper we have analyzed different strategies for the decrease of failure risk of bus bodies, using FMEA method. Our job was "simplified" due to the maturity and the condition of the observed vehicle fleet, and the fact that almost no preventive measures had been applied previously. First of all, we wanted to cast light on a certain inconsistency of *RPN* values, especially relative to the expected cost (Table 2). It is evident that *RPN* values and the expected cost give different priorities to identical failure modes, which must be taken into account in decision making. A separate problem while using *RPN* values lies in the fact that failure detection value does not accurately measure the contribution to the risk. For more precise and valid results, we can consider failure detection value a conditional probability, or maybe completely neglect it. Furthermore, we wanted to point to the completely different priority level in decision making connected to the use and maintenance of our vehicle fleet, once we took into account results from Table 3. This is especially evident in Fig. 4, where, depending on the criteria we observe, completely different bus failure modes are prioritized. Our proposition is to adopt the new approach as the most adequate solution, which has actually been the result of our project in the first place. It is evident that, at decision making, one should bear in mind all the other failure modes that occur on buses, which don't exclusively refer to bus superstructure. In the next phase, this new approach should be applied to all the other bus systems. After performing the analysis of the complete vehicle, the method can be applied to the other segments of the business system of Public Transport Company "Belgrade" (maintenance, acquisition, ...), since, just as FMEA, this new method does not have to be applied only to the product. Furthermore, its application to service activities might bring equally positive results. A successful performance of the new methodology in such a complex system as Public Transport Company, might open the possibility for its implementation in a much broader environment, which does not have to be connected with the same field of economy.

The possibilities for FMEA advancement that we have presented in this paper, are for the time being referred to as the New Approach, leaving the following question unanswered: Is the appropriate term for this method Failure Modes, Effects and Risk Analysis (FMERA), Failure Modes, Effects and Cost-Benefit Analysis (FMECBA) or there is a third solution?

6 ACKNOWLEDGEMENTS

This paper is a part of an extensive project of the development of public transport in Belgrade. The project is supported by European Bank for Reconstruction and Development (EBRD) and European Investment Bank (EIB), as well as by the Assembly of the City of Belgrade. Authors wish to express their gratitude to the investors of this project, and a number of colleagues who helped in gathering data for the purposes of this paper.

7 REFERENCES

[1] Klein, G. (2009) Operating System Verification - An Overview. *Sādhanā*, vol. 34, part 1, p. 27-69.

[2] O'Connor, P. (2002) *Practical Reliability Engineering*, 4th ed. John Wiley & Sons Ltd.

[3] Rausand, M. (2004) *System reliability theory - models, statistical methods and applications*, 2nd ed. John Wiley & Sons Inc.

[4] Popović, V., Vasić, B., Blagojević, I., Curović, D. (2009) Implementation of

modified fmea method into the process of logistic support to bus life cycle. *Proceedings of 15th ISSAT International Conference on Reliability and Quality in Design*, San Francisco.

[5] Bevilacqua, M., Braglia, M. (2000) The analytic hierarchy process applied to maintenance strategy selection. *Reliability Engineering and System Safety*, vol. 70, p. 71-83.

[6] Gilchrist, W. (1993) Modeling failure modes and effects analysis. *International Journal of Quality and Reliability Management*, vol. 10, no. 5, p. 16-23.

[7] Kmenta, S. (2000) *Advanced failure modes and effects analysis: a method for predicting and evaluating failures in products and processes.* PhD Dissertation, Stanford University.

[8] Bongiorno, J. (2000) Improving FMEAs: FMEAs can transform compliance into competitive advantage. *Quality Digest*, vol. 20, no. 10, p. 37-40.

[9] Popović, V., Vasić, B., Curović, D. (2008) Failure Modes, Effects and Risks Analysis – FMERA. *Journal of Institute for Research and Design in Commerce & Industry* vol. 20, p. 33-42. (in Serbian)

[10] Rhee, S., Ishii, K. (2003) Using cost based FMEA to enhance reliability and serviceability. *Advanced Engineering Informatics*, vol. 17, p. 179-188.

[11] Popović, V., Vasić, B., Curović, D. (2008) Cost-benefit analysis of the tram rolling stock. *Proceedings of International Applied Reliability Symposium*, Singapore.

[12] Lee, B.H. (1999) Design FMEA for mechatronic systems using bayesian network causal models. *Proceeding of ASME Design Engineering Technical Conference*, Las Vegas.

[13] Popović, V., Vasić, B., Stanojević, N. (2006) Contribution to development of new failure analysis methods. *Proceedings of 18th EuroMaintenance Congress / 3rd World Congress of Maintenance*, Basel.

[14] Mitić, S., Rakićević, B., Popović, V. (2003) Calculation optimization of bus strength, applied at the safety rings of a bus superstructure. *Proceedings of Conference "Computer-Simulation in Automotive Engineering"*, Graz.

[15] IEC 60300-3-3 (2004) *Dependability management - Part 3-3: Application guide - Life cycle costing*. Geneva, International Electrotechnical Commision.

[16] Kušar, J., Bradeško, L., Duhovnik, J., Starbek, M. (2008) Project management of product development. *Strojniski vestnik - Journal of Mechanical Engineering*, vol. 54, no. 9, p. 588-606.

[17] Zadnik, Ž., Karakašić, M., Kljajin, M., Duhovnik, J. (2009) Function and functionality in conceptual design process. *Strojniski vestnik - Journal of Mechanical Engineering*, vol. 55, no. 7-8, p. 455-471.

[18] Popović, V., Vujanović, N., Vasić, B. (2006) Contribution to development of new risk analysis methods. *Proceedings of 12th ISSAT International Conference on Reliability and Quality in Design*, Chicago.