Improving Reliability of Designed Technical Products Using FMEA

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Abstract
The article presents the practical application of the FMEA method for identification and an elimination of flaws at the design - manufacture stage, and for assessment of a designed product's reliability. The method presentation is based on the design process of a new mechanical device. The described FMEA was completed in a scattered organisation environment. The results achieved were analysed and discussed.
Keywords: FMEA, process design, reliability

1 Introduction
Any new product being introduced to the market should comply with many requirements concerning its functionality, usefulness, quality, price, etc. Many of the above mentioned features are opposite in terms of obtaining, e.g. quality and price. Purchasers, however, have their own requirements and demands concerning many aspects connected with concept developing, designing, manufacturing of the final product. These are usually precisely specified in the order and the acceptance of the product (device) depends on their fulfilment. Frequently, the following requirements are presented to the manufacturers of mechanical machines and devices in ordinary industry practice: FMEA analysis, threats analysis, reliability evaluation, damage intensity evaluation or MTBF indicator [1,2,4,5].

The Failure Modes and Effects Analysis (FMEA) is an issue known for years [3]. It may seem it is such an efficient and popular method that it should be used by all construction offices to analyse each newly designed product. Unfortunately, it could not be further from the truth. Actually, the engineering designers are cautious about this method, as well as many other modern methods assisting the design process. There seems to be a resistance to take any steps in this field. The engineering designers explain it with their lack of the necessary knowledge, experience, or time, resulting from their busy time schedules. They also claim that the benefits from such analyses are doubtful. The most important factor is the inability to see advantages of the analysis. Hence, it is necessary to make the engineering designers see the benefits, using an example [1,6].

2 A new approach to the FMEA implementation
A company manufacturing machines and devices used in heat treatment was commissioned to produce a large and complex processing line for heat treatment. The company was obligated by the client (through the contract) to ensure high quality and reliability standards. One of the required operations was the implementation of FMEA at the device design stage to evaluate its reliability. Only after the FMEA approval and reliability calculation by the client was it possible to begin production of the device. Performing the FMEA of the designed processing line by the manufacturer proved to be inconvenient due to the need to engage human resources simultaneously working on the project and technology of the device. Moreover, the experience from previous FMEA studies carried out by the company pointed to the need for changes in the organisation and implementation of this particular analysis. Therefore, the manufacturing company decided to change their approach to FMEA. Because of the complexity and importance of the task the management decided to create a proper plan of action. It was decided that the implementation of FMEA tasks should not be delegated to designers participating in the construction process of the object being manufactured. Their lack of practical knowledge in this area would have resulted in the necessity to devote a considerable amount of time to training and proper execution of the task. It would have caused disorder in the overall project schedule, which could result in prolongation of the deadline. Hence, a team of external experts forming an executive group for FMEA studies was created. The team was entrusted with the proper implementation of analyses and coordination of all related activities. Furthermore, a new way of organising the participants (teams) and communication among them was accepted.

2.1 A proposition of work organisation for the FMEA implementation
The pattern and the structure of work organisation are presented in **Figure 1**. In the diagram presented in this figure team 1 is the most important and is responsible for the analysis.

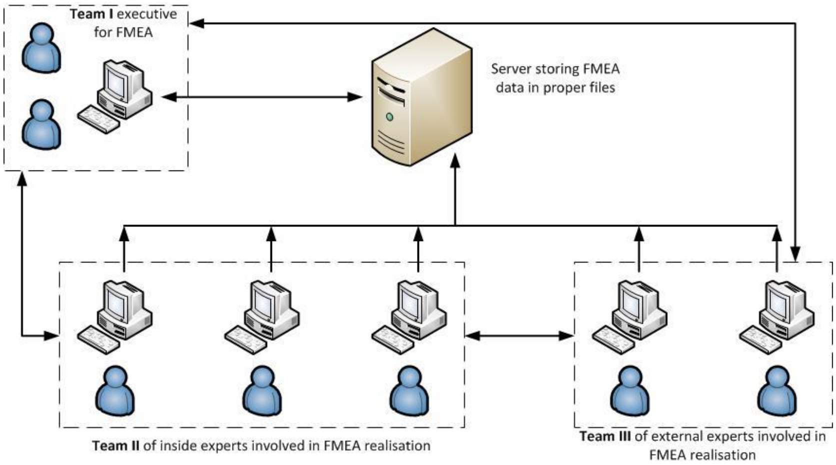

Fig. 1 Structure and organisation of teams implementing FMEA

This team is in control of arranging meetings with the inside experts (team 2), contacts with the external experts (team 3) executing FMEA for completed, ordered, and produced outside components and systems, FMEA studies for systems designed inside the company, as well as coordination of all operations and compiling a comprehensive final report. Team 2 consists of staff representing the executive company directly involved in the project realisation. The team is formed by constructors (mechanics, electricians, and computer scientists), process engineers, service workers, supply department workers, and those working at the technological level who participate in the project. Their main goal is to support team 1 during the evaluation process for particular FMEA indicators pertaining to components and systems. Team 3 consists of the external experts from subcontractor companies whose job is to design device modules. This way, team 3 is the group (or groups) formulating FMEA for systems manufactured outside. Team 1, which synchronises the actions related to FMEA, contacts this group to obtain necessary information.

2.2 FMEA stages

FMEA was divided into five main stages, which are presented in **Figure 2**. This figure also shows the three teams engaged in the implementation of particular stages (indicator "x").

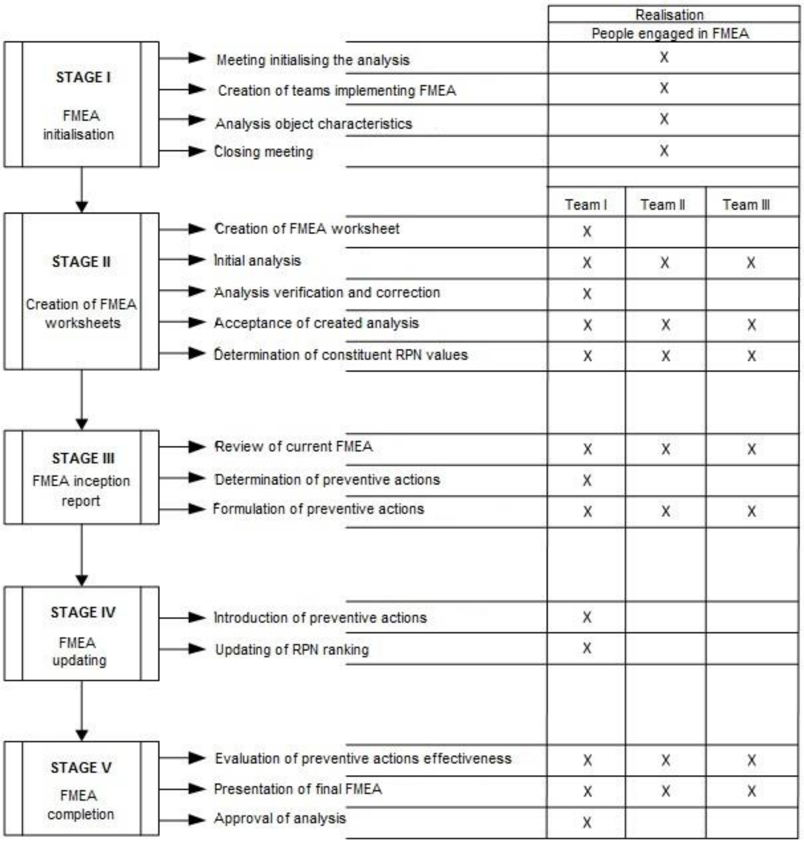

Fig. 2 FMEA stages and teams engaged in their implementation

The specified FMEA stages are:

- Stage 1 – FMEA initialisation
- Stage 2 – Creation of FMEA worksheets
- Stage 3 – FMEA inception report
- Stage 4 – FMEA updating through the preventive actions
- Stage 5 – Meeting closing FMEA

It was accepted that the first stage of the analysis (FMEA initialisation) would include steps related to the meeting which initialises the analysis, creation of the teams implementing FMEA, and characterising the analysis object. Each member responsible for FMEA implementation should take part in this stage.

The second stage, during which the FMEA worksheets are created, is divided into five steps. Individual elements of this stage concern the development of the FMEA evaluation worksheet tailored to the needs of the company, the implementation of FMEA in the determination of defect, cause and effect, verifying and correcting the analysis by all team members (each member has got an individual access to the analysis on-line (website) and has the ability to comment on the application of FMEA), acceptance of the created analysis, determination of RPN (Risk Priority Number) indicators including components: Occurrence - Po, Severity - S, Detection - Pd (**Table 1**). While determining the RPN indicator every member evaluates the three constituents for specified failures. A scale is adopted to evaluate the constituents; it is in accordance with the standard PN EN 60812:2009 [3]. Determination of final values of the indicators is achieved through averaging which the executive team is responsible for.

Next stage of the analysis is the compilation of an inception report. This stage should include a meeting of the whole team in order to present the initial FMEA together with calculated RPN indicator for each identified potential failure. After the analysis, the team determines threshold RPN values requiring preventive actions. If the RPN value for certain actions is too high, countermeasures are formulated, including establishing responsibility for the control of the actions work progress.

In the fourth stage (FMEA updating) every member responsible for specified preventive actions fills in the FMEA worksheet with information resulting from those actions. Additionally, he or she updates the ranking of constituents of RPN indicator.

The last stage of FMEA implementation is the closing meeting, during which the final FMEA (taking into account previous preventive actions) is presented. In this meeting it is allowed to make final corrections to preventive actions and their evaluation. This stage ends with the approval of FMEA.

3 Description of the analysed project

The FMEA object was a processing line designed to heat treatment of pipes used in heat exchangers. The line is unitary and it was assumed that it had to meet stringent requirements for reliability (at 99%) and accessibility (97%). This line features several innovative solutions.

Following, due to the volume of this article, attention was focused on the water system of the analysed line.

3.1 Characteristics of the water system

In the analysed processing line the water system is designed to cool the furnace feed after heat treatment. The initial scheme of the water system project is presented in **Figure 3**. In the analysed system two circuits can be distinguished. The first circuit allows the water flow through a heat exchanger, where it is cooled down and brought into the cooling space of the processing line again. This circuit is marked by the numbers from 1 to 13 (fig. 3). The second circuit is used to cool the water.

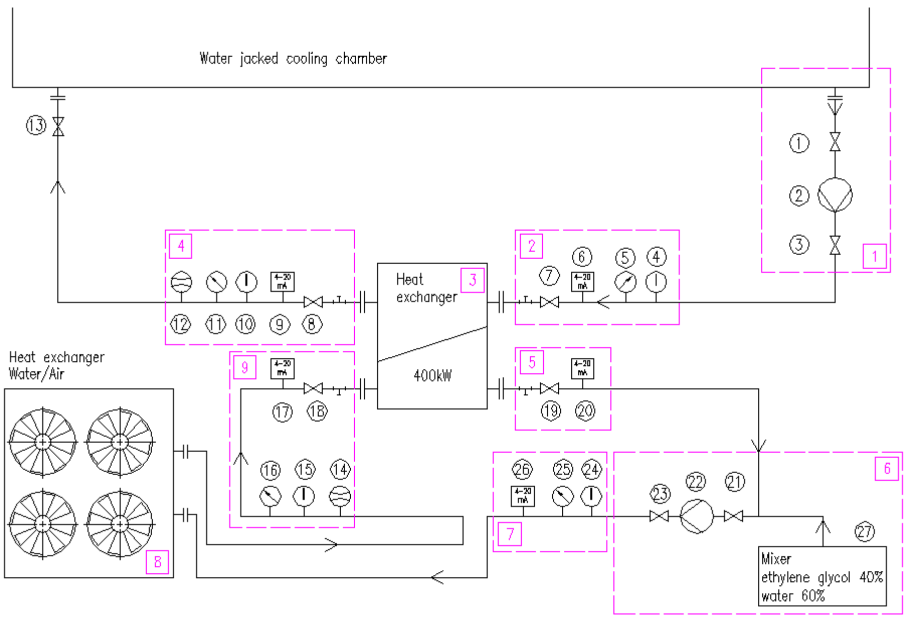

Fig. 3 Initial scheme of water system project

The coolant is a mixture of ethylene glycol and water, proportions respectively 40% and 60%. It is represented by the remaining elements on the scheme.

The tested water system consists of 9 interrelated subsystems. The following subsystems have been distinguished:

1 – Water pumping subsystem (consists of two shut-off valves 1, 3, and water pump 2),

2 – Subsystem of water parameters control on the entrance to the exchanger 3 (consists of a shut-off valve 7 and measuring and control devices 4, 5, 6),

3 – Plate heat exchanger,

4 – Subsystem of water parameters control on the exit from the exchanger 3 (consists of a shut-off valve 8 and measuring and control devices 9, 10, 11, 12),

5 – Subsystem of coolant parameters control on the exit from the exchanger 3 (consists of a shut-off valve 19 and pressure transducer 20),

6 – Coolant pumping subsystem (consists of two shut-off valves 21, 23, pump 22, and a tank refilling the coolant 27),

7 – Subsystem of coolant parameters control on the entrance to the exchanger 8 (consists of measuring and control devices 24, 25, 26),

8 – Heat exchanger (forced-draught cooling tower),

9 – Subsystem of coolant parameters control between the heat exchangers (consists of a shut-off valve 18 and measuring and control devices 14, 15, 16, 17).

Detailed FMEA involving all constituent elements was conducted for each of the above subsystems.

4 FMEA for the water system

Only a short part of FMEA for the water system is described in this point. The analysis of this system was conducted in the stage of designing its project. The emphasis during the analysis was placed mostly on reliability of the system components. Certain fragments of FMEA for the water system are presented in **Table 1**. They are related to those components for which preventive actions necessitating the project corrections were formulated. It was assumed that the preventive actions had to be applied in the case when the RPN indicator value was higher than 30.

Basing on the past experience, in the first subsystem (water pumping) an occurrence of a damage (defect) to the water pump (component 2) was detected. Its level exceeded the acceptable values. This meant that in the case of any pump failure a disturbance in the flow of water cooling the furnace feed would appear. It would result in an incorrect heat treatment process of the feed, which would lead to production of an incorrect batch and large financial losses.

In the sixth subsystem (coolant pumping), as in the first, an occurrence of identically severe damage to the coolant force pump (component 25) was found. The damage or partial malfunction would influence the intensity of heat receiving from the coolant by the heat exchanger module (15). This could lead to incorrect water cooling in the heat exchanger (8) and, as a consequence, to inappropriate parameters of water in the furnace. The result would be a failure to meet the feed cooling parameters, and production of an incorrect batch.

Table 1 Part of FMEA worksheet for the water system

PART		CHARACTERISTICS OF FAILURE				1st RATING			
No	Function / Part / Operation	Failure mode	Causes of failure	Undesirable customer effects Effects of failure on syst. / part / operation	Testing - Simulation	Po	S	Pd	RPN
	Water system								
1	Water pumping subsystem	pump not working due to mechanical causes	no coolant flow	Liquid temperature increase in the circuit		3	8	2	48
		reduced pump efficiency	limited coolant flow	Liquid temperature increase in the circuit		2	5	4	40
		pump not working due to electrical causes	no coolant flow	Liquid temperature increase in the circuit		3	8	2	48
		seizure, locking of the shut-off valve	no coolant flow impossible	Liquid temperature increase in the circuit		2	5	2	20
6	Coolant pumping subsystem	no protection against excessive pressure increase	pressure increase in the coolant system	Possibility of installation unsealing, possibility of dangerous substance leak		5	9	2	90
		pump not working due to mechanical causes	no coolant flow	Liquid temperature increase in the circuit		3	8	2	48
		reduced pump efficiency	limited coolant flow	Liquid temperature increase in the circuit		2	5	4	40
		pump not working due to electrical causes	no coolant flow	Liquid temperature increase in the circuit		3	8	2	48
9	Subsystem of coolant parameters control between the heat exchangers	Compensation for increased coolant volume	pressure increase in the installation between the heat exchangers	Possibility of installation unsealing, possibility of dangerous substance leak		5	7	2	70

Other defects in this subsystem were the inability to remove the excess coolant, which could be caused by a sudden increase of its pressure, and protection of the system against an uncontrolled pressure surge. Furthermore, in the ninth subsystem, a possibility of coolant pressure disturbance between the heat exchangers 3 and 8 was identified.

Remaining components of the analysed water subsystem did not pose any hazards that needed to take preventive actions.

5 Preventive actions

On the basis of conducted FMEA studies preventive actions decreasing the probability of damage to particular components of the water system were formulated and introduced to the project.

In the cases where there was no possibility of exchanging a component with an object of superior quality (lesser probability of a defect), the decision to duplicate the component (or the string of cooperating components) was made. The changes and addenda to the water system project are indicated red and presented in the **Figure 4**.

In the first subsystem, because of the lack of a pump of a higher quality, the system of components 1, 2, and 3 was duplicated by a parallel system (components 27, 28, and 29). Apart from that, the duplicated water pumping systems were made to work interchangeably in defined time periods, according to the instructions in the manual. Therefore, in both cases of the components coupled in parallel, shut-off valves were incorporated (30 and 31). This eliminated the possibility of water flowing back into the idle system.

In the sixth subsystem, similarly to the first one, components 21, 22, and 23 were duplicated by components 35, 36, and 37 respectively, and shut-off valves were incorporated (34 and 38, one for each of the duplicated pumping systems). Protection of the coolant circuit against excessive pressure increase was achieved by the use of two elements: a safety valve (32) linked to an additional coolant tank (33).

To ensure pressure adjustment in the section between the heat exchangers, an equalising tank (40) and pressure transducer (39) were planted.

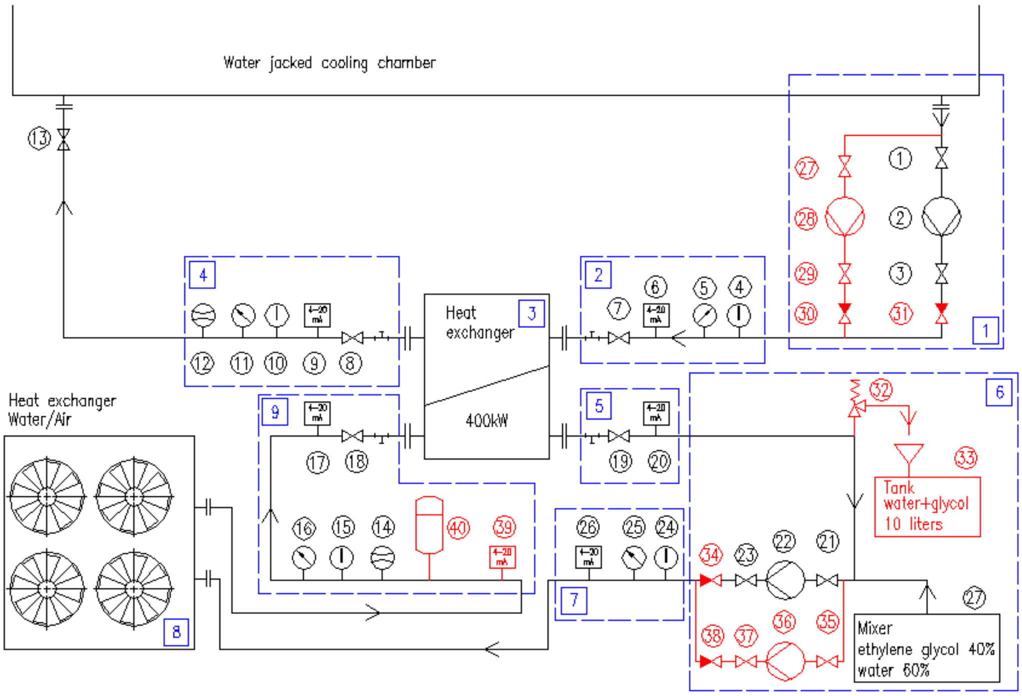

Fig. 4 Final scheme of water system project

6 Final project analysis

The analysis allowed localising the vulnerable spots of the tested subsystems. The proposed alterations have significantly accelerated the reduction of their original RPN rating. In the most unprotected spots the indicator was reduced to values below the allowed, that is RPN<30.

As it was mentioned in section 3, another crucial indicator, whose value was determined by the client in the assumptions as a required value, is the reliability of the designed furnace. According to the requirements, this indicator is supposed to be higher than 99%. In order to decrease the dimensionality of the task of assessing the reliability indicator it has been assumed that the smallest element of consideration in the reliability analysis is the commercial element. Hence, each of the suppliers was made to determine the reliability indicator for every supplied component, assuming it had two-year span of failure-free work. If the supplied components did not possess such data, or the parts were made independently, the reliability indicator was specified based on the component damage probability included in FMEA.

The change (increase) of the reliability indicator is shown below, on the basis of the mentioned water system.

Assessment of the reliability indicator is achieved through the reduction of individual system components to objects between which it is possible to define mutual dependencies: serial or parallel [2,4].

Acting accordingly to the commonly known formulae, taking into account serial and parallel dependencies, it was calculated that the reliability indicator for the water system in original condition (**Figure 3**) is equal to **0,998331**. For the water system after the alterations (fig. 4) resulting from FMEA, the indicator is **0,999329**.
The modifications to the most vulnerable spots of the system affected the increase of the reliability indicator, as the dependency between individual components was transformed from the serial to parallel, thanks to the components duplication.

These alterations are shown in **Figure 5**, where one can see the components of the original subsystem and this subsystem after the changes.

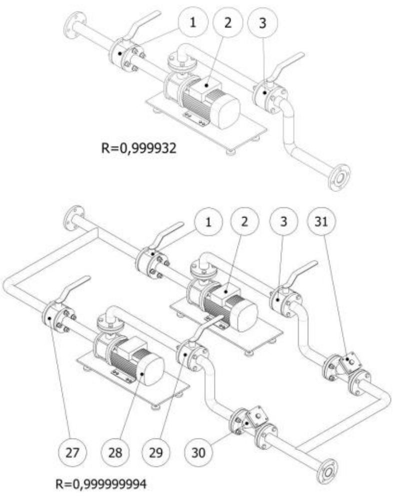

Fig. 5 Change of configuration in subsystem 1-3

Similar steps for the remaining furnace elements realised accordingly to FMEA conclusions allowed increase of the assessed value of the reliability indicator for the whole furnace. It was changed from the original value **0,9754213** do the final **0,9964216**. The final value of the reliability indicator was expressed in % (99,64%), which met the client requirement.

7 Summary

FMEA described in the article is a method helpful in the process of identification of potential failures (defects) in designed systems. The analysis efficiency depends on the moment of its application in the design process. Its implementation is recommended at the possibly early stage of designing and manufacturing, especially of new devices. In the article FMEA was used at the initial design stage of a heat treatment processing line. The conducted analysis allowed identification of potential errors and introduction of preventive actions. As a result, a much better project of the designed processing line construction was obtained. This project was characterised by the required quality and reliability, both of which create a base for the order realisation in relation to the client's demands. To implement FMEA a new model of this analysis was employed. The implemented FMEA appeared also to be useful in assessing reliability of designed devices, which is not an easy task.

To sum up, the article presents a new approach (in the conditions of the described company) to FMEA implementation. The new approach is based on a different than universally accepted work organisation when conducting FMEA. It is described in point 2 of this article. In actual conditions such an organisation appeared to be efficient in relation to the smaller time amount required from the employees of the ordering company, as well as to engagement of external specialists conducting the analysis, whose knowledge was not based only on their expertise in designing such devices. This way the level of commitment of people involved in design, technological, and manufacturing work related to a new device was reduced to the necessary minimum, whereas before the work on the device design and its FMEA was continuous and required a lot more effort. The article simultaneously confirms the relevance of conducting such analyses in new, unitary projects, which are characterised by a modern, different from the past company's experience, structure of design and construction.

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