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Hydrogen in Glass Sector: A Comparison between Risk-Based Maintenance and Time-Based Maintenance Approaches

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Abstract: Hydrogen can be the key to decarbonisation, even for energy-intensive industries. The glass sector, for instance, burns natural gas to reach high temperatures necessary to melt the raw materials, leading to a considerable amount of CO2 emissions. Introducing hydrogen in a new sector brings many challenges in technological development, but of no less importance are the safety issues due to its hazardous properties. Hydrogen is highly flammable and can interact with many metals. Avoiding hydrogen leaks or, even worse, preventing catastrophic losses should be a priority: adopting proper maintenance planning is an effective means. In this study, a comparison of two different maintenance approaches is proposed in a line supplying hydrogen to the furnace case study. Time-based maintenance is a consolidated technique that programs the operations based on the reliability of the data on the pieces of equipment. On the other hand, the Risk-Based Maintenance approach leads to planning the maintenance activities based on the risk evaluation. Applying this approach to a hydrogen facility for the first time represents the novelty of this study. The advantages of adopting a methodology based on risk evaluation when handling a safety-critical system are highlighted.

Keywords: Hydrogen, Glass manufacturing, Maintenance, Risk-Based Maintenance, Time-Based Maintenance, Hydrogen Safety.

1. INTRODUCTION

The global energy landscape is experiencing a significant transition as countries seek to address climate change and improve energy stability by shifting towards cleaner and more sustainable energy solutions. Attention to hydrogen is growing rapidly in Europe and around the world. The European Commission indicated hydrogen as a key priority to achieve the European Green Deal and Europe's clean energy transition (European Commission, 2020). Among the several potential applications, hydrogen can replace fossil fuels in energy-intensive industrial processes to lower carbon emissions. Steel, cement, aluminium, and glass manufacturing industries are promising candidates in this decarbonisation scenario. Specifically, the latter sector was responsible for 18 Mt CO_2e in 2020 (EEA, 2020) due to the necessity of reaching temperatures above 1500°C to melt the raw materials. Research initiatives are progressing in this direction, working on several projects, such as the H2GLASS – advancing Hydrogen (H2) technologies and smart production systems TO decarbonise the Glass and Aluminium SectorS – project (H2GLASS, 2023).

In addition to the technical challenge of scaling up hydrogen production and distribution, another hindrance is the safety-critical properties of hydrogen. The small dimension of the molecule makes hydrogen liable to leak from joints and seals, but detecting leakages is challenging for its colourless and odourless properties. It is highly flammable (flammability ranges from 4 % to 75 % in air) and has a low ignition energy (0.018 mJ) (Nicoletti et al., 2015). Moreover, hydrogen can embrittle and permeate most metallic materials, leading to the degradation of their mechanical properties and, eventually, their failure (Dwivedi & Vishwakarma, 2018). Several undesired events occurred due to the hydrogen-materials interaction (Campari, Nakhal Akel, et al., 2023), which could be avoided through adequate equipment maintenance.

Maintenance management has experienced significant progress throughout the years, shifting from a corrective to a preventive approach (Leoni et al., 2021). An effective maintenance program allows for increased equipment reliability and decreased downtime. Time-Based Maintenance (TBM) is a widely used strategy that bases operations on a pre-determined schedule. In the 2000s, Risk-Based Maintenance (RBM) became popular, considering the potentiality of

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combining process safety with maintenance management (Khan & Haddara, 2004a). This strategy focuses on programming activities based on the risk assessment results. The total risk is not equally distributed: a significant percentage is attributed to a limited amount of equipment. This approach addresses maintenance efforts on high-risk components, maintaining them more frequently than low-risk ones.

The RBM approach has been successfully adopted in various sectors. The onshore chemical and petrochemical industries have been the most popular since the American Petroleum Institute developed RBI for these industries (API, 2016). In an ethylene oxide production facility, the pipeline used for ethylene transportation is associated with the highest risk, so maintenance activities are prioritised to bring down the risk to an acceptable level (Khan & Haddara, 2004b). The best maintenance actions have been identified in the context of an oil refinery (Bertolini et al., 2009). The optimal shutdown intervals for a gas chilling/liquefaction unit in an LNG processing plant have been estimated, ensuring that the high level of risk is below an acceptable level (Hameed & Khan, 2014). Other examples of this approach come from hydrocarbon transportation (Dawotola et al., 2013), (Bhatia et al., 2019) and distribution to final users (Leoni et al., 2019), (Leoni et al., 2021). In addition, this procedure has also been adopted in some offshore systems, such as the rotating control device and blowout preventer of managed pressure drilling (Pui et al., 2017), or offshore wind turbine farms. The development of this approach can result in reduced maintenance costs and increase the availability for ship and naval vessel applications (Cullum et al., 2018). Also, in the energy sectors, this approach has been adopted for power plants (Krishnasamy et al., 2005) and nuclear power plants (Nilsson, 2003). Recently, the development of risk-based approaches to schedule maintenance activities has been adopted in combination with different tools, such as Analytic Hierarchical Process (AHP), Fuzzy Inference System (FIS), Bayesian Network (BN) (Leoni et al., 2021).

The novelty of introducing the RBM approach in the context of hydrogen technologies is attractive because of the potentiality of keeping the risk as low as possible, facing the safety criticalities of this substance. Moreover, introducing this strategy in glass manufacturing, which represents an energy-intensive sector, could be extremely valuable in supporting the shift to the usage of renewable energy carriers, such as hydrogen, having an important impact on the decarbonisation path.

This paper is structured as follows. Firstly, the "Methodology" section shows the procedure adopted in this study. The Risk-Based Methodology is applied to the part of the glass plant responsible for the hydrogen supply to the furnace where the raw materials are melted thanks to the high temperatures reached, as described in the "Case study: hydrogen supply to the furnace" section. Then, "Results" shows the outcome of the maintenance plan, and "Discussion" highlights the advantages of this approach compared to the well-consolidated TBM approach and underlines the limitations of the analysis. Finally, the "Conclusion" section summarises the study.

2. METHODOLOGY

RBM approach starts with the identification of the equipment in the plant and the hazardous scenario identification. It is then structured into three main modules: risk evaluation, comparison with risk acceptability, and maintenance planning. Figure 1 shows the procedure adopted in this study.

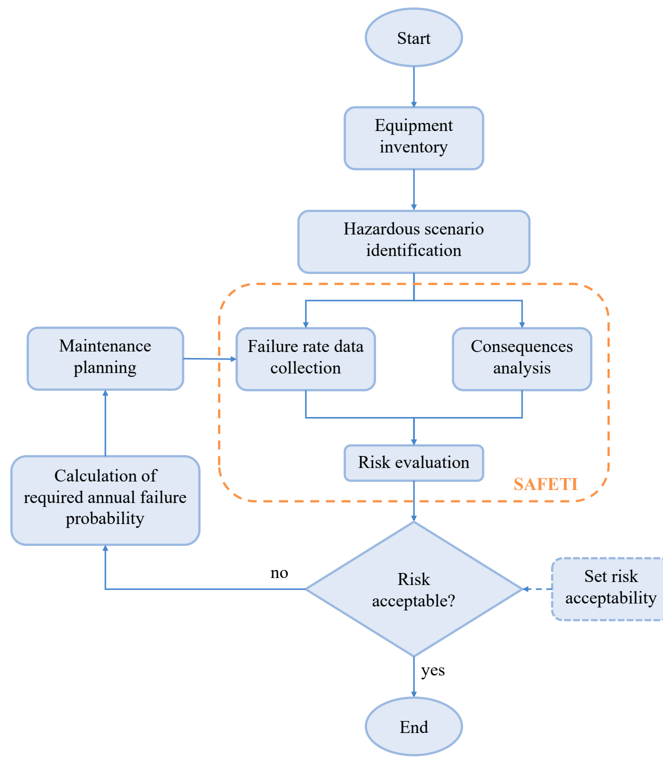

Figure 1. Risk-Based Maintenance methodology applied in this study.

First, the items of the plant described in the following section are identified. The MIMAH – Methodology for the identification of major accident hazards – allows for the association of the critical events to the equipment and the corresponding dangerous phenomena (Delvosalle et al., 2006).

Risk is the combination of the frequency and consequence of failure. The risk evaluation step is carried out through Safeti (DNV, 2023), a professional simulator for consequence modelling. Data on the failure rate for each scenario is extracted from the literature available for process industry (TNO, 2005) and (Delvosalle et al., 2006). In addition, for the risk evaluation, the software requires the selection of the harm criteria, as in Table 1, and the weather conditions. The simulation is run once the necessary inputs are provided to the software.

Safeti provides multi-level individual risk graphs for each equipment or scenario: each contour on the plot represents a specific likelihood of death per year. The results are compared with the criteria established by HSE, which considers 10^{-3} ev/year to be an acceptable value for workers (HSE, 2001). When the requirements are not met, the equipment is marked for maintenance planning.

Table 1. Harm criteria implemented on Safeti for each Dangerous Phenomena (DP).

Final event (DP)	Criteria	Fatality
Flash fire	LFL	100 %
	0.5·LFL	0
Jet fire	4 kW/m$_2$	1 %
	12.5 kW/m^2	10 %
	37.5 kW/m^2	99.9 %
Vapour Cloud Explosion	0.0103 bar	0 %
	0.02068 bar	0 %
	0.1379 bar	5 %
	0.2068 bar	100 %

2.1 Maintenance planning

The probability of failure, $P(t)$, is calculated based on the failure rate data, λ, available in the literature (TNO, 2005), as in (1):

$$P(t) = 1 - e^{-\lambda t} \quad (1)$$

where t is set equal to 8760 h/year.

The required annual failure probability to fulfill the risk criteria is obtained through a trial and error procedure, varying the software input. Once the value is obtained for each equipment, the maintenance interval, T, to achieve this target probability is calculated as in (2):

$$T = -\frac{\ln\left(1 - P_{upd}(t)\right)}{\lambda} \quad (2)$$

where $P_{upd}(t)$ is the updated probability of failure (Khan & Haddara, 2004a).

3. CASE STUDY: HYDROGEN SUPPLY TO THE FURNACE

The methodology is applied to the plant section required in a glass production factory, in the event of replacing natural gas with hydrogen, as Figure 2 shows. As of now, there is no hydrogen infrastructure like the one for natural gas. Hydrogen is delivered to the site through bottles and truck, and an appropriate line to reduce the pressure before feeding the furnace is necessary.

The two hydrogen suppliers are indicated as pressure transport equipment, and the connections between them and the rest of the plant are indicated as hoses. The truck part is at 300 bar, while the bottle part is at 200 bar. All the pipes at different pressures are indicated as pipes because the referred scenarios do not change. However, the software processes them as different equipment based on the operating conditions of the plant, resulting in various final events.

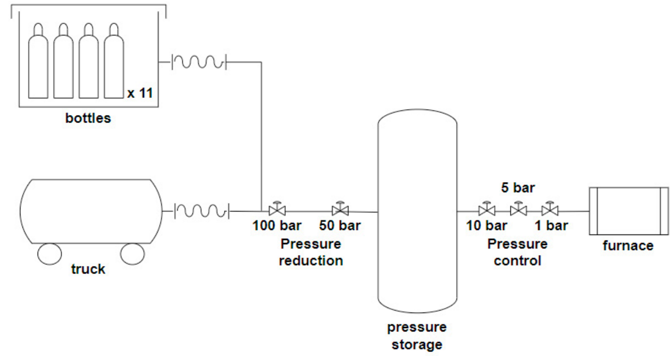

Figure 2. Layout of the plant.

Table 2 shows the equipment list and the corresponding scenario, as the MIMAH methodology indicates (Delvosalle et al., 2006).

Table 2. Equipment list and reference scenarios.

Component	Simulated scenarios
Hoses	10 % diameter leak
	Full bore rupture
Pressure transport equipment	10 mm leakage
	35 mm leakage
	100 mm leakage
	Catastrophic rupture
Pressure vessel	10 mm leakage
	35 mm leakage
	100 mm leakage
	Catastrophic rupture
Pipes	10 % diameter leak
	22 % diameter leak
	44 % diameter leak
	Full bore rupture

4. RESULTS

The first two blocks of the methodology are partially proposed in the previous section. This section provides the risk evaluation results and the outcome of the maintenance plan.

Figure 3 shows the contours at two risk levels, referring to the Location-Specific Individual Risk (LSIR) (CCPS, 2009). Figure 3a shows the results corresponding to a risk level of 10^{-2} ev/years: only the dangerous phenomena from the two pipes connecting the supplier to the line providing hydrogen to the furnaces are involved in this risk level. The rest of the equipment only appears if the risk level is 10^{-5} ev/years, as shown on Figure 3b.

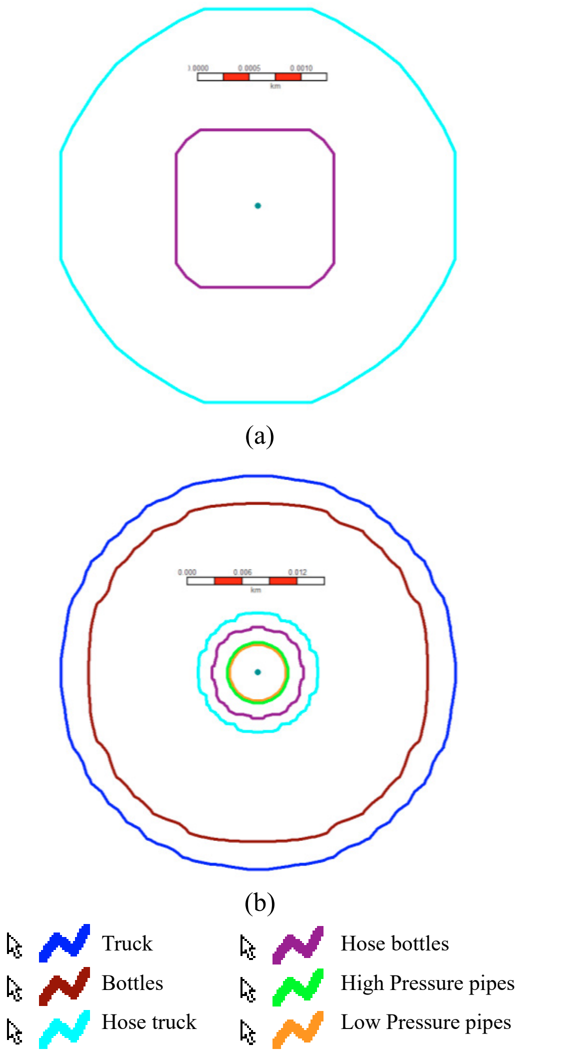

Figure 3. Individual risk contour results. (a) Risk level 10^{-2} ev/years. (b) Risk level 10^{-5} ev/years.

Figure 4 shows the results associated with the 10% diameter leak scenario from the hose connecting the truck to the glass plant. This figure provides data on the radiation level of a jet fire: the maximum peak is 800 kW/m^2, and it occurs at a downwind distance between 0.4 m and 3.5 m.

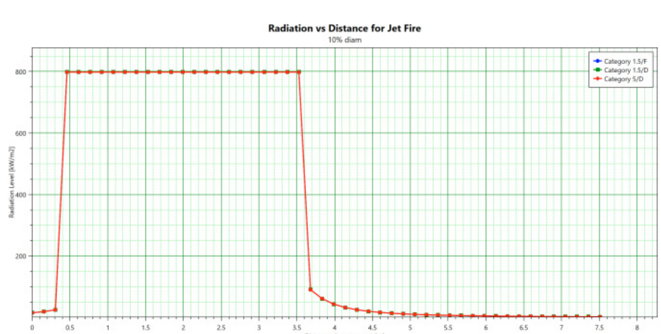

Figure 4. Consequence modelling results: radiation level of a jet fire generated by a leak of 10% of the diameter of the truck hose. Distance along transect [m] as x-axis, radiation level [kW/m2] as y-axis.

The selected weather conditions for the simulation are the standard suggested by the software: Pasquill class F (stable) and wind speed equal to 1.5 m/s; Pasquill class D (neutral) and wind speed equal to 1.5 m/s and 5 m/s.

The software also provides the results of the consequence modelling of the flash fire and the vapour cloud explosion, but they are not reported for space constraints.

The most critical components are the two flexible hoses, which are the candidates for more frequent maintenance. The required interval is calculated by changing the input of the most critical scenarios in the software until the risk falls below the 10^{-2} ev/years level, as explained in the "Methodology" section. The posterior probability of components necessary for this aim is equal to 0.1051 and 0.1086, respectively, for the truck and bottle hose. The corresponding maintenance intervals to ensure an acceptable risk level are 231 and 239 days.

5. DISCUSSION

The simulation through Safeti allows for the analysis of all the scenarios selected, as shown in Table 2. Based on the input provided about the properties of the substances and the conditions of all the equipment, the software can develop all the corresponding dangerous phenomena, such as jet fire, flash fire, and vapour cloud explosions, and calculate the significant effects. The combination with the input on the failure rate leads to the risk evaluation, a step of the Risk-based maintenance approach. The calculation demonstrates that the two flexible hoses are the most critical items, as they are the only ones responsible for the calculated higher risk level. The trial and error procedure finds the maintenance optimal time to decrease the risk level under an acceptable value. This result proves the potential of this methodology when handling hazardous substances. Although slight, the difference between the results on the two connection hoses highlights the advantages of the method. The initial failure rate of the two items is taken from the literature, and it is the same value for both items. rowth r, maintenance planning sets different operation schedules for the two components: the pipe connecting the truck is at a higher pressure than the one connecting the bottle suppliers. A higher pressure of the equipment means a higher intensity of the dangerous effect, which results in a larger safe distance, as shown in Figure 3a. Therefore, the influence of the consequence analysis is evident; if the risk were only related to the probability of failure, there would be no reason why the two maintenance intervals are different.

In this specific case study, the difference is only eight days, so from a practical perspective, it is more reasonable that the replacement is carried out after the shortest interval, 231 days, for both of the equipment, reducing the downtime and the possibility of having undesired events during the maintenance operations, since it is very critical (Collina et al., 2023). On the other hand, the benefits of this approach are more appreciable as the pieces of equipment increase in number and, therefore, the number of required maintenance interventions grows. The possibility of using hydrogen as a fuel in the glass furnace requires supplying hydrogen, as depicted in Figure 2. Another option could be the onsite production of green hydrogen through electrolysis, as desired in the context of the H2GLASS project (H2GLASS, 2023). In this case, the electrolyser would be an additional equipment to be considered in the analysis, resulting in an even more interesting application for this methodology.

In opposition to the RBM approach, the well-known TBM strategy relies only on equipment failure probability. However, the model applied in this study has no parameters for maintenance optimisation. The input data used in this analysis considers an exponential probability distribution of failures, as in (1). This model assumes that the failures are due to completely random or chance events: based on this theory, following a pre-determined maintenance schedule is not advisable (Briš & Byczanski, 2013). With only these data available, a corrective approach would be preferable since the TBM does not have the capability of decreasing the probability of failure, and the only outcome would be increasing the possibility of having problems during maintenance operations since it is critical, as already specified before. Taking action after a failure (corrective approach) is not recommended when handling a hazardous substance such as hydrogen, which can lead to dangerous events, as resulted from the analysis carried out in this study.

A drawback of this analysis is the extreme sensitivity to the data on the failure probability. It is necessary to underline that these data are collected from statistical data available in the literature developed for the process industry, and they are not hydrogen technologies specified. A significant breakthrough would be possible over the years if a hydrogen component reliability database will be structured as some researchers are trying to accomplish (Groth et al., 2023).

The biggest limitation of this study is the consideration of risk as time-independent: continuous risk updating makes the analysis more realistic through the regular modification of the probability of failure (Villa et al., 2016). Since the equipment degrades over time, the probability of failure should be considered time-dependent, as in (3), suggested by the American Petroleum Institute (API, 2016).

$$P_f\ (t, I_E) = gff \cdot D_f\ (t, I_E) \cdot F_{SM} \quad (3)$$

where gff represents the generic failure frequency available in the literature, D_f is the damage factor, and F_{SM} is the management system factor. The damage factor is the key term in this approach since it introduces the time dependence considering the equipment degradation. Developing a maintenance plan considering the risk increasing over time is a way forward. Again, the lack of hydrogen-specified data on failure mechanisms is the main bottleneck of these studies, even though research efforts are addressing this issue (Campari, Alvaro, et al., 2023) through collaboration with experts in material sciences.

Considering failures as not random but time-dependent would also be possible with the Weibull distribution method (API, 2016) in the case of hydrogen-specified data availability. A quantitative comparison between the maintenance approaches mentioned in this study will be possible as this knowledge gap will be covered.

6. CONCLUSIONS

The willingness to use hydrogen as a means to the decarbonisation path has to face some impediments, including dealing with the issues related to its safety-critical properties. Maintenance has always been considered a safety barrier in the process industry, and some previous studies have shown that its lack was crucial in hydrogen-related undesired events. In light of this, the study applied Risk-Based Maintenance to a hydrogen facility for the first time. The selection of glass manufacturing relies on the high impact that this shift can have in the energy transition due to the amount of carbon emissions. This methodology allowed for identifying the most critical components by comparing the risk assessment results and the risk acceptability criteria. Then, a trial and error procedure was employed to calculate the maintenance interval for these components. The results underlined the value of this strategy, showing that the combination of the consequences of failure and the probability of failure led to two items with identical failure data being assigned different maintenance intervals.

This approach is extremely promising to guarantee safe operations when introducing hydrogen in several sectors, not only glass manufacturing, considered in this study. However, it showed some limitations associated with the current data availability on hydrogen systems. The further development of this approach will progress in parallel with the improvement and increase in available data as hydrogen penetrates different sectors.

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