STUDIA UBB CHEMIA, LXVIII, 1, 2023 (p. 265-274)
(RECOMMENDED CITATION)
DOI:10.24193/subbchem.2023.1.19

PREVENTIVE AND PREDICTIVE MAINTENANCE OF AMMONIUM NITRATE GRANULATION PROCESS BASED ON PRELIMINARY HAZARD ANALYSIS TECHNIQUE

Ramona LEORDEAN[a], Alexandru OZUNU[a], Zoltán TÖRÖK[a,*]

ABSTRACT. A technological accident in a fertilizer production plant often results from the interaction between several hazards. Preliminary Hazard Analysis (PHA) being a general level, qualitative method, it is easily applicable for all types of operations and functions of a system. The objective of this paper is to demonstrate the importance of using PHA in the context of preventive and predictive maintenance, and to highlight the potential benefits of these strategies in mitigating the risks of potential accidents related to the granulation process of fertilizer grade AN. The results of the study show that the most dangerous scenarios identified, in terms of consequences, are potential explosions of AN due to friction and melting in case of rotative equipment failure, or auto-decomposition and explosion of AN due to contamination with organic substances. Since qualitative deterministic approaches are lacking in uncertainty and sensitivity analysis, their use should be completed by more complex quantitative analyses, in order to support efficient decision making for risk mitigation and balanced maintenance efforts.

Key words: *ammonium nitrate, granulation process, preliminary hazard analysis, predictive maintenance, preventive maintenance*

[a] *Babes-Bolyai University, Faculty of Environmental Science and Engineering, Research Institute for Sustainability and Disaster Management based on High Performance Computing (ISUMADECIP), 30 Fântânele Str., RO-40294, Cluj-Napoca, Romania*
* *Corresponding author: zoltan.torok@ubbcluj.ro*

INTRODUCTION

While the simple periodic maintenance is still the most applied strategy in industries [1], in the recent years many chemical production companies have implemented a specific preventive maintenance (PM) strategy, such as age-based PM, respectively block PM [2], and predictive maintenance (Pr.M) strategies are also under implementation. These strategies aim to reduce, on one hand, the maintenance-related costs, estimated up to 25 % of the overall operational costs [3]. On the other hand, they can be used in order to increase the performance of a system [2], for effective risk reduction, by preventing potential accidents caused by aging or external shocks. A study investigating 183 major chemical accidents, which occurred between 2000 – 2011 in the US and Europe, reveals that 44% of these were linked to maintenance problems [4].

As a result of numerous accidents that occurred worldwide involving chemical fertilizers, especially ammonium nitrate (AN), the conditions for the production, use, handling, storage and transport of AN have become increasingly stringent, being regulated as clearly as possible both at national and international levels [5]. Besides the risks related to the AN's lifecycle, there are some other important risks that can be identified in the fertilizers production plants, such as raw and auxiliary materials, respectively the equipment carrying those materials [6]. Efficient and safe operation of the installations from the fertilizers production sites supposes their continuous operation as much as possible, in order to avoid fluctuations at start-ups and shutdowns. This practically implies a substantial reduction in the number of stops caused by various faults [7], which can be achieved by implementing PM and Pr.M strategies.

The European standard EN 13306 – Maintenance Terminology [8] defines preventive maintenance as "the maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item". Predictive maintenance is defined as "the condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item" [8].

Although more companies are recognizing the importance of a maintenance plan, gaps in understanding remain regarding the concept of maintenance, which includes all actions and processes - scheduled or unscheduled - aimed at ensuring uninterrupted access to operational equipment in a process plant, and the potential consequences of superficial execution [9]. As Shin and Jun underline in their study, the prediction of an item's degradation relies on the premise that most anomalies do not arise suddenly, but rather progress gradually from a state of normal functioning to an abnormal one [10].

Maintaining the system is increasingly critical due to technical advancements, regulatory changes, and operational variations [11]. Inadequate planning leads to unreliable procedures and disruptions to production, as Basri et al. argue [6]. Proper planning prioritizes essential maintenance tasks and considers resources, information, and scheduling [12]. Ensuring system safety involves a formal procedure to identify and mitigate risks. Complex systems increase the likelihood of hazards, requiring effective risk analysis and management [13].

Fertilizers and other chemicals manufacturing processes rely on several key equipment to maintain efficient production rates. The ability to produce globally competitive, high-quality goods like chemical fertilizers is considerably impacted by subpar maintenance management [14].

Besides prilling, granulation is one of the most common processes used to produce solid AN, with improved handling, bulk storage and packaging qualities. Fertilizers production processes and systems are often very complex, which is why they contain a significant number of hazards, that often can lead to technological accidents in a fertilizer production site.

Preliminary Hazard Analysis (PHA) being a general level, qualitative hazard analysis method, it is easily applicable for all types of operations and functions and can be performed on a system, subsystem, unit or even on integrated set of systems [15].

The objective of this paper is to demonstrate the importance of using qualitative hazard analysis techniques, such as PHA, in the context of preventive and predictive maintenance, and to highlight the potential benefits of these strategies in mitigating the risks of potential accidents related to the granulation process of fertilizer grade AN. As Arunraj and Maiti highlight in their literature review on risk-based maintenance [16], qualitative deterministic risk analysis methods are very often used in maintenance planning.

RESULTS AND DISCUSSION

The results of the PHA are presented in table 2, in the experimental section. The analysis took into consideration only a small part of the whole AN production process, respectively the granulation step, with the main and most critical equipment involved, the rotary drum granulator and its components.

Some of the safety measures and actions proposed in the PHA analysis that are commonly used include:

- compliance with working procedures and parameters;
- periodic update of working procedures, according to legal requirements, best practices and specific guidelines;

- periodic trainings of personnel;
- laboratory check-ups, where necessary;
- emergency intervention devices and equipment are accessible and maintained in good working condition;
- employees to wear individual protective equipment in accordance with the health and safety requirements in force.

According to table 3, the results show that the majority of the hazards identified in the granulation process fall under the low and moderate risk levels. The highest risk level obtained is 12 – moderate risk, generated by potential leaks in the technological flow, due to excessive vibration of equipment.

The probability of the hazards identified ranges from *Improbable* to *Occasional*, while their consequences range between *Minor* and *Catastrophic* (in case of melted AN explosion).

As we can observe in table 2, there were also identified three of the most severe potential risks that could lead to fires and explosions, caused by leaks, contaminations or overheating due to mechanical errors or failures on specific parts of the equipment involved in the granulation process.

By the application of the PHA method several important preventive and predictive actions and measures have been identified, including visual inspections, routine realignment, tire and trunnion grinding, lubrication, and periodic operator training. For predictive measures, techniques such as vibration analysis, noise monitoring, fluid analysis, oil monitoring, tribology, and thermography were considered relevant [17].

While it is true that some of the actions and techniques suggested are already performed in fertilizer production plants as part of their routine equipment maintenance, the PHA carried out on the rotating drum granulator, as a critical piece of equipment, emphasizes the importance of visual inspection as an early and trusted method of evaluating an asset’s condition. Its primary goal is to identify and address problems before they worsen. As such, it is important for operators and maintenance personnel to receive training on what to look for and when to conduct inspections.

Tires and trunnions play a crucial role in supporting the drum and ensuring its smooth rotation. Due to constant load and friction, these components are often the first to show signs of wear when problems occur, with potential causes ranging from misaligned drums to fugitive material and improper lubrication. Given their structural importance, any indication of wear should be promptly addressed and properly inspected.

Under normal conditions, rotary drum granulators produce minimal vibration signals. However, when intensive vibration signals are detected in terms of velocity, acceleration, or displacement, it is a clear sign of major issues such as unbalance, misalignment, or worn gears or bearings, all of which require attention and repair. Special sensors and detection devices can be used for this purpose [18].

Another important predictive maintenance action is noise monitoring, which involves using acoustic sensors to detect ultrasonic and audible frequencies.

For rotating drums, oil plays a crucial role in providing lubrication, cooling, and insulation, making it essential to monitor the quality of the oil as part of the maintenance process. The oil is susceptible to contamination from various types of particles, including those caused by bearing wear and tear, partial discharges, and friction of streaming oil.

CONCLUSIONS

Effective and appropriate maintenance actions, including both predictive and preventive measures, can play a crucial role in identifying and addressing operational anomalies and equipment defects before they result in failures. Firstly, these proactive maintenance measures can help to reduce the costs associated with maintenance activities. Secondly, they can also enhance process safety by reducing the frequency of equipment breakdowns, which can be critical in some cases. Additionally, they can improve the quality of the production process and the final products.

Predictive maintenance is a type of maintenance that is triggered by the condition of a system, as opposed to preventive maintenance, which is time-driven. As a result, predictive maintenance is only performed when necessary, making it a more reliable approach compared to preventive maintenance.

The overall aim was to perform a PHA-type (Preliminary Hazard Analysis) qualitative risk assessment of hazards and associated risks found in the granulation stage of fertilizer grade AN production, emphasizing the utility and necessity of an appropriate maintenance plan comprising specific preventive and predictive measures. However, the authors acknowledge the fact that qualitative deterministic approaches are lacking in uncertainty and sensitivity analysis, therefore, their use should be completed by more complex quantitative analyses, in order to support efficient decision making for risk mitigation and balanced maintenance efforts.

The results of the study show that the most dangerous scenarios, in terms of consequences, are potential explosions of AN due to friction and melting in case of *hazard 4. Broken screw feeder shaft*, *hazard 5. Screw feeders shaft's belt overheating* or auto-decomposition and explosion of AN due to hazard 6. *Contamination with organic substances.*

A potential research objective for the future could involve examining the influence of maintenance on a fertilizer manufacturing company's profitability and product quality, utilizing data from a specific company and considering variables that offer insight into the impact of maintenance on quality. The objective is to gain a comprehensive understanding of the financial impact of maintenance measures in the long run, and how they may inform a company's strategy for reducing maintenance costs.

EXPERIMENTAL SECTION

Methods and techniques

A system is inherently susceptible to deterioration during continuous use, causing its functionality to evolve over time. Maintenance operations are conducted over a period of time, and figure 1 displays the number of failures occurring as a function of operational time [19]. Consequently, newly installed equipment is at an increased risk of malfunctioning during the first week of operation, typically due to installation issues. Thereafter, the likelihood of failures is relatively low for an extended period.

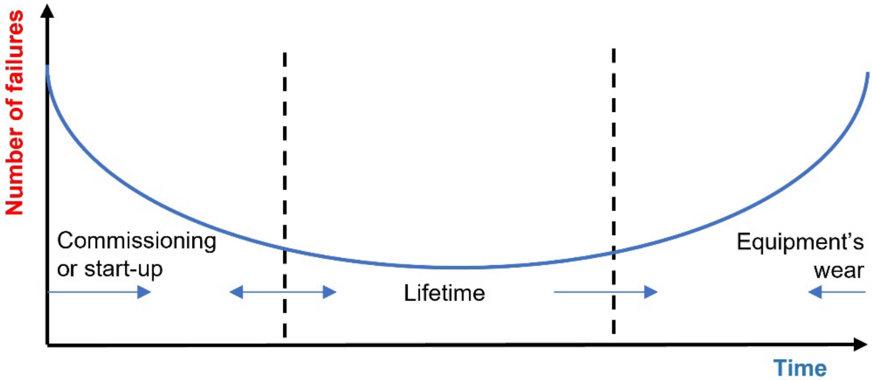

Figure 1. Representation of machine's / equipment's / system's failures during its lifecycle [19]

All fertilizers processing units, have some key equipment such as rotary drums, turbines, compressors, pumps and product transport pipes, all subject to a variety of process-driven conditions that lead to corrosion, erosion, fouling and a lot of other process-related issues, causing serious problems for the companies, the quality of the products, the environment, the health and safety of the workers [20] [21]. According to U.S. EPA AP 42, *Ammonium nitrate manufacturing industry – Technical document (1981), "*rotary drum granulators produce granules by spraying a concentrated ammonium nitrate melt (99.0 to 99.8 percent) onto small seed particles of ammonium nitrate in a long rotating cylindrical drum" [22].

In the PHA performed in this study, we tried to identify all potential hazards and failures that may lead to an accident during the AN granulation process, especially due to the AN's hazardous properties [23]. The identification of the hazards has been performed considering different aspects, such as the quality of the final product, working conditions and mechanical components involved in the AN granulation process. The order of the hazards presented in table 2 is based on the appearance of ideas and discussions during the "brainstorming" process for the analysis.

The next step was to rank the identified hazards according to their probability of occurrence and their consequences' severity, all these considering the key role of the rotary drum granulator as a critical equipment in the process [22] [24]. In the end, we have proposed some control measures and follow-up actions, based on the preventive and predictive maintenance concept, in order to mitigate the potential risk.

The risk matrix used (table 1) in the PHA aims to categorize risks, based on their level of probability (P) and consequences (C), where the risk (R) is the product of these two. The qualitative values allocated for these risk components (on a scale of 1 to 5, described in details in [25]) were chosen based on the working procedures and instructions for the AN granulation process, maintenance plan, HAZOPs, scientific literature and on the experience of the team.

Table 1. Risk matrix used in the PHA

			Consequence				
			Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
			1	**2**	**3**	**4**	**5**
Probability	**Improbable**	**1**	*1*	*2*	*3*	*4*	*5*
	Isolated	**2**	*2*	*4*	*6*	*8*	*10*
	Occasional	**3**	*3*	*6*	*9*	*12*	*15*
	Probable	**4**	*4*	*8*	*12*	*16*	*20*
	Frequent	**5**	*5*	*10*	*15*	*20*	*25*

Legend:

Risk level	Definition
1 – 3	*Very low risk*
4 – 6	*Low risk*
7 – 12	*Moderate risk*
13 – 19	*High risk*
20 – 25	*Extrem risk*

All the methodological aspects mentioned above were taken into consideration in order to underline the interdependence between maintenance, quality, productivity and safety [26].

Table 2. PHA results for the AN granulation process

Hazard	Causes	P	C	R	Expected conseq.	Existing safety measures and actions	PM actions / Pr.M actions
1. Too fine or too coarse granulation	a. Clogged, incorrectly adjusted or broken sieves	3	2	6	Affecting product quality	The concentration and pH are checked by laboratory analyses; The granulation of the recycling is checked; The opening on the mills is checked; If required, the sieving line is changed	***Preventive actions*** Visual inspections;
2. High level of humidity in the granules	a. Temperature too low in granulator	3	2	6	Affecting product quality	Visual analysis Laboratory analysis for humidity and granulation; Measuring temperature in the granulator;	***Predictive actions*** Thermographic testing;
3. Variations of the vacuum in the granulator	a. Clogged or uncorrelated cyclones	3	2	6	Variations in the humidity of the final product, respectively affecting the quality of the product	Unclogging the cyclones; Replacing the bags; Adjustments on the flap opening;	***Preventive actions*** N.A. ***Predictive actions*** Pressure monitoring
	b. Broken cyclones bags	2	2	4			
4. Broken screw feeder shaft	a. Mechanical failure	2	5	10	Belt friction and ignition which can lead to possible explosion	Smoke detectors; Compliance with work parameters and manufacturing procedures; Keeping emergency intervention devices and equipment in working order	***Preventive actions*** Checking the technical condition of the machines by non-destructive methods, applying up-to-date technologies; Visual inspections; ***Predictive actions*** Hot-spot identification using thermal imaging cameras and warning by acoustic and optical signals;
	b. Broken screws	2	5	10			
	c. Broken pallets	2	5	10			
5. Screw feeders shaft's belt overheating	a. Technical / mechanical error	2	5	10	AN melting and possible explosion	Compliance with work parameters and manufacturing procedures; Keeping emergency intervention devices and equipment in working order;	***Preventive actions*** Visual inspections; ***Predictive actions*** Hot-spot identification using thermal imaging cameras and warning by acoustic and optical signals;
6.Contamination with organic substances	a. Crack / leaks in the granulator	1	5	5	Auto decomposition of AN and possible explosion	Compliance with work parameters and manufacturing procedures;	***Preventive actions*** Visual inspections;
7. Leaks in the technological flow	a. Granulator's excessive vibrations	3	4	12	These types of leaks can lead to the occurrence of fire conditions, due to oxidizing properties of AN	Periodic check to detect any notable vibration; Periodic check to detect any notable leakage; Wearing individual protective equipment in accordance with the requirements set forth in the labor protection regulations;	***Preventive actions*** Visual inspections; ***Predictive actions*** Vibration detection and analysis;
8. Irregularities in the technological process	a. Partial or total non-functionality of the measuring and control equipment	1	3	3	Affecting product quality Granulation process stops	Periodic check on the measuring and control equipment, according to legal requirements and internal procedures	***Preventive actions*** Visual inspections; Calibration;
9. Inconstant rotation	a. Rotary drum granulator's misalignment	3	3	9	Additional stress is put on all components; Tire wear; Bearing failure; Gear damage;	Compliance with work parameters and manufacturing procedures;	***Preventive actions*** Visual inspections; Routine realignment; Tire and trunnion grinding; ***Predictive actions*** Specific types of tribological tests; Ultrasonic tests;

Hazard	Causes	P	C	R	Expected conseq.	Existing safety measures and actions	PM actions / Pr.M actions
10. Tire and trunnion wear	a. Misaligned rotary drum granulator	3	3	9	Extensive tire / wheel wear; Damage to the tire / wheel; Major contact between the drum and thrust rollers; Additional downtime and maintenance actions;	Compliance with work parameters and manufacturing procedures;	***Preventive actions*** Visual inspections; Routine realignment; Tire and trunnion grinding; ***Predictive actions*** Fluid analysis – oil monitoring; Specific types of tribological tests;
	b. Improper lubrication	3	3	9	Contamination; Increased noise; Leakages that can increase the chances of seal shrinkage, resulting in the process failure; Component failures; Intensive vibration; Production losses; Added maintenance repairs and actions;	Compliance with work parameters and manufacturing procedures;	
11. Intensive vibration signals	a. Granulator's unbalance	2	3	6	Premature bearing destruction; Production losses;	Compliance with work parameters and manufacturing procedures;	***Preventive actions*** Visual inspections; ***Predictive actions*** Specific types of tribological tests; Ultrasonic tests; Vibration sensors
	b. Rotary drum granulator's misalignment	2	3	6	Excessive wear or damage to tires or trunnion wheels;		
	c. Worn gears or bearings	2	3	6	Added maintenance repairs and actions;	Periodic lubrication; Compliance with the operating conditions and procedures;	
12. Contaminated oil	a. Bearing wear and tear	2	3	6	Added maintenance repairs and actions;	Periodic change of the oil;	***Preventive actions*** Visual inspections; ***Predictive actions*** Fluid analysis – oil monitoring; Specific types of tribological tests; Ultrasonic tests;
	b. Partial discharges or friction of streaming oil	2	4	8	Thermal degradation of the insulation;	Compliance with work parameters and manufacturing procedures;	
13. Granulation process accidentally stopped	a. Breaking of the transmission belts of the motor - reducer drive system of the granulator	2	3	6	Added maintenance repairs and actions;	Compliance with work parameters and manufacturing procedures;	***Preventive actions*** Visual inspections;
	b. Blockage of the axles with pallets due to the penetration of hard, metallic bodies	1	3	3	Added maintenance repairs and actions;		
	c. Stopping of the drive motor through the overload relay (the motor takes more amperage than the maximum set value), due to material deposits (melt, crust) on the vat and on the pallets	1	3	3	Added maintenance repairs and actions;		
	d. Leaks in the melting path	2	3	6	Added maintenance repairs and actions;		

Table 3. Risk matrix completed for the AN granulation process PHA

			Consequence				
			Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
			1	**2**	**3**	**4**	**5**
Probability	**Improbable**	**1**	*1*	*2*	*3: 8a, 13b, 13c*	*4*	*5: 6a*
	Isolated	**2**	*2*	*4: 3b*	*6: 11a, 11b, 11c, 12a, 13a*	*8: 12b*	*10: 4a, 4b, 4c, 5a*
	Occasional	**3**	*3*	*6: 1a, 2a, 3a*	*9: 9a, 10a, 10b*	*12: 7a*	*15*
	Probable	**4**	*4*	*8*	*12*	*16*	*20*
	Frequent	**5**	*5*	*10*	*15*	*20*	*25*

REFERENCES

1. H. E. Van Staden; L. Deprez; R. N. Boute; *Eur. J. Oper. Res.*, **2022**, *302(3)*, 1079-1096.
2. M. Hashemi; M. Tavangar; M. Asadi; *Comput. Ind. Eng.*, **2022,** *163*, 107829.
3. A. Haroun; *J. Qual. Maint. Eng.,* **2015**, *21(3)*, 258-270.
4. P. Okoh; S. Haugen; *Process Saf. Environ.*, **2014**, *92(4)*, 346-356.
5. D. T. Anh; K. Dąbrowski; K. Skrzypek; *Found. Manag.*, **2018**, *10(1)*, 283 – 292.
6. E.I. Basri; I.H. Abdul Razak; H. Ab-Samat; S. Kamaruddin; *J. Qual. Maint. Eng.,* **2017**, *23(2)*, 114-143.
7. T. Kletz; *What Went Wrong. Case Histories of Process Plants Disasters*, 4th ed.; Gulf Publishing Company, Houston TX, USA, **1999**, pp. 370- 371.
8. EN 13306 Standard – *Maintenance – Maintenance terminology*.
9. P. Gackowiec; *Multidiscip. Asp. Prod. Eng.,* **2019**, *2(1)*, 126-139.
10. J.-H. Shin; H.-B. Jun; *J. Comput. Des. Eng.*, **2015**, *2(2)*, 119-127.
11. P Söderholm; *Reliab. Eng. Syst.*, **2007**, *92(1)*, 1-14.
12. O. Merkt; *Proc. Fed. Comput. Sci. Inf. Syst.*, **2019**, 693-704, doi: 10.15439/2019F101.
13. L. Swanson; *Int. J. Prod. Econ.*, **2001**, *70(3)*, 237-244.
14. R.S. Velmurugan; T. Dhingra; *Int. J. Oper. Prod. Manag.*, **2015**, *35(12)*, 1622 – 1661.
15. B. Martel; *Chemical risk analysis: a practical handbook,* Butterworth - Heinemann, United Kingdom, **2004**, pp. 29-31.
16. N. S. Arunraj; J. Maiti; *J. Hazard. Mater.*, **2007**, *142*, 653-661.
17. Endevco an amphenol company, Applications, Accessed on 4 February 2023, *www.endevco.com/applications/chemical-processing.*
18. Wilcoxon sensing technologies, Accessed on 4 February 2023, *https://wilcoxon.com/vibration-transmitters-it-series-3/*.
19. S. O. Duffuaa; A. Raouf; J. Campbell; *Planning and Control of Maintenance Systems: Modelling and Analysis*, John Wiley & Sons Inc., New York, USA, **1999**, pp. 59-66.
20. B. Al-Najjar; *Int. J. Prod. Econ.*, **2007**, *107(1)*, 260–273.
21. J. C. Reynolds; R. M. Reed; *Environmental Symposium of the Fertilizer Institute,* Progress Report on Spherodizer Granulation 1975-1976, New Orleans, USA, **1976**, p. 23.
22. United States Environmental Agency; *AP 42 - Ammonium nitrate manufacturing industry – Technical document,* **1981**, pp. 7.
23. Z. Török; A. Ozunu; *Environ. Eng. Manag. J.*, **2015**, *14(11)*, 2671-2678.
24. D. Goyal; A. Chaudhary; R. K. Dang; B. S. Pabla; S. S. Dhami; *World Sci. News*, **2018**, *113*, 98-108.
25. Z. Török, N. Ajtai, A. Ozunu, *Applications for assessing the risk of major industrial accidents involving dangerous substances (In Romanian: Aplicaţii de calcul pentru evaluarea riscului producerii accidentelor industriale majore ce implică substanţe periculoase)*, EFES, Cluj-Napoca, Romania, **2011**, pp. 27.
26. M. R. R. Khan; I. A. Darrab; *J. Qual. Maint. Eng.*, **2010**, *16(4)*, 341-353.