The Method of Selecting the Interval of Functional Tests Taking into Account Economic Aspects and Legal Requirements

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Abstract: *The article discusses the problem of choosing the optimal frequency of functional tests, taking into account the reliability and law requirements, but also the impact of business aspects in the company. The subject of functional test interval is well described for purposes of the process industry. Unfortunately, this is not the case for the machinery safety functions with low demand mode. This is followed by a presentation of the current business approach, which, in order to achieve industrial excellence, monitor their performance through the appropriate selection of key performance indicators. In addition, companies are increasingly exploring potential risks in the following areas: new challenges in advanced risk management, including the perception of the company's facilities as a safe workplace insight of customers and business partners. Eliminating potential hazards is increasingly taking into account, especially the impact of human activity and its interaction with machines. The case study has been presented based on the machines used for the production of tire semi-finished products. In this article, the authors propose a solution for selecting the interval of functional tests of safety functions and additional machine protection measures as a compromise to achieve satisfactory results in terms of safety requirements, performance and legal requirements.*

Keywords: *Functional test, maintenance engineering, parameter, optimisation, safety analysis, time-schedule control, tires*

1. Introduction

At present, there is a sharp increase in the requirements and scope that every enterprise manages. Year after year, the business requirements set by companies are increasing. Those results in finding further areas which can be better managed to get tangible benefits for the company. One of such areas is planned stoppages for maintenance.

Planned maintenance consists of functional test, inspection, cleaning, lubrication, planned replacement of elements, e.g. batteries, condition monitoring.

A comprehensive approach to maintenance and effective optimisation is implemented in companies through the implementation of Total Productive Maintenance (TPM) [1] and the implementation of the Reliability Centered Maintenance (RCM) [18].

In this article, the authors reflect on the testing and optimisation of functional tests. Optimisation of preventive stops is widely described in the literature. Their optimisation is analyzed in terms of incurred costs [21], in short term cost optimisation and long term cost optimisation [3] and time-dependent inspection frequency models [20]. Most of the current articles focus on a narrow range of individual cost optimisations. In industry, in addition to compliance with costs, law, safety standards, workplace requirements, increasingly essential interactions between them and other business risks (e.g. brand strength perceived by customers) are becoming increasingly important. The approach to business management has also changed rapidly in recent years. This can be observed in many changes over the years in standards, e.g. in the quality management standard, which in the latest version of ISO 9001:2015 [8] introduces new, additional requirements of stakeholders. The certification of this standard has now become the basis for company management. However, it still does not cover the entire scope of activities.

For this reason, ISO 31000 [12] and ISO 22301 [11], which cover risk management and business continuity management, were created. The reason for this is that the management process is becoming more complicated than at the end of the 20th century and new threats to companies are being identified. The actual methods presented in the literature do not cover these issues. Therefore, a new policy has to be implemented and the approach has to be modified and adapted.

The authors in this article present a new integrated approach to this subject, based on well-known methodology presented in international standards [4],[6],[9],and the impact of environment and humans aspects to the functional test interval selection. Due to the new risk areas managed by companies, counting the stoppage connected to the functional test interval has also taken into consideration other factors, in addition to the direct costs of stoppages, or the costs of potential defects. They are taking into account the wide range of risks in accordance with ISO 31000. It can be stated that the brand good image loss, costs a company (e.g. an accident at work) much more than the cost of additional machine stops associated with the proof test or functional test. Direct costs and efficiency of planned maintenance can be evaluated through Key Performance Indicators (KPIs). The KPIs can be defined according to international standard ISO 22400 [10].

2. Background

The following tests and fault detection help to detect and remove hidden faults in the safety system. We have three possibilities for failure detection [19]:

- failure detection by automatic (diagnostic) self-tests (including operator observation),
- failure detection by functional test (manual test), e.g. proof test,
- failure detection during process requests/shutdowns.

2.1 Relevance of Proof Test

The term proof test is sometimes used interchangeably with the function test, while some authors consider them to be identical, others see them as different and even use other terms such as functional proof test. As was mentioned the elaborate description about the proof test is given in process industry literature and on this basis. The definition of proof test given is a ''periodic test performed to detect failures in safety-related systems so that the system can be restored to an ''as new'' condition or as close as practical to this condition''[15]. The need for routine maintenance action to detect unrevealed failures is established by the standard, and the proof test is one of these activities. Those tests should be made in conditions as close as it is possible to normal operating conditions of Safety Requirement Specification (SRS). The test has to include all elements of SRS starting from sensors, by logic controllers up to output devices. The proof test has to be complex what means all elements have to be tested at the same time. The term functional testing as used in IEC-61508 [4] part 7 means to "reveal failures during the specification and design phases to avoid failures during implementation and integration of software and hardware". This consequently means that proof test and functional tests have different meanings. Sometimes because of production specificity, there are made tests only of few elements, what is called partial tests. However, also with rare frequency entire tests has to be done. Differences between them arrive in three most important aspects: frequency of tests, percent of failure detection and need to stop complete installation or made during standard work. The partial tests (e.g. visual inspections) can detect only some system failures. The full tests done mainly during overhauls granted restore the system to full operating condition. According to IEC61508-2 [4], the frequency of proof test will be dependent upon the target failure measure associated with the Safety Integrity Level (SIL), the architecture, the automatic diagnostic coverage and the expected demand rate.

2.2 Scope of Functional Tests

In the article, it is assumed that a proof test is one of the functional tests. Functional testing shall include, but not be limited to, verifying the following:

- the operation of all input devices including primary sensors and Safety-Related Electrical Control System (SRECS) input modules;
- logic associated with each input device;
- logic associated with combined inputs;
- trip initiating values (set-points) of all inputs;
- release of alarms functions;
- the speed of response of the SRECS when necessary;
- operating sequence of the logic program;
- the function of all final control elements and SRECS output modules;
- computational functions performed by the SRECS;
- timing and speed of output devices;
- the function of the manual trip to bring the system to its safe state;
- the function of user-initiated diagnostics;
- complete system functionality;
- the SRECS is operational after testing.

For those applications where partial functional testing is applied, the procedure shall also be written to include [15].:

- describing the partial testing on the input and logic solver during operation;
- testing the final element during unit shut down;
- executing the output(s).

There are two ways to minimalise the percentage of planned stops. First is a reduction of the time spent on planned stops which means optimisation and increase the efficiency of works done during those stops. The second way is to maximise the frequency of planned stops. Finding the root cause of failure mentioned in the previous point can result in the elimination of some checking and planned jobs. The most critical to optimise is the time spent on actions required by the law and other regulations. The fact which cannot be neglected is a crucial role of maintenance in maintaining the safety at the appropriate level in operation [22], maintenance and repair stage of overall safety lifecycle [4]. After machine commissioning the maintenance department take care of safety aspects [13] as well as cost criteria what has to be done choosing correct maintenance strategy [14].

2.3. Types of Testing Methods

There exist three general types of systems testing methods:

- Shutdown testing. Cons of this type of test are that demands stop of the whole installation to perform the test. This inconvenience is much more severe in the process industry, but it also affects in other

branches of industry. The second disadvantage is the need to perform the test manually and to record it also manually.
- Bypass testing. On the other hand, for this type of testing, the inconvenience lies in need to disable the safety function during the test and manual testing and to record it manually. The manual test also involves the risk of human error. In addition, additional costs related to bypassing elements are linked to the last item.
- Partial stroke testing (PST). Pros for this type of test is that it can be done automatically and registered automatically. Cons is that it does not give absolute certainty about the operation of tested elements.

In the machinery, the most common type of testing is shutdown testing.

2.4 How to Determine the Test Frequency

At start-up, the operation of the safety function is validated but the safety function must be maintained by periodic proof testing. The full proof test performing a safety function is treated as the undesired stopping of the production process, which reduces production effectiveness. According to the general safety standard 61508 stated that the proof test interval could be determined based on Average Probability of Failure on Demand (PFDavg) value [4]. According to standard PN-EN ISO 12100:2011 product manufacturer should provide information for end-user about the nature and frequency of inspections for safety functions [6]. Unfortunately, in safety manuals frequently can be found no information about proof test frequency or there is a statement that proof test is recommended to be performed at least once per year. The frequently encountered rule is also that Proof Test Interval should not be more than 50% of demand rate. The standards assume that lifetime of the machinery as twenty years. It is based on the assumption that only a few modern systems last more than twenty years without being replaced or rebuilt. It is also assumed that machine controls get at least one proof test during the lifetime.

The proof test is performed as a test of a complete subsystem and not some separate components (subsystem elements) unless the subsystem contains only one element.

Subsystem could include the following elements:
- complex electronic devices, e.g. PLCs,
- electronic devices with the predefined behaviour are, e.g. IO modules,
- electromechanical elements, e.g. relays, contactors.

The obligation for end-user touch three main domain:
- follow the law and regulations,
- follow the safety manuals of the manufacturer of the machines,
- follow the PFDavg and Probability of Failure per hour (PFH) calculations.

The first obligation can be fulfilled partially by applying the rules contained in the Recommendation of Use CNB / M / 11.050 published by European co-ordination of Notified Bodies for Machinery concerning dual-channel safety-related systems with two channels with electromechanical outputs:
- If the safety integrity requirement for safety function is SIL 3 (Hardware Fault Tolerance (HFT) =1) or Performance Level (PL) e (Cat.3 or Cat. 4) then the proof test of this function shall be performed at least every month;
- If the safety integrity requirement for safety function is SIL2 (HFT=1) or PL d (Cat.3), then the proof test of this function shall be performed at least every twelve months.

The excellent example of this recommendation is contactor relays, safety relays, emergency stop buttons, switches which are typically safety devices with electromechanical outputs. Second obligation to perform periodic inspections is given by Directive 2009/104/EC of the European Parliament and of the Council of 16 September 2009 concerning the minimum safety and health requirements for the use of work equipment by workers at work. It is implementation done by national law regulations.

Following the second obligation only in the standard PN-EN ISO 14119 covering interlocks, we can find direct values of test proof interval. For applications using interlocking devices with automatic monitoring, it is stated that for PL e with Category 3 or Category 4 or SIL 3 with HFT equal one functional test should be performed every month. Moreover, for PL d with category 3 or SIL 2 with HFT=1 functional test should be carried out at least every twelve months [7]. In safety manuals of safety equipment, it can often be found that the producer advises or recommend to make a proof test of the device at least once per year or IEC 61511-1:2016 for the process industry states in clause 16.3.1.3:" The schedule for the proof tests shall be according to the SRS. The frequency of proof tests for a SIF shall be determined through PFDavg or PFH calculation in accordance with 11.9 for the SIS as installed in the operating environment." [5]. Also, in IEC EN 61508, it is stated that the proof test interval should be based on the PFD calculations [4]. IEC/EN 62061 states that a proof test interval of twenty years is preferred (but not mandatory) [10]. Recently in many safety manuals, manufacturers write that maximum proof test interval in a high demand mode of operation is twenty years.

The third obligation is assuming those written above, generally consider PL ≤ c or SIL 1. Determination of the optimal frequency of testing poses difficulties in many companies. The mathematical approach is not very common and demands a high level of technical knowledge and familiarity with the standards and safety aspects. Determining the level of safety after the modification of equipment and adapt it to the requirements put technical departments in the face of new requirements and problems [16]. It was assumed that the hardware component with the smallest value for the proof test interval determines the proof test time for the subsystem.

Simplified calculation of *PFD* with perfect proof-test can be obtained as shown below.

$$PFD(t) \approx \lambda_D t \quad (1)$$

where:
λ_D – dangerous failure rate,
t – time.

Assuming that the system is using non-repairable elements in configuration 1*oo*1, equation receives following form equal:

$$PFD_{avg1oo1} \approx \frac{1}{2}\lambda_{DU}T_I \quad (2)$$

where:
λ_{DU} – dangerous undetected failure rate,
T_I – proof test interval.

Values of the failure probability requirements are required for the whole safety function, including different systems or subsystems. The average probability of failure on demand of a safety function is determined by calculation of PFD_{avg} for all subsystems, which as a whole create safety function.

The end-user of the safety-related system has to make an analysis of PFD_{avg} based on the data received from the producer of each part of the safety-related system.

2.5. Measuring Production Efficiency

The efficiency of a production plant can be evaluated through KPIs. This method is widely utilized in many companies. Recently definition of KPIs was defined by international standards, e.g. ISO 22400 [10]. KPIs in manufacturing facilities are ranked according to many categories. Indicators are reflected in the objectives of the plant. They play the role of a performance measure of plant operations. Typically, they are different at different levels of business management. Their right choice often determines the success of the company. KPIs can be implemented in all types of industries, including machinery, continuous and batch processes. Proper selection of indicators allows for quick identification of losses. The key maintenance indicators set out in standard ISO 22301 allow for increased dynamics in maintenance operations.

2.6. Impact of Risk Management on Business Operations

As presented earlier, the role of quality management in improving business performance is growing year by year. This is due to strong market competitiveness and comparable technical solutions used in both machines and processes. In many situations, manufacturers purchase machines from third-party companies, which means that competitors have the same machine park. Therefore, in order to be competitive, companies work on improving management efficiency, which will increase revenues and thus profits. In order to be effective, the aspects of management analysed by the author must represent all the opportunities and threats that arise. This is an essential development in the approach to analysis proposed by ISO 9001: 2015 [8]. As a result of these changes, the management models presented in the past have recently been expanded with the identification of internal and external risks. Risk management can be performed at any level and type of business activity. The process of risk identification consists of searching, identifying, classifying sources of risk and dangerous events, taking into account their causes and effects. The risk identification process may be based on various sources of information, such as historical expert knowledge, theoretical analysis and risks arising from stakeholder needs [2]. The risk management may also include business continuity management described in ISO 22301 [11]. In this article, the solution proposed by the authors takes into account the results of the risk management process analysis. This is due to the fact that many procedural imperatives have their origin in the results of risk analysis. An example can be the instructions that oblige departments to perform a monthly functional test. The frequency of these tests does not result from the risk analysis of the safety function, but rather from minimising the risk of an accident at work.

3. Proposed Solution

As it was presented in previous chapters, a test of machinery issue is not precisely defined taking into consideration three crucial factors: law and standards requirements, new aspects of risk analysis, the increase in productivity.

The proof test objective is to discover critical errors not found by the diagnostics. Definition of proof test frequency is stated as diagnostics of components, sub-systems and whole control systems. Is intended to determine their state in the formulation of the assessment of the willingness to perform safety functions. The proposition consists of two elements:

a) The proposition of test interval for machinery;
b) Method of estimation additional risk influences into proof test frequency for low demand mode.

The first part of the proposition helps to increase the productivity of the machines by standardisation of test frequency. The second part takes into account the risks defined by a broader approach to company risk management [17].

3.1. A Proposal for Estimating Test Intervals for Machinery

The variety of applications in many sectors of industry required periodic proof testing and functional tests. There is a gap in the law and standards in explaining the frequency of functional tests, proof tests and shutdowns used to detect failures. This mainly affects the functions of SIL 1. As is apparent from the literature, the user defining a functional test must rely on the data provided by the machine manufacturer.

Tab. 1. Recommendation for test periods for machinery

Preconized test interval	Source	SIL (EN 62061)	HFT (EN 62061)
1/year	Authors	1	1
	CNB / M / 11.050	2	1
1/month	CNB / M / 11.050	3	1

Frequently proof test interval is estimated by the manufacturer to twenty years. The second source of information can be historical data about the frequency of demands for the safety-related action of the Safety Related Part of the Control System. Based on this data, the frequency may be changed. The first component of the authors' proposal is presented in Table 1.

3.2 Assessment of the Impact of the Identified Risks on the Frequency of Proof Test in Low-Demand Mode

For some machines equipped with safety function and complementary protective measures working in low demand mode because of construction, the specification of production, ergonomics, lack of space happens that safety functions or complementary protective measures can be activated incidentally, e.g. forklift attacked safety mate, product fall and activate safety line. This provokes that machine stops because of function activation. The more dangerous is the situation, where this function was not activated, and only some mechanical parts were defected. That in the future can result in incorrect operation of the safety function. Usually, operators should alert maintenance stuff, and after verification, the machine can be given back for production. This situation has taken place in general but taking into consideration human errors (e.g. incidental impact by a forklift), based on the author's analysis quarter of such incidents are not reported [17]. To assure that safety function or complementary protective measures are still able to fulfill its function authors propose to made additional estimation shown in Fig. 1 [17].

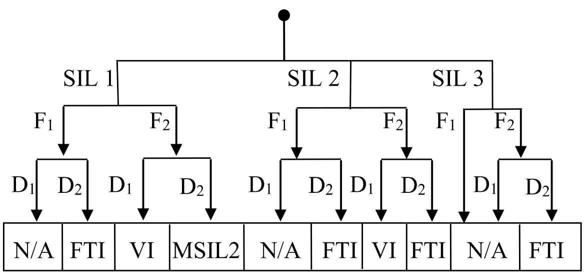

Fig. 1. Graph of additional action estimation for machines working in low demand mode

where:
- Safety Integrity Level: SIL1, SIL2, SIL3.
- The frequency of unplanned activation of the function: F1 – seldom to less often; F2 – frequent;
- The possibility of detection eventual damages without stopping machines/production line: D1 – possible; D2 – practically impossible;
- Action: N/A – No action necessary, VI – Visual inspection, FTI – More Frequent Time interval; MSIL2 – Modification to SIL2;

The presented analysis took into account three categories: SIL of the system and dived it into three scopes. First for SIL1, the second one for the SIL2, and the third one for SIL3.

The second category is the frequency of such unintended safety function activation. It is divided into seldom and frequent. The third category is the possibility of eventual damages detection without stopping the production line or machine. This category is divided into possible to detect cases and impossible to detect without stop events.

As a result, it can be obtained four possible scenarios. First with the lowest risk finish with no actions. The second result is adding into maintenance preventive plan additional visual verification of safety function elements, or complementary protective measures elements state. The term complementary safety measures are used in ISO 12100 standard and are used to avoid or to limit the harm [6]. Example of this can be emergency stop systems. The frequency of that inspection should be not less than twice as often as the period between two proof or functional tests. The third action is requested to modify the elements to fulfill the requirements of SIL2. The last scenario is an increase in the frequency of proof or functional test interval. The frequency of the test should be not less than twice the period between two known accidental activation.

4. Case Study – Tire Cord Treating Line

The chosen for case study object is a modern single end impregnation line used to treat yarns made of polyamide, polyester, viscose and other raw materials so they are suitable for applications – use in tires. The pull roll section is a part of a line analysed in this case study.

Following a risk analysis (Failure Modes, Effects and Criticality Analysis), one safety function and two complementary protective measures were identified in this section of the production line. The safety function secures by restricting access to the machine's rotating parts and parts with ingress angles. The first complementary protective measures role is to prevent the hand or forearm from being caught by the thread of textile cord by installing a cable pull safety switch. The second is a typical emergency stop button. The safety function has SIL 2. The other two complementary protective measures have an estimated SIL1. It can be calculated from the manufacturer's data that each of the given safety functions and supplementary measures has reached the factory SIL level (SIL 2, SIL1, SIL1).

In the course of the productivity loss analysis, one of the elements of the maintenance work – preventive maintenance time causing downtime – was identified as one of the leading productivity losses. This indicator shows that a company loses three hours of production per month for a given machine (including procedures for stopping and starting machinery). In order to improve this result, it was decided to analyse the indicated machine according to the model presented above.

The first supplementary measure, which prevents staff from being caught by the threads of a textile cord, based on the reliability data of the components of this function, has a functional test equal to a service life of twenty years, which means that there is no need for a control test of this function. The analysis proposed by the authors has been carried out taking into account the facts of risk management.

During the analysis it was assumed – SIL1. The analysis of entries to the Computerized Maintenance Management System application and conversations with both production operators and maintenance staff shows that an unintentional activation of complementary protective measures by the operator or product takes place on average once every twelve months. Therefore, it can be qualified to group F1. The last analysis criterion, which is the possibility of detecting a defect, was assessed as practically impossible to detect.

Based on the estimation of additional actions (Fig. 2), it can be concluded that it is necessary to change the time interval of the functional test. Taking into account the frequency of activation of the function and damage, on average once a year it is proposed to double the frequency of activation – which corresponds to six months. In conclusion, the result of the analysis is to change the functional test interval to six months. The company's profit can be estimated as an additional 30 hours of machine operation per year and minimisation of the risks identified in the risk analysis.

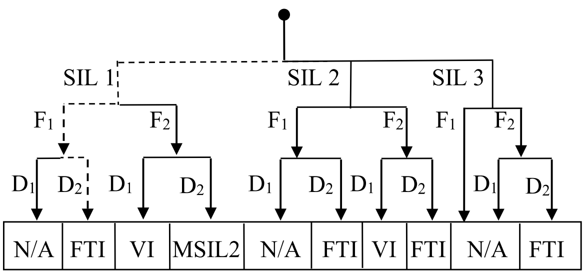

Fig. 2. Graph of additional action estimation for a first complementary measure of a section of impregnation line working in low demand mode

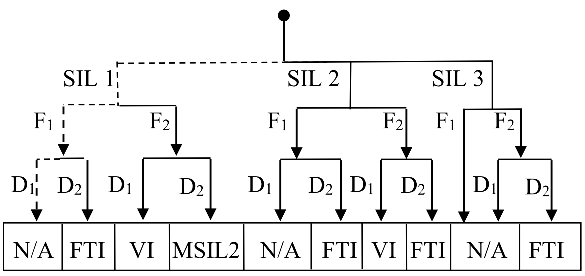

Fig. 3. Graph of additional action estimation for a second complementary measure of a section of impregnation line working in low demand mode

Second complementary measure – emergency stop. The frequency of use is rare, and detection was quantified as possible. For this reason, no additional action is necessary (Fig. 3). Also, in this case, the manufacturer gave T1 value to twenty years. Concluding there is no proof test necessary during the lifetime of this function. According to the authors proposition (every year test for SIL1) time the functional test of that complementary measure is done in the double frequency as the first one.

The case study is based on pull roll section with the safety function of door locking and monitoring. The required Safety integrity level is the result of a risk assessment and refers to the amount of the risk reduction to be conducted by the safety-related parts of the control system. Part of the risk reduction process is to determine the safety functions of the machine. Safety function which protects by restricting access to the cabinet has estimated SIL2 based on SIL assignment matrix proposed in the EN 62061 standard. The severity of the injury was estimated as level 3. Frequency and duration with note 3, the probability of hazard event as possible and note 4, avoidance as possible with note 4. Cl=Fr+Pr+Av=3+4+4=11 (Fig. 4).

Severity (Se)	Class (Cl)				
	3-4	5-7	8-10	11-13	14-15
4	SIL2	SIL2	SIL2	SIL3	SIL3
3			SIL1	SIL2	SIL3
2				SIL1	SIL2
1					SIL1

Fig. 4. SIL assignment matrix for the analysed safety function

Safety function with value SIL2. Analysing available data was assumed that the frequency of unplanned activation is frequent, and the detection of possible damages is possible without stopping the machine. The following proposed method can be estimated that additional action, in this case, is additional visual inspection (Fig. 5). As the average frequency of unplanned activation or damage was estimated to six months, visual inspection of that element was planned for three months. Manufactures data presents the T1 value for proof test interval as 20 years. So, there is no need to plan an additional test for this element. According to authors proposal, functional test is completed with the frequency of twelve months.

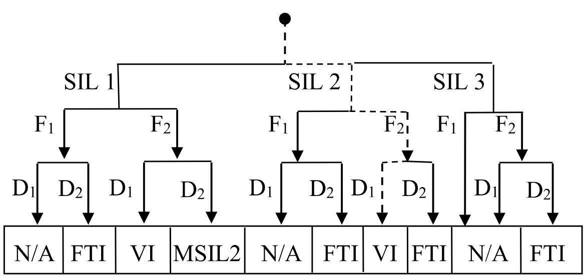

Fig. 5. Graph of additional action estimation for defined

safety function of the cord twisting machine

Summarizing achieved results can be stated that the use of the proposed method was achieved two goals. First, the rules of functional test frequency become clear from a user point of view. Based on risk analysis and manufacturer data, level can be stated required SIL and SIL achieved by the installation. With this information based on Tab. 1 user can stated recommended frequency. This influence into minimalisation of time spends into preventive maintenance. What in consequence increase productivity KPIs.

Second, a graph of additional action estimation helps the user to minimalise additional risks not covered before. The tool is easy in use and can be easily utilised by maintenance or responsible for safety personnel. Implementation of actions defined in proposed graph influence on results of risk analysis made at the different level of company management according to ISO 31000 [12].

5. Discussion

The proposed solution allows to provide the required SIL, taking into account the aspects of risk management in the company, which are not taken into account when calculating the SIL according to IEC 62061 [9]. This method takes into account EU recommendations and provisions of the standards. Additional verification or a shorter frequency of proof tests allows to minimize the risk of the performance level decreasing over time. The third important thing is to combine the frequency of the different tests in order to minimise machine downtime and consequently minimise production lose. The tools take into account the impact of the environment in the operational stage of life cycle. The tools presented above are a new approach taking into account the experience of the authors.

At the same time, it is recommended that an analysis of the causes of unintentional SIF activation be carried out, in order to eliminate the root cause of the increased risk. An in-depth analysis and subsequent action plan can eliminate this cause, which will result in a return to a regular interval.

6. Conclusion

The tool presented by the authors serves to improve the productivity KPIs defined above, helps to optimize the functional and proof test intervals taking into account specific aspects of risk management. This tool is the authors' response to problems encountered in their professional practice and takes into account typically practical aspects. An important point to emphasize is the fact that many safety system manufacturers assume that the mission time of the machines is twenty years. This fact must be taken into account by the user for machines that are already around twenty years old, as they have to prepare for the wear-out phase of the systems. Other conditions, which could be included in new versions of the risk management or quality management standards, may necessitate changes to the proposed method. This tool has been used several times so far and further testing is needed to confirm its effectiveness in different cases.

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