International Journal for Quality Research 10(4) 847–870
ISSN 1800-6450

Cristiano Fragassa[1]
Martin Ippoliti

FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS (FMECA) AS A QUALITY TOOL TO PLAN IMPROVEMENTS IN ULTRASONIC MOULD CLEANING SYSTEMS

Article info:
Received 27.03.2016
Accepted 16.09.2016

UDC – 54.061
DOI – 10.18421/IJQR10.04-14

Abstract: *Inside the complex process used for tire production, ultrasonic cleaning treatment probably represents the best solution to preserve the functionality of tire moulds, by removing residuals from moulds and keeping an unaltered quality for their surfaces. Ultrasonic Mould Cleaning Systems (UMCS) is, however, a complicated technology that combines ultrasonic waves, high temperature and a succession of acid and basic attacks. At the same time, an UMCS plant, as part of a long productive chain, has to guarantee the highest productivity reducing failures and maintenances. This article describes the use of Failure Mode Effects and Criticality Analysis (FMECA) as a methodology for improving quality in cleaning process. In particular, FMECA was utilized to identify potential defects in the original plant design, to recognize the inner causes of some failures actually occurred during operations and, finally, to suggest definitive re-design actions. Changes were implemented and the new UMCS offers a better quality in term of higher availability and productivity.*

Keywords: *tire, mould, failures, availability, productivity, maintenance, redesign*

1. On tire moulds

1.1. Importance and problems

A tire mould is a complex and expensive object consisting in several different parts, assembled together. It is built up on a drum and, then, cured in a press under heat and pressure. Heat facilitates a reaction of polymerization that crosslinks rubber monomers creating long elastic molecules. These polymers affects the elasticity of the constitutive materials permitting the tire to be compressed in the area where the tire contacts the road surface and spring back to its original shape under high-frequency cycles. Because of the use of synthetic materials in the compound of modern tires, mould fouling is formed from organic and inorganic material (Figure 1). Each utilization of the mould lays down a little deposit of residues. Finally between 1.000 and 3.000 different layers are present on the mould (this depends on tire type and process), each one containing

[1] Corresponding author: Cristiano Fragassa
email: cristiano.fragassa@unibo.it

organic and inorganic dirt, that must be removed by a cleaning treatment. At the same time, considering the high cost of the mould, the cleaning technique has to fully safeguard the integrity of the mould.

Figure 1. Dirty segments and sidewall

According to the general overview offered by Young (2002), a correct mould cleaning permits to:

- keep a proper surface finish of bead chaffer ensuring a proper adhesion of tire to wheel;
- make tire code clear and readable as required by law or other uses (as in Dias *et al*., 2015);
- keep logo and name of tire manufacturer clearly legible;
- keep clean vents or spring-vents;
- keep clean the contact surfaces between the sections of the mould, so no interruption in tire surface and tread design occurs
- ensure the coupling of the fields at high pressures;
- reduce the load on mechanical attacks of segments and other components;
- avoid the formation of surface irregularities during the drying phase due to previously listed aspects;
- improve mould durability and reliability.

1.2. Cleaning technologies

In Ippoliti and Fragassa (2016), conventional and advanced cleaning techniques for tire moulds are deeply investigated and compared. A brief synthesis is here reported.

An obsolete mould cleaning technology is the alkaline washing machine. It uses an alkaline-based cleaning product, that is unfortunately ineffective against inorganic dirt. This limit was initially overcome by adding mechanical cleaning technologies. Between the others, sandblasting was preferred since it is cheaper and simpler to use. However, even with slightly abrasive particles, sandblasting erodes the mould. After a certain number of cleaning cycles, the mould is definitely damaged and has to be changed. Another critical aspect is that the mould has to be cleaned off board. Mould extraction from the plant is a long operation causing relevant downtimes and costs (Gidey *et al*., 2014).

In the mid '80s, a new technology, dry ice blasting, came into use as a mould cleaning method. Dry ice pellets or flakes, at -78.5 °C, are fired against the mould with a 180-200 °C temperature. The thermal shock blows dry ice particles producing shock waves. These waves break the fouling residue deep inside the mould geometry. The dry ice blasting technology is very effective, especially in the case of single-hose systems, with pellets and very hot mould. In this case it is able to clean vents up to 0.7 mm. On the other hand, dry ice blasting is coupled with very high levels of noise, that are rarely appropriate for manual use or in unprotected environment.

Accepting this complexity in cleaning

systems, a new approach has been also developed: the laser cleaning. A laser, with power up to 10 MW, cleans moulds by abrasion. Nor dry ice blasting neither laser generate a stream of secondary waste and can be used on board, reducing downtime. A 5-axis robot is used for positioning the dry ice or laser source. Comparing the two technologies, it is possible to say that a single intervention of cleaning laser is cheaper than dry ice, but the investments for laser are higher.

1.3. Spring-vent and Ultrasonic cleaning

As also discussed with details in Ippoliti and Fragassa (2016), after 2010 a new type of mould, in which the vents are always replaced by spring-vents, made practically obsolete the previous cleaning technologies. Spring-vents are small valves, which are closed when, during moulding, the tire is in contact with the mould surface (Figure 2).

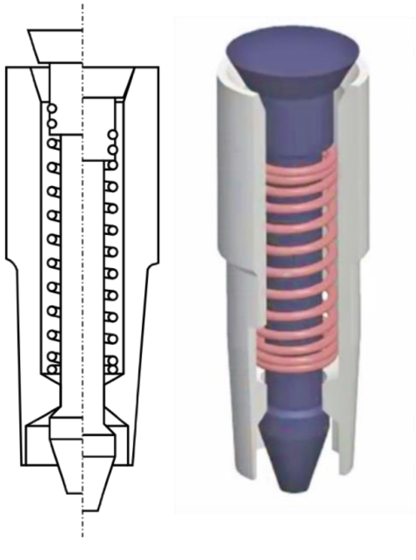

Figure 2. Spring-vent [Courtesy Glebus]

In this way, the spring-vent prevents the formation of the typical “hairs” on the tire surface. Special machines repair these defects adding costs and creating waste to be disposed. A manual finishing is also necessary and the cleaning staff uses expensive hand tools causing additional costs.

Advantages in using spring-vents for the quality of products are evident, but none of the above technologies is able to clean spring-vents. Even, in the case of laser, it chars dirt inside the spring-vents without removal, and, consequently, it locks them.

The problem of spring-vents cleaning was solved with moving to the ultrasonic cleaning. Ultrasound is sound waves whose frequency is higher than the threshold of audible for the human ear, conventionally above 20 kHz. Ultrasonic cleaning technology is industrially used since the 50s and has become economically viable since the 70s. It is largely apply in washing small metal parts such as jewelry, lenses, optical parts, watches, coins. In particular, it serves mainly to wash away polishing pastes, which are a mixture of organic and inorganic components. The ultrasonic cleaning is also utilized on dental instruments, surgical instruments, tools, weapons, electronic components, circuit boards and moulds.

1.4. Spring-vent and Ultrasonic cleaning

Specifically, ultrasound is efficiently used in industry, since its ability to cause cavitation (Pilli *et al.*, 2011). The cavitation is the formation, growth and collapse of micron-sized bubbles (Figure 3), resulting in the release of enormous energy. The local temperature can exceed 5000 °C and pressure 700 N/cm2 (Johnson, 2007). The phenomenon is the same that occurs on propellers and pump impellers, which are destroyed when they are pushed to work at excessive speed. These shock waves can also be used for breaking the residual materials on tire moulds.

In general, ultrasounds for industrial applications range from 20 to 100 kHz. In the case of moulds cleaning, employed frequencies comprised between 20 and 40 kHz. Ultrasonic transducers convert electrical signal to ultrasound waves (Figure 4). If the frequency is low, the bubbles are few, but large and powerful; when the frequency rises bubbles increase in number, but they are smaller and less powerful (Figure 5).

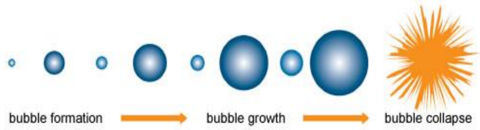

Figure 3. Process of formation, growth and collapse of a cavitation bubble [Courtesy Hanzhou Ultrasonic]

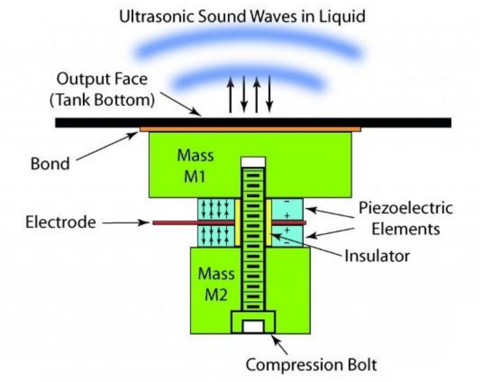

Figure 4. Ultrasonic transducer type Langevin [Courtesy Cleaning Technologies Group]

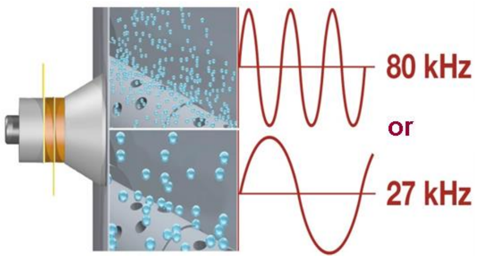

Figure 5. Effect of the change of frequency on the bubbles [Courtesy KKS – Ultraschall]

With these frequencies and energies, ultrasound waves vibrate the fluid, which compresses and expands alternately. During the compression phase, the positive pressure makes them closer together the molecules of the liquid, while in the expansion phase the negative pressure does move the molecules. When expanding exceeds the tensile strength of the liquid, in the liquid cavities containing steam can appear. These cavities are called cavitation bubbles. Even if theoretically this phenomenon is hard to appear in pure liquids, in reality the impurities substantially facilitate the formation of bubbles. In the ultrasonic cleaning specific chemical additives are employed with the aim at facilitating the creation of bubbles, increasing the vapor pressure and, at the same time, decreasing the viscosity and the surface tension of the liquid (Adewuyi, 2001). The small size of the bubbles and short times of the treatment ensure the surfaces cleaning without a perceptible degradation in the mould integrity. Studies demonstrated, for instance, that, in the case of austenitic steel, high stresses caused by the ultrasound are absorbed by the transformation of the surface layer from austenite γ to ε-martensite (D'Oliveira, 2003). Moreover, in the same investigation it was demonstrated that, if the mould surface is properly finished, an incubation period of erosion of more than 30 hours could be considered, well above the few minutes needed for cleaning. However these considerations, exclusively focusing the attention on moulds, forget to take into account the necessity to simultaneously protect from waves the process plant and its overexposed parts. Furthermore, to ensure the highest quality in cleaning, ultrasounds are used in combination with high temperature (80°C) and strong chemical attack (0-1 pH). The mixture of these different "loads" can create unplanned critical conditions, up to unexpected failures in gaskets, weld joints and other parts (Bignozzi *et al*., 2016).

In synthesis, ultrasonic cleaning is the only technology able to clean spring-vents. Since spring-vents seem essential for the realization of modern products, ultrasonic waves represent a necessary option. Its utilization cannot however overlook from a sentient approach in design of process plant.

This research aims at explaining failures occurred in a specific family of advanced Ultrasonic Mould Cleaning Systems (UMCS), identifying other potential defects and proposing a definitive list of re-design actions. A standard FMECA approach has been used for that investigation.

2. On cleaning system

2.1. Generality

The Ultrasonic Mould Cleaning Systems (UMCS) uses various agents to ensure a high quality of cleaning: ultrasonic cavitation, alkaline and acids products, high temperature and agitation of tanks' fluid. The system is then able to clean spring-vents, also effectively cleans even inorganic dirt caused by new compounds. In particular, the UMCS under investigation consist of six or eight tanks according to their use:

- UMCS-6-PCR (six tanks, car's tire mould)
- UMCS-8-PCR (eight tanks, car's tire mould)
- UMCS-6-TBR (six tanks, truck's tire mould)

Plants for car tire moulds are almost identical; the only difference is that the plant with eight tanks is faster. The plants for truck's tire moulds is instead equipped with larger tanks, since bigger moulds. The cost of these plants varies from 320.000 to 450.000 Euros. The TBR type plants are the most expensive, because of the greater size.

2.2. Cleaning process

A plant to six tanks is formed by two tanks containing alkaline liquid, a tank for rinsing, a tank containing acid liquid, a tank for passivation and a tank for dewatering (Figure 6). The pieces of the mould are mounted on ruck frames. A single ruck frames can carry a sidewall or four segments. The plant is equipped with four ruck frames and four trolley, the trolley used to move the ruck frames. The designs of the ruck frames and trolley are patented by Keymical.

An automatic Bridge Carriage moves ruck frames, immersing and extracting them from the tanks (Figure 7). The moving system can handle more ruck frames, each in different tanks, at the same time. The ruck frame with mould pieces is immersed in the alkaline tank, then in the rinse tank, then in the acid tank, then again in rinse tank. The rinse tank is one; this is because it washes alternately pieces from the acid tanks and pieces from alkaline tanks, so its pH is therefore considerable constant. The alkaline tanks are duplicated because, experimentally, in them dirt accumulates more than in the other tanks.

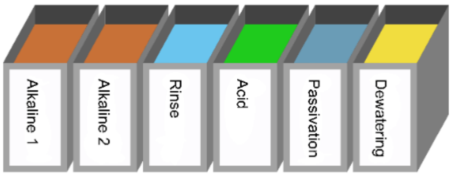

Figure 6. Tanks layout

Figure 7. The automatic Bridge Carriage moves a ruck frame with a sidewall along the row of tanks [Courtesy Keymical]

The alkaline solution used in the first two tanks, contains a corrosion inhibitor, otherwise the aluminum would become sodium aluminate. The cycle alkaline-rinse-acid-rinse is repeated 6-7 times. Following the ruck frame is put in the passivation tank and, finally, in the dewatering tank, which contains an oily solution. The high surface tension between oil and mould separates water from the mould. The water accumulates on the bottom and is sucked away. At the end of the process, the mould is transported in a dry-box, where an operator with a compressed air gun to remove the excess liquid. A glass wall is interposed between the operator and the mould. At this point, the mould can be inserted into the press or it can be carried in stock, where it is guaranteed for two years. Ultrasounds are working at 28 kHz. Only alkaline tanks, rinse tank and acid tank have ultrasounds. In the passivation tank, ultrasounds are unnecessary. In the dewatering tank, the liquid are 100% oil and prevents the formation of cavitation. The overall time of cleaning is less than two hours. To reduce the environmental impact, the plant is equipped with a filtering system and an evaporator. The evaporator, connected to a 5.000 liters tank, is a large cylinder that creates a vacuum to -950 mbar. The liquid solution of dirty water is evaporated at 32-33 °C, while the cooling plates condense the vapor creating distilled water that is recirculated. After a few hours is no longer pumped new water and dirt on the bottom left is sent to drying and, having reached a certain density, it is drained and discarded. Only the solid waste is disposed off, reducing the process environmental impact. In Zattini *et al*. (2016), the solid waste was characterized. Plants with eight tanks are as those with six tanks, with the difference is that they contain three alkaline tanks and two acid tanks.

2.3. Tanks

The tanks are made of stainless steel AISI 304 (Figure 8). A bath is made with various main parts: the bottom, two long sides, two short sides and an upper frame (Figure 9). To facilitate the discharge of the dirt, the bottom is inclined. The two long sides have the shape of a frame. The rectangular opening serves to accommodate the flange with the transducers. A frame, provided with holes, is welded on the edge of the opening of the side. An operator uses these holes as a guide to weld the studs. It needs to secure the flange. The flange that contains the transducers is made of AISI 316 L/S. In one of the long sides it is also present the probe that measures the level of liquid in the tank (Figure 10). One of the short sides is provided with two cavities. In the cavity bottom, there are four electrical resistors that serve to heat the liquid and the probe that measures the temperature (Figure 11), into the cavity at the top there is a tube, with holes, through which is pumped the liquid. In the other short side, at the top there is a hole connected to a rectangular bowl, in which ends the excess liquid (Figure 12). In the lower part of the side is the drain hole. Also the bowl has a drain hole.

With the aim at assuring an optimal adherence between parts,, a Teflon gasket is positioned between the frame and the flange. This gasket can represent a critical aspect in plant design, as generally highlighted by (Fragassa, 2016) and other recent studies. In particular, the fast degradation in the excellent properties of Teflon related to an unexpected acid attack emerged [investigated via Fourier Transform Infrared and Thermal analysis by, respectively, Giorgini *et al*., (2016) and Fragassa *et al*., (2016)].

All the pieces of the tank are welded together. The welding between the long sides and short sides is obtained in a particular way. The vertical side of the long sides is bent outwards. The edge of the long side is therefore parallel to the edge of the short side. The edges are welded from outside, with a continuous weld. On the inner side, instead, the operator performs some welding spots to keep the pieces in position.

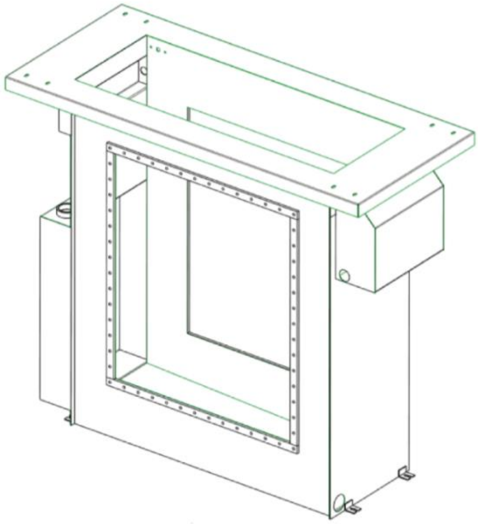

Figure 8. Tanks from plant [Courtesy Keymical]

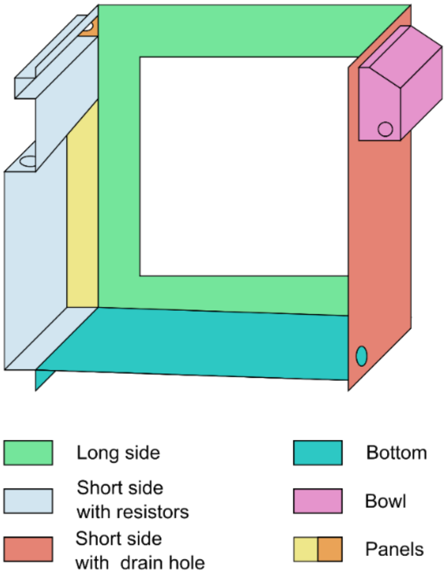

Figure 9. Cutaway of a tank

Figure 10. Short side with the loading tube, long side with liquid level's probe [Courtesy Keymical]

Figure 11. Electrical resistors and probe [Courtesy Keymical]

Figure 12. Square hole of the lateral bowl [Courtesy Keymical]

There is therefore a gap between the two sides, in which the liquid can penetrate, and is stopped by the external welding (Figure 13). The weld between the bottom and the short sides is similar to this. The edges of the bottom, which are in contact with the short sides, are folded down. Outside there is a continuous weld, inside there are only spot welds (Figure 14). The edges of the bottom which are in contact with the long side, cannot also be folded. To this, it is added to a support element, in the shape of parallelepiped, which is welded both to the bottom, both to the long side. From the inner side there are only soldering points (Figure 15).

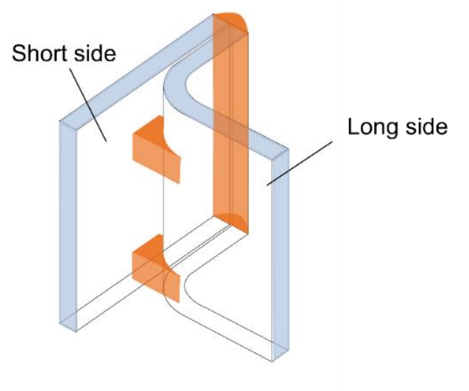

Figure 13. Welding between the short side and the long side, welds are highlighted in orange

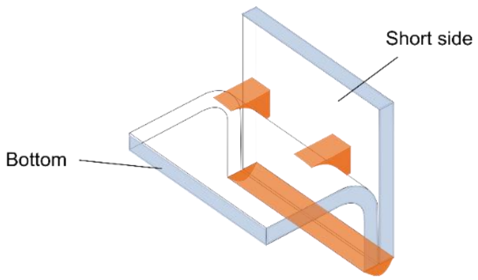

Figure 14. Welding between the short side and the bottom

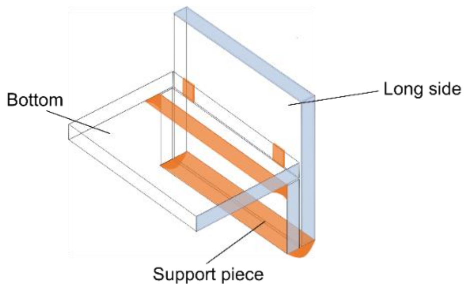

Figure 15. Welding between the long side and the bottom

The tank is inserted in a holder. Such support is composed of a rectangular base, formed by square tubes welded together, and by four columns with an L section. The tank is lowered into the support, and is screwed to the base and welded to the columns.

2.4. Observing defects

During the first year of use, several fails appeared. In some plants, acid tanks began to leak fluid. In general, a leakage in this kind of tanks can present two alternative origins: leakage of the welds between the walls and the bottom, leakage from the flange's gasket. In the first case, the fail is probably caused by an accumulation of dirt, progressively deposited in the gap between the sides and the bottom. This dirt prevents to air, and therefore oxygen, to penetrate inside. The atmosphere deoxygenated corrodes the welding. In the second case, the gasket is simply inadequate to resist to the combination of thermal and mechanical stresses and it lastly fails.

In the specific UMCS under investigation, the hooks of the ruck frames, to which are hung the pieces of the mold, were quickly corroded by the fluid, dripping from the acid tanks.

These hooks, initially realized in carbon steel. were replaced by stainless steel hooks as a first-aid action, while the present FMECA for complete redesign was launched.

2.4. New tank

Because of the problems encountered, new tanks were designed to replace the old ones. The new model of tank is formed by two main pieces, that are: 1) the side with the resistors and the bottom; 2) the longer sides and the side with the bowl. The ends of the long sides are shaped in order to cover the recesses in the side with resistors. This technical solution permits to have a lower number of welds. Furthermore inside the tank there are seam welding. Adding, all the sides are thicker and made of a better alloy. At the same time, the overall dimensions, the inclination of the bottom and the diameter of the storm drain are the same as in the old tank. In this way, it was possible to directly install the new tanks on the old frames.

3. On FMECA methodology

3.1. New tank

In general, the reasons why companies performs a risk analysis are numerous (Stamatis, 2003):

- Safety,
- Legal, statutory requirements,
- Warranty and service cost,
- Development of technical risk,
- Management emphasis,
- Market pressure,
- Competition,
- Customer requirements,
- Public liability, and
- Others.

According to Stamatis (1989), Stamatis (1991), and Stamatis (1992), a risk analysis is crucial to answer two questions:

- What can go wrong?
- If something goes wrong, what is the probability of it happening and what are the consequences?

Answering to these questions represents the better way to analyze and solve the technical problems. Over time, a change in the way to approach the risk analysis took place: specifically prevention has become the heart of the matter (Table 1).

Table 1. General targets for a risk analysis (Stamatis, 2003)

Past	Present
Solutions of the problems Monitoring of waste Quantification of reliability	**Prevention of problems** Elimination of waste Reduction of unreliability

FMECA is one of the most common methodology for the prevention of risk.

3.2. Brief history

In the 40's United States Armed Forces developed the first FMECA, and in 1949 published the Military Procedure MIL-P-1629, titled Procedures for Performing a Failure Mode, Effects and Criticality Analysis (Anleitner, 2010). In the 60's, FMECA was used by NASA in the Apollo Program (NASA, 1966). After the success of the Apollo program, NASA has used the FMECA in several other space programs, such as Viking, Voyager, Magellan, Galileo and Skylab (Muralidharan and Syamsundar, 2003). In 1970, Ford introduced the FMEA in the automotive industry (Ibid.) largely spreading this methodology for quality all over the sectors and applications.

3.3. Brief history

According to NASA, 1966, FMECA is a reliability procedure, which documents all possible failures in a system design within specified ground rules and determines by failure mode analysis the effect of each failure on system operation. FMECA is composed by two separate analyses, the Failure Mode and Effects Analysis (FMEA) and the Criticality Analysis (CA). The FMEA analyzes different failure modes and their effects on the system while the CA relates failure rate and severity of the effect of failure (NASA, 1966; DA, 2006). The principle at the basis of this method is that the severity of a fault is more important of the occurrence, and that the occurrence is much more important than the detectability (Anleitner, 2010). In particular, an injury is the most serious effect of a fault (Stamatis, 2003). For a proper execution, the FMECA must be done by a team, and not by a single person. A good FMECA team includes people directly involved with the topic under analysis, for example engineers and specialists, but also operators and maintenance technicians (Nolan and Dodson, 1999).

There are different types of FMEA/FMECA [as detailed by Stamatis (2003)]:

- System/Concept FMECA (S/CFMECA): It is applied to system functions. A system is a set of parts or subsystems designated to carry out one or more functions. This analysis is applied in the very early stages of labor, when it was not yet defined the specific hardware.
- Design FMECA (DFMECA): It is applied to part or component functions. This analysis is done when the final hardware has already been chosen.
- Manufacturing or Process FMECA (PFMECA): It is applied to production or assembly process.
- Service FMECA: Used to improve the serviceability of the product.
- Environmental FMECA: It is used on projects, systems or machines that need to achieve certain environmental objectives.
- Machinery FMECA: Extension of FMECA; specializes in tooling and equipment.
- Software FMECA: Variant of FMECA developed specifically for software.

As described above, the FMECA is composed of two steps; the first of these is the FMEA. In FMEA, risk is calculated using Risk Priority Number (RPN). The RPN is obtained by multiplying *Severity* [S], *Occurrence* [O] and *Detectability* [D]. These three parameters are measured against a scale from 1 to 10 (Lipol and Haq, 2011). So the RPN of a failure mode can vary from a minimum value equal to 1 (S = 1, O = 1, D = 1) up to the maximum value of 1000 (S = 10, O = 10, D = 10). FMEA is done on spreadsheets (Figure 16).

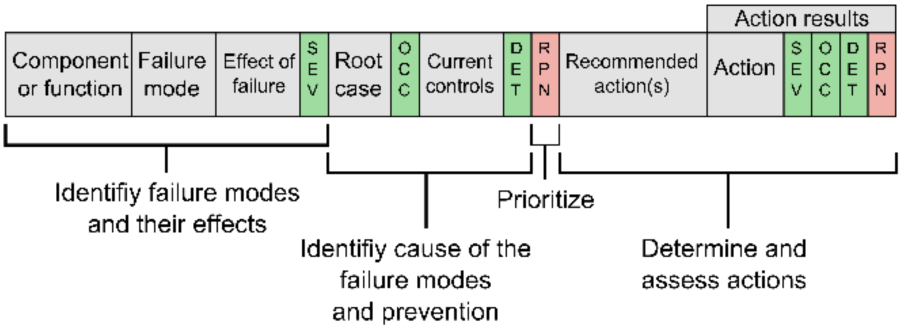

Figure 16. FMEA spreadsheet

Component/function: In the case of a component FMEA, each element of the test system is analyzed, and any possible failure mode is analyzed. In the case of function FMEA, first the team identifies the basic functions of the system (e.g. for a car could be "speed", "brake", "handling", etc.), and then identifies the failure modes such influence functions. Each line of the spreadsheet will then be dedicated to a failure mode.

Failure mode: It must be described in technical or physical terms (e.g. bending, cracks, breakage, etc.) and not as "sensations of the customer" (Lipol and Haq, 2011).

Severity index: From 1 to 10. Normally, it is agreed with those who commission the FMEA.

Root case: It must be something that can be corrected or controlled (Lipol and Haq, 2011). For example worn tools, parts missing, incorrect programming, etc. In the case of a DFMEA, this causes are design parameters, such as thickness, material, position of an element, etc. These causes can be easily identified with the Fault Tree Analysis (FTA)

(Levine and Kalal, 2003).

Occurrence: From 1 to 10. Normally, it is agreed with a table that relates each value to the probability of occurrence of fails, also considering the number of products in operation and their technical specificities.

Controls: There are two types of controls: prevention and detection. Prevention is preferable, as it reduces the occurrence (Lipol and Haq, 2011).

Detection: From 1 to 10. Normally, it is agreed with a table that graduates each value to the real possibility of detecting fails before they start an chain of events up to the final accident.

RPN: Risk Priority Number = Severity x Occurrence x Detection. The RPN does not have thresholds. That is, there is no value above which the team is obliged to recommend a solution and there is no value below which the team is exempt from proposing action (Lipol and Haq, 2011). The customer may, however, establish a limit value, or a scale, of the RPN, such as:

- Not relevant: RPN <50
- Very low: RPN <100
- Low: RPN <150
- Medium low: RPN <200
- Middle: RPN <250
- Medium high: RPN <300
- High: RPN <350
- Very high: RPN <400
- Critic: RPN >400

The team must then propose corrective actions for failure modes that exceed this limit.

Recommended Action(s): Recommended actions by the team to reduce the RPN

Action results: How Severity, Occurrence, Detectability and consequently the RPN vary after the implementation of recommended actions.

In the MIL-STD-1629A it is described two types of Criticality Analysis: Quantitative and Qualitative Analysis.

Quantitative Analysis: For each failure mode, the team identifies all the elements whose failure is caused by that mode. The criticality of a failure mode is calculated as: number of elements at risk*severity*occurrence. The criticality of an element is instead equal to the sum of the criticalities of element's failure (Lipol and Haq, 2011).

Qualitative analysis: Performed via Risk Matrix (Figure 17), which has occurrence on the horizontal axis and severity on the vertical axis (Lipol and Haq, 2011).

The Criticality Analysis entails the additional benefits (Lipol and Haq, 2011):

- It helps in the analysis of the product or process
- It helps to document the rationale behind the recommended actions

3.4. Benefits

In NASA (1966), FMEA shows the following benefits:

- Highlight single point failures requiring corrective action
- Aid in developing test methods and troubleshooting techniques
- Provide a foundation for qualitative reliability, maintainability, safety and logistics analyses
- Provide estimates of system critical failure rates
- Provide a quantitative ranking of system and/or subsystem failure modes relative to subject importance
- Identify parts and systems most likely to fail.

In Lipol & Haq (2003), benefits are expressed more concisely in three points:

1) Improvement of product design or process:

- Upper reliability.
- Better quality
- Enlarged safety

2) Improved customer satisfaction:

- Contributes to cost savings.

- Decreases development time and re-design costs.
- Decreases warranty costs.
- Decreases waste, non-value added operations (Lean Management)

3) Contributes to the development of control plans, testing requirements, optimum maintenance plans, reliability growth analysis and related activities

To achieve these benefits the FMEA must be done according to the procedures. For example, in the automotive industry, an unrestricted application of FMECA did not carry the expected improvements. According Bendell *et al*. (1999), several factors caused this inefficiency:

- The FMECA has been applied too late in the production process.
- The RPN were manipulated. The goal was to reduce the corrective actions, and therefore the costs, in the production phase, not in the design phase.
- The Method was not handled better.
- People involved in the analysis did not have the necessary knowledge of the product.

As suggested by Bendell *et al*. (1999), large companies should employ the FMECA in quality control, environmental impact, safety and health.

4. FMECA analysis of tanks

4.1. Composition of FMECA team

Stainless steel hooks and new tanks was only a temporary solution, and a DFMECA on both tanks was commissioned, to determine the actual improvements and to give advice on the design of an advanced generation of tanks. The team that conducted the analysis consisted of:

- An expert of the plant,
- The designer of the new tanks,
- The executor of expertise on older tanks, and
- An expert of reliability and quality control.

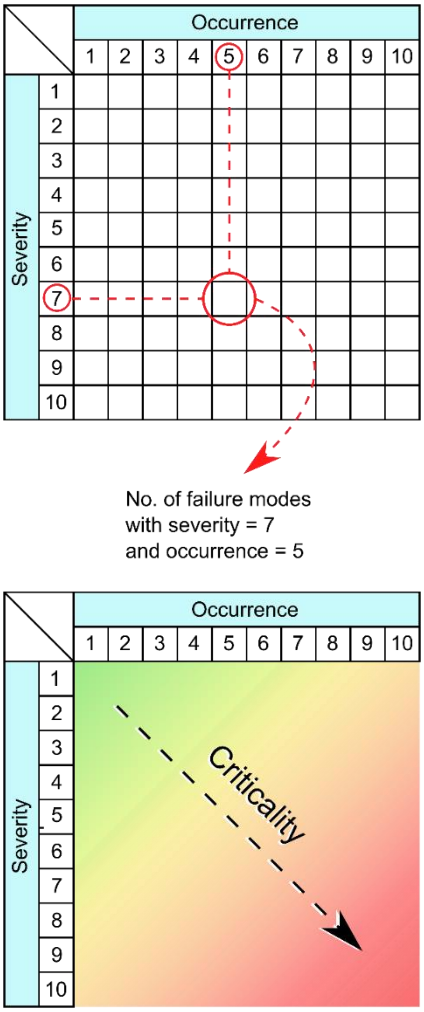

Figure 17. Risk Matrix

4.2. Analysis

In the first part of the research, the general problem of mould cleaning, and in particular the technology of ultrasonic cleaning were studied. The next step involved the collection of information on the plant, the process and in particular the tanks. In this phase, it was therefore necessary to study the drawings of tanks, both old and new, and to ask information to the engineer who oversaw the design of the new tanks. It was then possible to identify the functions of the tanks, on which to apply the FMECA. These functions are:

1) Containment of the liquid
2) Maintaining the proper fluid level
3) Maintaining the proper temperature of the liquid
4) Ultrasonic operation

When the functions were established, it was possible to draw a matrix in an Excel spreadsheet. Such matrix is composed of four columns that identify the four functions (Figure 18). Each line contains an item: such items are all the individual pieces of the tank, the welds between the pieces, probes, resistors, drain holes, the gasket, the studs and the flange. The analysis is only limited to the tank and does not consider physically internal elements to it such as probes and resistors, but takes into account their position in the tank, i.e. the position and size of their fixing points. Below, for each function and for each item, it was assessed whether the considered element affects the function. Every positive match would be assessed later in another Excel spreadsheet. As the long side is considered as an example, it is possible to make the following observations. If it is punctured, the bath will lose liquid (*function* 1). Also, on one of the long sides is fixed probe, which measures the liquid level (*function* 2). If the side is too thin and/or is made of a material with high thermal conductivity, the thermal losses might be excessive (*function* 3). Finally, the long side contains the flange with the transducers. A loss of fluid can damage the transducers (function 4). As stated previously, the results are transferred to another Excel spreadsheet (Table 2). This spreadsheet contains the following columns:

- N°: Sequential number of lines,
- Function,
- Anomaly,
- Severity,
- Root case of the anomaly,
- Component considered,
- Incorrect design features that cause the anomaly,
- Value of incorrect design features that cause the anomaly,
- Occurrence,
- Checks required,
- Detectability,
- RPN,
- RPNC,
- Recommend action(s),
- Recommend action(s)' design effort (from 1 to 5),
- Advantages of recommend action(s).

Every feature of each component was considered separately:

- Panels: thickness, material, thermal conductivity (function 3), surface finish, any bending radii, any tilt;
- Holes and openings: diameter/ dimensions, position, distance from the edge of the panel or by neighboring holes/opening, any sharp (square openings);
- Welds: method (e.g. TIG), type of joint, chamfering of the edges, the thickness of the cord, fillet radius, filler material.

As far as the old tank is concerned, the final excel table comprises 218 rows. The spreadsheet on new tanks, however, had 185 lines. This is because of fewer components and welds.

Table 2. Typical life history of a complex product

N°	Function	Anomaly	Severity	Root case	Component	Incorrect design feature	Value of design feature	Occurrence	Checks	Detectability	RPN	RPNC	Recommend action(s)	Actions'design	Advantages of
1	Containment of the liquid	Leaking long side	10	Wrong thickness	Long side	Thickness	2 mm	1	Check that thicknes is adequate to the stresses received	1	10	10	Increase the thicknes	3	Reduce the possibility of punctures
2	Containment of the liquid	Leaking long side	10	Wrong material	Long side	Material	AISI 304	1	Check that materials is adequate to the stresses received	1	10	10	Choose a better alloy		Reduce the possibility of punctures
…															
35	Containment of the liquid	Leaking welding between short side with resistors and panel	10	Poorly designed welding	Welding	Welding type	TIG	5		2	100	50			
36	Containment of the liquid	Leaking welding betw	10	Poorly designed weldi	Welding	Joint type	Butt joint	5		2	100	50			

		een short side with resistors and panel		ng											
37	Containment of the liquid	Leaking welding between short side with resistors and panel	10	Poorly designed welding	Welding	Joint geometry		5		2	100	50			
38	Containment of the liquid	Leaking welding between short side with resistors and panel	10	Poorly designed welding	Welding	Seam thickness		5		2	100	50			
39	Containment of the liquid	Leaking welding between short side with resistors and panel	10	Poorly designed welding	Welding	Filler material		5		2	100	50			

40	Containment of the liquid	Leaking welding between short side with resistors and panel	10	Poorly designed welding	Welding	Seam fillet radius		5		2	100	50			
…															
167	Maintaining the proper fluid level	Loading tube occluded by dirt	7	Loading tube position	Lateral panel with loading tube connection	Distance of the connection from the upper edge of the tank	155.5 mm	1		1	7	7			
168	Maintaining the proper fluid level	Loading tube occluded by dirt	7	Dirty not discharged from the drain hole	Drain hole	Diameter	61 mm	1		2	14	7			
…															
218	Ultrasonic operation	Leaking flange connection	10	Insufficient pressure to ensure sealing	Studs	Induction welding	/	2		20	10				

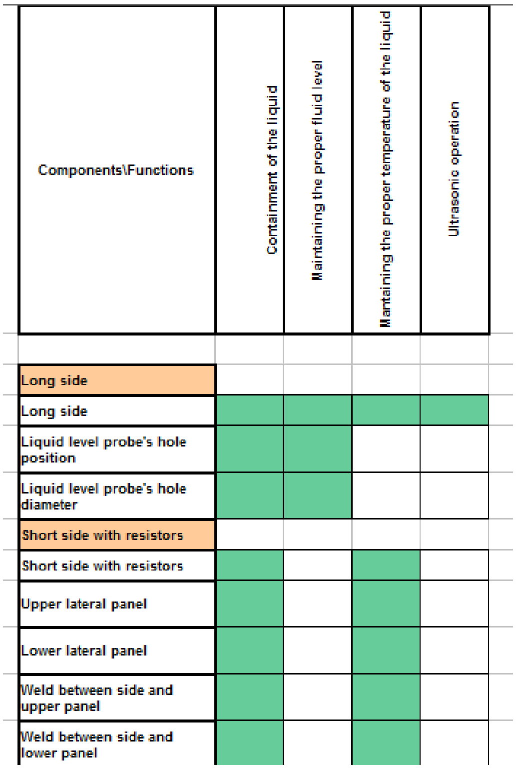

Figure 18. Matrix that contains functions and elements

The severity index has been agreed with an expert of this plant (Table 3). The plant is in operation 24/7, every day. In compiling the occurrence index (Table 4), indexes 10 and 1 were first established. The criterion would be the Mean Time Between Failures (MTBF). Failures of 10 index are those with MTBF> 24 h, while the index 1 have a MTBF> 40,000 h, i.e. 4.5 years. In the final spreadsheet, in order to obtain more precise results, the index of occurrence includes decimal values. Finally, detectability index was compiled (Table 5). For each type of fault, the team determined the values of occurrence and detectability. The RPN and RPNC were calculated. The RPNC equals S*O. When necessary corrective actions were suggested.

4.3. Results

First, a comparison between RPNs was made. RPN>150s have fallen from 8 to 1, while 100<RPN<150 have fallen from 79 to 62

Table 3. Severity index

Effect	Criterion: effect's gravity	Index
Failure without warning	Very high gravity - Involves the safety and/or integrity of the system, the integrity of the moulds and/or effect of compliance with the laws in force in the absence of alerts	10
Failure with warning	Very high gravity - Involves the safety and/or integrity of the system, the integrity of the moulds and/or effect of compliance with the laws in force	9
Very long downtime with impossibility for the operator to solve the problem	Downtime of six hours (critical case)	8
Broken hardware caused by a technical problem of system components (sensor, float) or a downtime of the evaporator	Downtime of four-six hours	7
Broken hardware that does not cause downtime but affect cleaning (e.g. a broken resistor)	Clean affected	6

Technical problem to the dosing system of the chemical products	Preclude a good cleaning result (the drop in quality is not immediate but slow and the staff has time to intervene)	5
Lack of maintenance (and failure to replace the filter of the buffer tank)	Short downtime	4
Failure to remove the water from the bottom of the dewatering tank (weekly)	No downtime but moulds oxidize	3
Negligible effects (e.g. negligence in the post cleaning)	Mould's quality problem	2
No effect		1

Table 4. Occurrence index

Failure rate	Criterion: MTBF	Index
Very high	MTBF < 24 h	10
Very high	25 h < MTBF < 168 h	9
High	169 h < MTBF < 720 h	8
High	721 h < MTBF < 2,000 h	7
Moderate	2,001 h < MTBF < 4,000 h	6
Moderate	4,001 h < MTBF < 8,000 h	5
Moderate	8,001 h < MTBF < 13,000 h	4
Low	13,001 h < MTBF < 25, 000 h	3
Low	25,001 h < MTBF < 40,000 h	2
Very low	MTBF > 40,000 h	1

Table 5. Detectability index

Detectability	Criterion: Probability of detecting the fault through checks	Index
Absolute uncertainty	The operator or the control device is not able to detect the potential cause and the consequent failure, or there is no control activity of the project (design review)	10
Very vague	Very vague possibility that control of the project or of the machine reveals a potential cause and the resulting failure mode	9
Vague	Slight possibility that control of the project or of the machine reveals a potential cause and the subsequent failure mode. A control equipment will provide an indication of the impending failure	8
Very low	Very low possibility that the control of the project or the machine proves to be a potential cause and the consequent failure mode, and that the control of the machine prevents an impending failure (e.g. machine stop)	7
Low	Low possibility that the control of the project or the machine reveals a potential cause and the consequent failure mode and that the control of the machine prevents an impending failure	6
Moderate	Moderate chance that control of the project or of the machine reveals a potential cause and the resulting failure mode and that the control of the machine prevents an impending failure and isolating the cause	5

Discreet	Fair possibility that control of the project or of the machine reveals a potential cause and the resulting failure mode and that the control of the machine prevents an impending failure and isolating the cause. For this reason, a machine control system must be installed.	4
High	Good possibility that control of the project or of the machine reveals a potential cause and the resulting failure mode and that the control of the machine prevents an impending failure and isolating the cause. For this reason, a machine control system must be installed.	3
Very high	Excellent possibility that control of the project or of the machine reveals a potential cause and the subsequent failure mode. The machine control system in this case is not necessary.	2
Almost certain	The control process of the project (design review) detects almost certain potential causes and failure modes. The machine control system in this case is not necessary.	1

There has been a subsequent increase of the middle and low RPNs (Figure 20). The cause of this shift was the decrease of the occurrence (Figure 19); the other two indexes have remained almost constant. The implementation of thicker elements and consequently of thicker welds has caused the reduction of occurrence index. Moreover, the decrease of the number of elements and the lower quantity of welding between them have eliminated criticalities. For example, a consequence of this improvement was the disappearance of welding spots. The fall of occurrence caused a shift in values in the Risk Matrix (Figure 21, Figure 22, Figure 23). Remaining criticalities are caused by the connection between tank and flange (Figure 23).

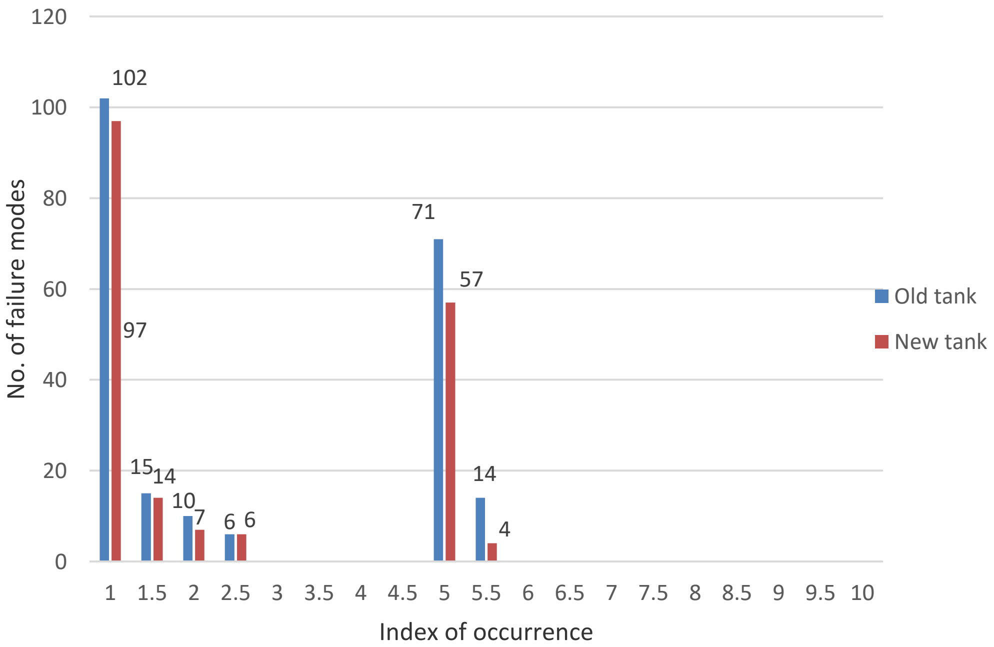

Figure 19. Comparison between Old and New tank respect to the Occurrence

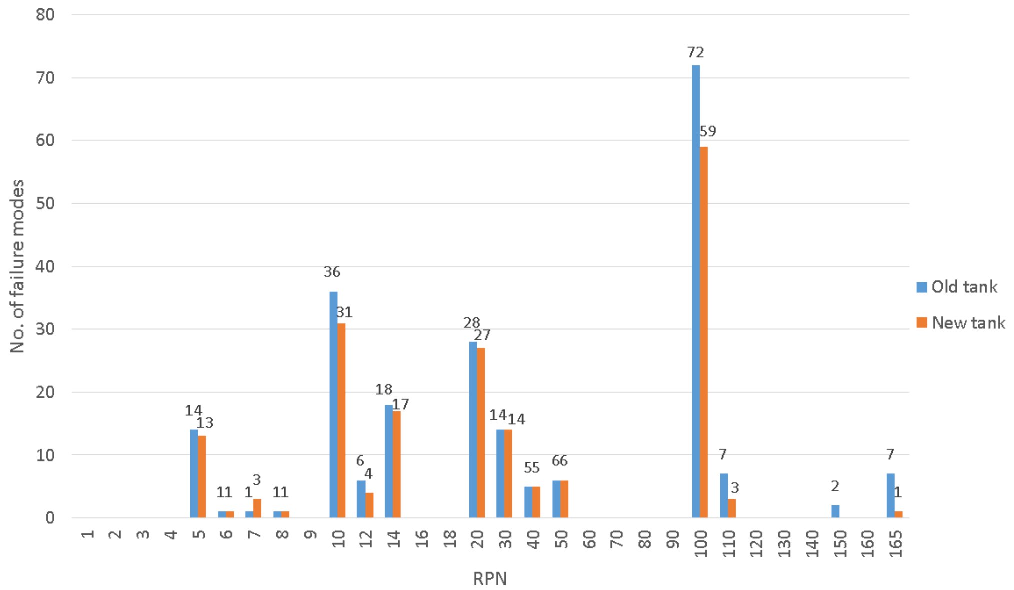

Figure 20. Comparison between Old and New tank respect to the Occurrence

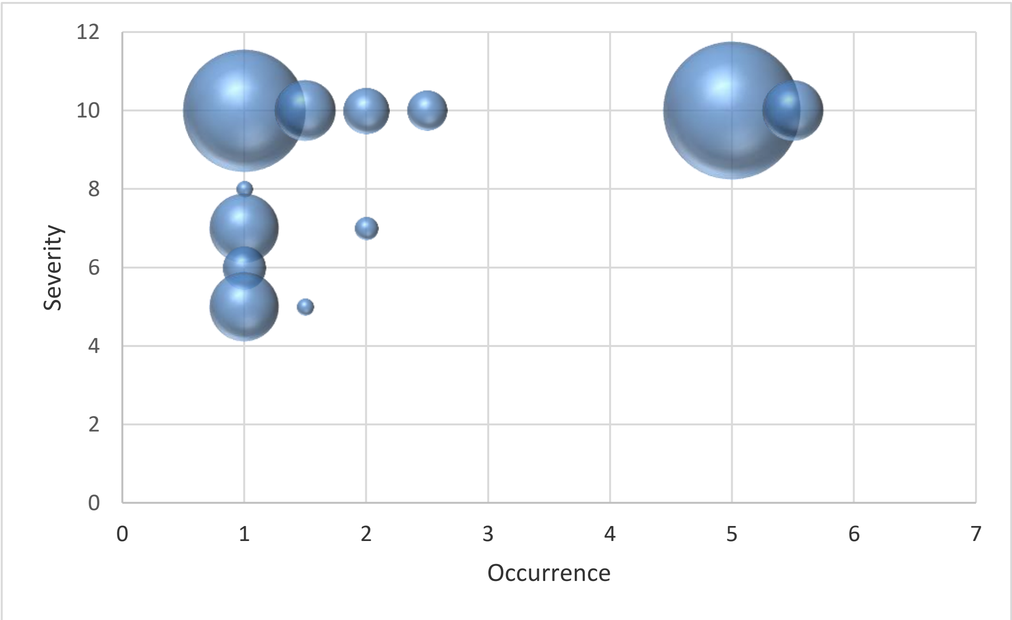

Figure 21. Criticality Analysis of old tank

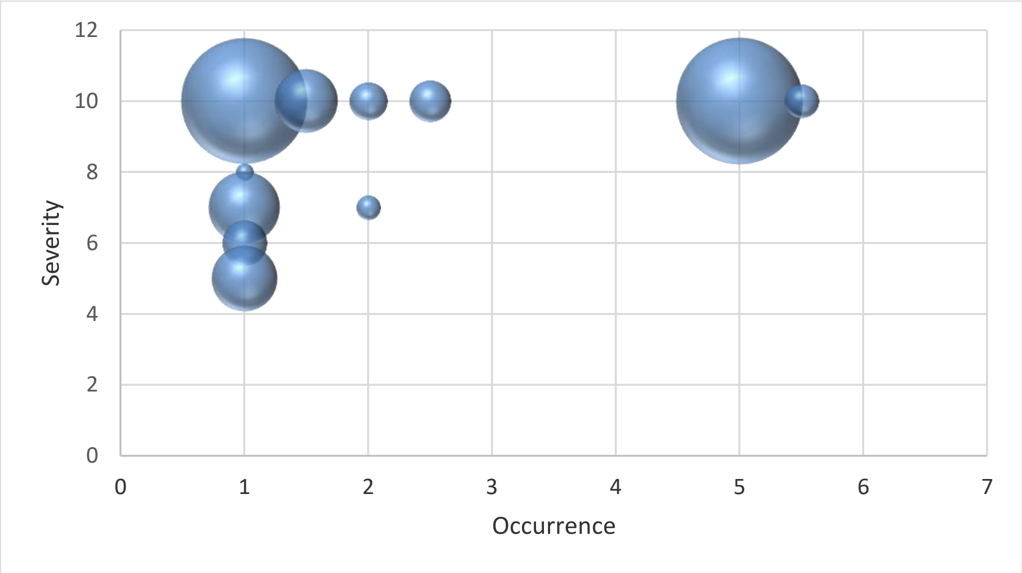

Figure 22. Criticality Analysis of new tank

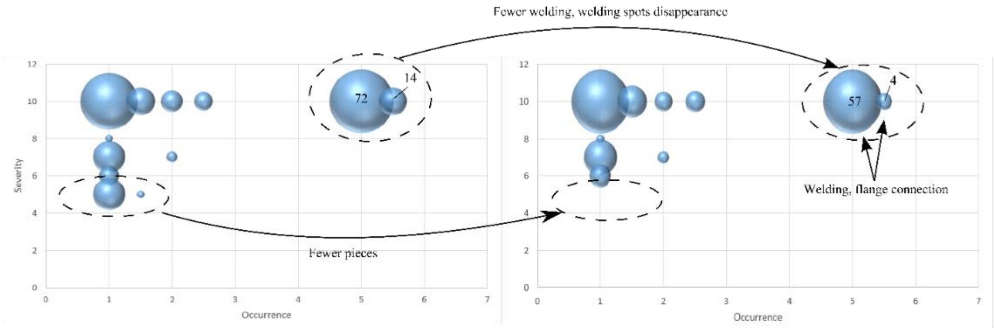

Figure 23. Comparison between old (left) and new tank (right) in term of Severity and Occurrence

5. Conclusions

The results of FMECA were important for various reasons. They have confirmed the correctness of the improvements made on the design of new tanks, namely, the reduction of the number of welding (one of the most critical points) and the increase in thickness accompanied by the choice of an alloy of better quality. Specifically, the failure modes with RPN>100 decreased by more than 28%. In particular, those with RPN>150 decreased by 87.5%. As it regards the Criticality Analysis, the failure modes with Criticality>15 decreased by almost 30%. In addition, they have confirmed the suspicions of the company, which is the critical element in the connection of the flange to the tank. Specifically, the welding of the frame and the gasket are the main cause of problems. Even if the old gasket was replaced by a new double gasket, leakage of fluids is possible. Transducers are put up on the flange and this therefore requires an inspection of the connection, which is already in action.

References:

Arsić Kokić, A., Milivojević, J., Zogović Karajović, M., & Savović, I. (2009). The Role of Eco-Inovation in the Energy. *International Journal for Quality Research*, *3*(3).

Adewuyi, Y. (2001). Sonochemistry: environmental science and engineering applications. *Ind. Eng. Chem. Res.*, 40(22), 4681-4715. doi: 10.1021/ie010096l

Anleitner, M. A. (2007). *The Power of Deduction: Failure Modes and Effects Analysis for Design.* Milwaukee, WI: ASQ Quality Press

Bendell, A., Disney, J. & McCollin, C. (1999). The Future Role of Statistics in Quality Engineering and Management. *Journal of the Royal Statistical Society. Series D (The Statistician)*, 48(3), 299-326. Retrieved on: http://www.jstor.org/stable/2680994

Bignozzi, M. C., Saccani, A., & Fragassa, C. (2016). Experimental Evaluation of the Surface Alteration of Gasket Samples under Operative Conditions. *Tribology in Industry,* Vol. 37, No. 4: pp 482-490.

D'Oliveira, A. (2003). Phase transformation during cavitation erosion of a Co stainless steel. *Materials Science and Engineering: A*, 10. doi: 10.1016/S0921-5093(03)00297-1

Department of the Army. (2006). *Failure Modes, Effects and Criticality Analysis (FMECA) for Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) Facilities.* The Pentagon, VA: DA.

Dias, A. P., Silva, M. F., Lima, N., & Guedes R. (2015). Identification of marks on tires using artificial vision for quality control. *International Journal for Quality Research*, 9(1), 26-37.

Fragassa C (2016). Investigations into the degradation of PTFE surface properties by accelerated aging tests. *Tribology in Industry* 38(2), 241-248.

Fragassa, C, Pavlovic, A, & Massimo, S. (2014) Using a Total Quality Strategy in a new Practical Approach for Improving the Product Reliability in Automotive Industry. *International Journal for Quality Research*, 8(3), 297–310

Fragassa, C., & Ippoliti, M. (2016) Technology assessment of tire mould cleaning systems and quality finishing. *International Journal for Quality Research*, 10(3), 523-546.

Fragassa, C., Giorgini, L., Pavlovic, A., & Zattini, G. (2016). Acid aging effects on surfaces of PTFE gaskets investigated by Thermal Analysis. *Tribology in Industry* 38(4).

Gidey, E., Beshah, B. & Kitaw D. (2014) Review on the evolving relationship between quality and productivity. *International Journal for Quality Research*, 8(1), 47–60

Giorgini, L., Fragassa, C., Zattini, G., & Pavlovic, A. (2016). Acid aging effects on surfaces of PTFE gaskets investigated by Fourier Transform Infrared Spectroscopy. *Tribology in Industry*, 38(3), 286-296.

Ippoliti, M., & Fragassa, C. (2016) Technology assessment of tire mould cleaning systems and quality finishing. *International Journal for Quality Research*, 10(1).

Johnson, S. (2007). Cleaning Molds, Part III Ultrasonics Make Life Easier. *Plastics Technology*, 9.

Levine, M. A. & Kalal, T. T. (2003). *Improving Product Reliability: Strategies and Implementation*. Hoboken, NJ: John Wiley & Sons.

Lipol, L. S. & Haq, J. (2011). Risk analysis method: FMEA/FMECA in the organizations. *International Journal of Basic & Applied Sciences IJBAS-IJENS*, 11(5).

Muralidharan, K. & Syamsundar, A. (2012). *Statistical Methods for Quality, Reliability and Maintainability*. Patparganj, IN: PHI Learning Pvt. Ltd.

National Aeronautics and Space Administration. (1966). *Procedure for Failure Mode, Effects and Criticality Analysis (FMECA)* (RA–006–013–1A). Washington, District of Columbia: NASA

Nolan, D. & Dodson, B. (1999). *Reliability Engineering Handbook*. Boca Raton, FL: CRC Press

Pilli, S., Bhunia, P., Yan, S., LeBlanc, R., & Tyagi, R. (2011). Ultrasonic pretreatment of sludge: a review. *Ultrason Sonochemistry*, 18(1), 1-18. doi:10.1016/j.ultsonch.2010.02.014

Public Works and Government Services Canada. (2011). Failure Mode Effects Criticality Analysis (FMECA). Gatineau, Canada: AECON, Golder Associates Ltd.

Stamatis, D. H. (1989, 1991, 1992). *FMEA training manual*. Southgate, MI: Contemporary Consultant

Stamatis, D. H. (2003). *Failure Mode and Effect Analysis*. Milwaukee, WI: ASQ Quality Press

Young, F. C. (2002). Removing fouling residue from molds in-the-press with CO_2 pellet blasting. *Rubber World*, 227(3), 39-47.

Zattini, G., Pavlovic, A., Fragassa, C., & Giorgini, L. (2016). Characterization of solid residues emerging during ultrasonic cleaning treatments of tire moulds. *FME Transactions* 44(5).

Zivkovic, I., Pavlovic, A., & Fragassa, C. (2016). Improvements in wood thermoplastic composite materials properties by physical and chemical treatments. *International Journal of Quality Research*, 10(1), 205-218.

Cristiano Fragassa
Department of Industrial Engineering, University of Bologna
Italy
cristiano.fragassa@unibo.it

Martin Ippoliti
Department of Industrial Engineering, University of Bologna
Italy