Emerging Good Maintenance Practices in Italian Seveso Sites: Analysis of Experiences from an Industrial Case Study and from a National Near Miss Repository

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In Italy, industrial establishments with major-accident hazard are subjected to Seveso Directive to ensure effective safe conditions. This necessity also leads involved companies to regularly record accidents and near misses, even reported during the periodic inspections carried out by the competent authorities.

The analysis of these data typically points out a significant role of maintenance activities. Previous field investigations also showed that several high-risk industrial sites are more and more trying to refine and improve their maintenance habits, even by the introduction of new methodologies and dedicated software, increasingly based on the use of modern and interactive technologies.

The present work therefore aims to analyse new and efficient maintenance practices currently emerging in the Seveso industries, to start identifying good practices to be shared in the field for increasing safety.

For this purpose, two activities are carried out in parallel. Firstly, an Italian LPG storage is taken as case-study where new recently applied maintenance procedures are analysed. At the same time, a wide range of near miss events is extracted from an Italian national near miss repository (EsOpIA). These events are analysed in aggregate form, to describe and quantify the role of maintenance procedures in occurrence, managing and prevention of near misses and accidents in a wide variety of major-accident hazard establishments, especially in order to verify the actual potentiality of the study on a large scale.

1. Introduction

Industries with major accident hazards, as chemical and nuclear plants, are very complex systems potentially prone to serious accidents, since they deal with significant amounts of hazardous materials that can undergo releases with possible subsequent effective ignition. Moreover, they could be subjected to unexpected situations that cannot be treated through conventional hazard identification procedures. In Italy such industrial sites fall within the scope of Legislative Decree 105/2015, that is the Italian transposition of European Seveso III Directive, and they are therefore subjected to mandatory inspections.

In this kind of contexts, a correct management of maintenance procedures has a fundamental role to avoid accidents and guarantee safety both in the site and in the surrounding environment. Literature reports that a poor maintenance can significantly increase the rate of accidents, for example in relation to electrical failures (Vallerotonda et al., 2022). At the same time, the analysis of operative experiences, emerging from accidents and near miss data traced historically by companies, is recognized worldwide as a useful instrument to prevent catastrophic accidents, as demonstrated by European studies (Fabiano and Currò, 2012; Ansaldi et

al., 2021) and also in USA by the work by Awolusi and Marks (2015), who highlighted the importance of training for supporting workers in recognizing and reporting near misses in the local iron and steel industry. Scientific literature has proved that near miss analysis can provide important information on such strategic role of maintenance activity. Nowadays, maintenance 4.0 constitutes a well-structured infrastructure that can be enhanced by using Internet of Things (IoT), artificial intelligence and cloud computing (Di Nardo et al., 2021). Web smart solutions can help in alerting the operators when an alarm occurs on a machine through notifications and then by providing instructions for solving the alarm; in parallel, augmented reality can help in superimposing information on the physical layer and, at the same time, in allowing the workers to operate on the plant with free hands (Bottani et al., 2021). There is a widespread interest in smart maintenance and in a maintenance able to manage assets with a proactive and holistic approach (Hansler et al., 2022).

In some cases, implementation of intelligent predictive and data-driven maintenance, supported by 4.0 key enabling technologies, has been already realized in the Italian manufacturing industry (Stefanini et al., 2022), but preventive maintenance seems to be still dominant (while substituting pure corrective maintenance) and this is even more true for high-hazard industries. Ghasemi et al. (2023) suggested that each company needs to identify safety-critical equipment, that is equipment whose failure or malfunction contributes to a major accident, and to choose a methodology for correctly prioritizing maintenance, mainly based on failure probabilities, failure consequences or both (risk-based approach). The latter was recently applied in petrochemical plants considering operational impact, operational flexibility, maintenance cost and impact on safety and environment as main elements for risk evaluation of assets failure (Jaderi et al., 2019).

However, the scientific literature suggests that the peculiarity of the contexts at risk of major accident is the need to evaluate not only the advantages, but also the possible contraindications of a too frequent maintenance. Back in the '90s, Vaurio (1995) detailed a systematic procedure for optimizing test and maintenance intervals by minimizing the total testing and maintenance costs while satisfying a risk criterion. In its wake, Okoh and Haugen (2013) observed that maintenance may have a negative effect on barrier performance if the execution is not correct, uncomplete, delayed or excessive. They finally proposed a scheme (the so-called Work and Accident Process (WAP) scheme) for classification of maintenance-related causes of major accidents in the hydrocarbon and chemical process industries. More recently, Vinnem et al. (2016) gave some recommendations for achieving an optimum balance in maintenance between prevention and increase of risk in petroleum process plant systems. They noted that the emphasis on short maintenance intervals is often excessive, while, for example, planning of preventive maintenance should consider maintenance-induced leaks in addition to the focus on trade-off between maintenance interval and failure probability, on a case-by-case basis. The risk factor potentially added by maintenance activity is also related to the human factor, therefore some methodological approaches have been already proposed to identify and reduce human errors in maintenance activities (Sheikhalishahi et al., 2017), especially when they are performed under various and often harsh circumstances (Zarei et al., 2021).

Based on these findings, the present study arises from the need to investigate the actual role of maintenance activities in Italian Seveso industrial sites, to be shared in the field for increasing safety while highlighting current and emerging virtuous maintenance practices. Starting from the analysis of a wide series of unwanted events stored in the INAIL near miss repository "EsOpIA" and from the experience of an industrial Seveso site, the optimization criteria for maintenance intervals and the role of new technologies will be highlighted.

2. The industrial case-study: an LPG storage site

The "AGN Energia" site in Fontevivo (Parma area, in Italy) deals with receiving, storing, bottling and shipping LPG, which is unloaded from rail tankers by compressors, then transferred to mounded vessels and finally pumped into tankers for subsequent distribution and combustion or transport use. The storage site falls within the scope of Legislative Decree 105/2015, with a total storage capacity of almost 4000 m^3.

In a previous work (Di Girolamo et al., 2023), a dataset of 65 quasi-accidental events occurred in the period 2012-2021 in this site (extracted from the operating experiences of the company for Seveso inspections) was analyzed and a dominant role of maintenance was observed in 60 of those events.

In the present study, an initial more in-depth analysis of the same data has allowed to highlight some more specific aspects from the maintenance point of view. In most of the 60 events, maintenance service was called to remedy the cause of the anomaly (e.g. releases from pumps, compressors or from metallic arms during loading and unloading phases), through replacement or repair of the equipment and subsequent verification of the preventive maintenance program. In 3 of them, instead, the maintenance technician directly found out and reported the anomalies during scheduled controls. Sometimes, after maintenance, it was chosen to send machines (pumps or compressors) to complete revision. The general approach to maintenance has always been conservative and, where necessary, even redundant (spare machines). Thanks to the good economic availability of the company, it results in fact often convenient to replace rather than repair the equipment. As a

result of the undesirable events, in several cases it was decided to introduce the long-term monitoring of similar components and to start to consider the working hours (as indicated in the manufacturer's User Manual) by installing meters of operating hours on pumps and compressors. Maintenance operations are subject to work permit regime, in accordance with the procedure of the Safety Management System, in order to ensure safety during the execution. All maintenance interventions and their results are recorded.

In a second moment, the topic of the maintenance in the company has been ulteriorly deepened, through an analysis of the technological instruments that today it uses for managing automatically and in real-time the maintenance timings. A cloud-based software, able to monitor maintenance of critical elements and fire and emergency equipment, as well as audits deadlines, is used. The software operates through a web portal, where all equipment, deadlines and reports can be visualized by operators; moreover, the administrative area can insert/modify equipment and checklists and preload deadlines. A coloured sticker, for each equipment, shows if there is no expired activity nor anomaly (green), if there are deadlines maturing in the current month (orange) or if there is an expired activity or an anomaly in progress (red).

In addition, operators can easily interact with the equipment using QR codes and tablets to check its status. The software assigns for each element the checks to be carried out according to a predetermined program and proposes special check lists previously drawn up according to UNI standards or to the Use and Maintenance Manual. The tablet is used by both internal and external operators to generate reports of maintenance and there is the possibility to load documents with the references of the manufacturer regarding maintenance of each single equipment, normative references or operating experiences. Operators can receive emails in case of equipment problems and get a full reminder of all deadlines.

The identification of critical plant components is carried out based on the data contained in the Plant Safety Report. For this kind of site, critical components are mainly LPG tanks, pipes, pumps, compressors, valves, tanks level/pressure control systems, equipment for loading and unloading, pneumatic emergency system, gas detection system, accelerometers, electrical plants, odorization plant and draining system.

Preferably maintenance is carried out outside the site, to reduce risks introduced by external operators. All external maintenance technicians must be trained before entering the plant, to operate in safe conditions. The site manager provides the necessary information to the personnel involved in the intervention.

At first, maintenance is usually carried out in accordance with the instructions given by the manufacturer in the Instructions Manual. Then, the frequency of preventive maintenance checks can be updated based on experience, when it is not sufficient to consider only the number of working hours indicated in the Manual.

3. Analysis of experiences from a national near miss repository

The INAIL archive "EsOpIA" (Operational Experiences and Artificial Intelligence) can index, through machine learning algorithms, the operating experiences of plants at risk of major accident, collected during Seveso inspections and mainly including near-miss events. The model built in EsOpIA allows to extract information in a more targeted way than a classic database, because for each event the machine learning algorithm can identify concepts and representing the event in the form of entity-relationship graphs (Ansaldi et al., 2021). The EsOpIA database allows the user to search for individual words, groups of words or phrases that the machine learning algorithm reworks in terms of natural language.

3.1 Analysis criteria and methodology

Unwanted events (near-misses and minor accidents), that touched Italian Seveso plants and involved maintenance activities, were the objective of the study. A search of the word "maintenance" was set in EsOpIA, finding 1445 events in the period 2000-2022. Then, filters were applied to limit the analysis to the period 2019-2022, taking a picture of the most recent situation and finally finding 10 events in 2022, 53 events in 2021, 67 events in 2020 and 72 events in 2019, for a total of 202 events out of the 5785 ones at that time contained in EsOpIA. The database is constantly being updated and new data from other Seveso inspections are being introduced. It can be observed that the number of identified events is gradually reducing while approaching our days, since the updating of the database is progressive. The selected events were inserted into a spreadsheet where they have been analyzed by referring to specific attributes (Table 1). A lot of high-risk industrial activities and different typologies of anomaly are specified. It can be observed that maintenance assumes four different roles in the analyzed events: it can act as a safety barrier (through (i) an intervention following anomalies or (ii) an anomaly report made by the maintenance technician) or as a risk increasing factor (through (iii) an error made by the maintenance technician or (iv) an accident occurred to him).

3.2 Analysis results and discussion

All quasi-accidental events have been classified by applying the abovementioned attributes. Most of the identified events (81%) fall into the categories of severity levels 1-2, i.e. those with a reduced impact, but even

small releases of dangerous substances can be precursors of serious accidents. At the same time, cases of more severe events have been observed, e.g. releases of substance in significant quantities (12%) and fires (5%). Many high-risk industries are included in the analysis, as shown in Figure 1, with a prevalence of events in chemical plants (24%), LPG storage sites (18%) and pesticides and fungicides industries (13%).

Table 1: Attributes for classification of unwanted events

| Attribute	Description
Year	Year of event occurrence.
Activity of the industrial site	Seveso industrial areas: Mining; Ferrous metals; Refineries; Fuel storage; Explosives; LPG; Storage and distribution; Pesticides and fungicides; Fertilizers; Waste; Chemical plants; Plastics and rubber; Other activities.
Brief event description	Short title used to quickly identify and understand the event.
Event severity	Severity level according to the consequences of the event: 1 = no injury, no damage, no release of dangerous substances; 2 = no injury, no damage, small releases of dangerous substances; 3 = no injury, damage to property or equipment, no loss of containment; 4 = significant release of dangerous substances, but without injuries; 5 = minor injuries, with release of dangerous substances; 6 = event with further consequences on the surrounding environment.
Event typology	The typology of the anomaly that was observed, eventually giving rise to a possible chain of events: Accident with ignition; Release of dangerous substances; Abnormal behaviour of machines/components/processes; Abnormal behavior of alarms, sensors or control electronics; Observation of worn, damaged or defective mechanical components.
Actions taken and programmed	Interventions applied immediately to solve the anomaly or programmed at medium/long term in order to prevent similar events.
Role of maintenance	Function assumed by maintenance in the unwanted event: Barrier (intervention following anomalies); Barrier (maintenance technician reporting anomalies); Risk increasing factor (of accidents produced by the maintenance technician); Risk increasing factor (of accidents occurred to the maintenance technician).
Need for improvement of current maintenance procedures	Evidence of the need for the company to modify its maintenance procedures: Yes; No.
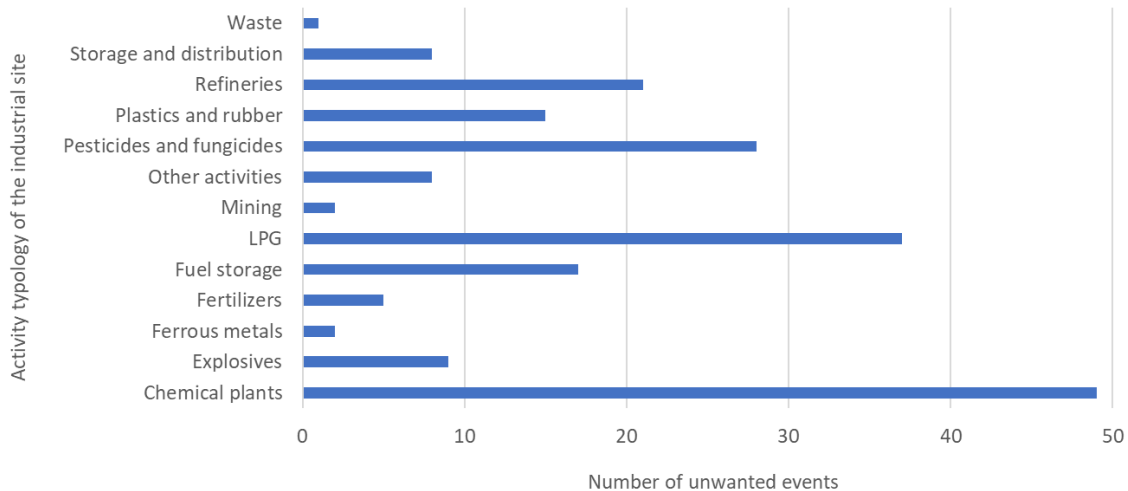
Figure 1: Number of events extracted from the EsOpIA database for different Seveso industrial areas

The abovementioned distinct roles of maintenance (safety barrier or risk increasing factor) seem to be fairly evenly distributed across all types of unwanted events, as shown in Table 2, and the most frequently assumed role is that of barrier (86.6% on the total of events). The remaining percentage of cases, where maintenance produces an increased risk, includes, for example, cases of not completed maintenance tasks, also performed inaccurately or without considering the concomitant risks related to the specific work environment. In 3.5% of

cases, the maintenance technician is instead involuntarily the object of quasi-incidental or incidental events that arise in the site during his stay, without him being the cause.

Table 2: Distribution of the roles assumed by maintenance on the different typologies of unwanted events

Role of maintenance - Event typology	Percentage of the total events	
Barrier (intervention following anomalies)	76.7%	
- Abnormal behavior of alarms, sensors or control electronics		18.7%
- Abnormal behaviour of machines/components/processes		20.0%
- Accident with ignition		4.5%
- Observation of worn, damaged or defective mechanical component		11.6%
- Release of dangerous substances		45.2%
Barrier (maintenance technician reporting anomalies)	9.9%	
- Abnormal behavior of alarms, sensors or control electronics		30.0%
- Abnormal behaviour of machines/components/processes		5.0%
- Observation of worn, damaged or defective mechanical component		45.0%
- Release of dangerous substances		20.0%
Risk increasing factor (of accidents occurred to the maintenance technician)	3.5%	
- Abnormal behavior of alarms, sensors or control electronics		14.3%
- Release of dangerous substances		85.7%
Risk increasing factor (of accidents produced by the maintenance technician)	9.9%	
- Abnormal behaviour of machines/components/processes		15.0%
- Accident with ignition		25.0%
- Observation of worn, damaged or defective mechanical component		5.0%
- Release of dangerous substances		55.0%

Considering only the four types of site activity with the highest number of events (Figure 1), the role of maintenance as a barrier maintains an 81.0% in refineries, a 79.6% in chemical plants, while reaching 100% of cases in LPG plants as well as in pesticides and fungicides plants. The analysis also showed that the most common event typology is the release of dangerous substances (45.0% of cases), followed by the abnormal behavior of alarms, sensors or control electronics (17.8%) and the abnormal behaviour of machines/components/processes (17.3%). Moreover, 17% of the accidental or quasi-accidental events have produced a consequent necessity of improving the maintenance procedures (i.e. introducing new controls or changing the timing of the existing ones), confirming that the historical analysis of near miss contributes to highlight organizational deficiencies that can be remedied.

In a previous work by some of the authors (Carra et al., 2023), dedicated to the identification of the role of human error in accidents and near-accidents occurred in Italian LPG storage sites, it already appeared evident that 63% of events depended on lack of maintenance, faulty plant components and wear of components. This significant quantity mainly included two types of situations: (i) an 82% of cases in which defects or aging of the components were considered "in the norm" or unpredictable and therefore simply manageable through appropriate stocks of spare parts or extemporaneous maintenance operations; (ii) a remaining 18% of the cases in which real maintenance deficiencies have emerged, such as to require organizational interventions also in the medium and long term, in order to compensate the human error involving the corporate figures who deal with the procedures management and maintenance programming. The present analysis confirms such trend, since in several cases maintenance procedures are updated and improved after the unwanted events.

It is therefore desirable to spread good maintenance practices and to potentiate them by using a modern dedicated software, as the one previously described in the analyzed case-study. In installations at risk of major accidents, the need to ensure safety makes mandatory - in practice - all checks, not only the statutory ones. The main goal should be managing maintenance to achieve an optimum balance between prevention and increase of risk, while in these sites, typically, costs optimization is not a priority with respect to safety.

4. Conclusions

Near-misses and minor accidents which occurred in a group of several Seveso plants in the period 2019-2022 have been retraced historically by the INAIL archive "EsOpIA". In parallel, the case study of a virtuous LPG storage site has been described with a focus on how maintenance times and deadlines are regulated and real-time controlled through a modern web portal software. The focus was on events where maintenance had emerged as a key element in resolving anomalies and/or preventing similar problems. The events have been classified and compared through a defined set of attributes, showing that maintenance is a fundamental safety

barrier, but it can also become a potential source of additional risk. This aspect should not be underestimated in the phase of identifying the optimal maintenance intervals and of establishing the working procedures for external operators, while cost constraints often represent the main constraint in other industrial contexts at a lower level of risk. In addition, it appears clear that in many cases the analysis of quasi-accidents has encouraged a change and an improvement in maintenance procedures.

The analysis of the industrial case study also confirmed that maintenance intervals, initially estimated according to equipment manufacturer's specifications (in addition to the statutory deadlines for mandatory verifications), can and should also be updated based on accidental or quasi-accidental experiences.

The use of special cloud software supported by tools for direct interaction with equipment (e.g. tablet for reading QR codes), which give operators an immediate perception of the maintenance status of the equipment, can certainly facilitate an optimized and safe management of plants in high-hazard industrial sites. Future work could include the verification of the diffusion of similar software for maintenance management in other Seveso companies and the identification of application cases in which predictive maintenance, supported by additional dedicated monitoring systems, may have replaced preventive maintenance.

Acknowledgments

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