

Risk-Based Maintenance models for hydrogen systems: a review for the glass and aluminium industry

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The urgent need to mitigate climate change has placed decarbonisation at the forefront of global energy policy. Among other sectors, industrial high-temperature heat is very energy-demanding (1280 Mtoe/year in 2018 (IEA, 2019)) and responsible for 1.1GtCO2/year of direct emissions (IEA, 2019). Hydrogen has the potential to play a pivotal role in replacing fossil fuels as the primary source of heat for the glass and aluminium industry sectors. In this context, the Horizon Europe project H2GLASS (advancing Hydrogen (H2) technologies and smart production systems TO decarbonise the GLass and Aluminium SectorS) was launched at the beginning of 2023. The target is to address the technical, economical, and safety-related challenges of decarbonising the glass industry by replacing natural gas with hydrogen as fuel to the furnace, as well as demonstrating the applicability of the findings to other sectors, such as the aluminium industry. The project includes 23 industry partners and six use-case demonstrations. In addition to focusing on technology development and economic feasibility analyses, there is a need to investigate the safety aspect, which is currently a bottleneck in the roll-out of hydrogen technologies. Hydrogen is classified as a dangerous substance: it is flammable and can be responsible for material degradation. One of the main issues related to its use is hydrogen embrittlement, which is the loss of ductility and strength due to the entry of atomic hydrogen into the metal lattice. Maintenance and inspection activities and procedures are crucial in preventing integrity loss of hydrogen systems and ensuring safe operations. In this perspective, maintenance should be considered to mitigate material degradation and to avoid loss of equipment integrity and consequent accidents. Over the last decades, different industry sectors have adopted several maintenance techniques and strategies. The Risk-Based Maintenance (RBM) methodology is analysed following the proposal to adopt the Risk-Based Inspection (RBI) methodology for hydrogen technologies (Campari et al., 2022). The RBM approach prioritises maintenance activities based on the associated level of risk to avoid unnecessary operations and to reduce shutdowns, lessening the overall costs. A questionnaire on the maintenance policies and approaches used for the glass industry has been distributed to the H2GLASS consortium. The survey aimed at identifying needs and knowledge gaps in the maintenance and inspection procedures when replacing natural gas with hydrogen as fuel for the furnace. This article presents a literature review of the RBM methodology for hydrogen technologies. Furthermore, the paper summarises the findings from the questionnaire shared with the H2GLASS partners and identifies the criticalities of applying RBM to the glass case. Changes to the maintenance and inspection policies are also suggested based on the combination of the survey findings and the RBM methodology review.

KEYWORDS: Risk-Based Maintenance, Hydrogen safety, Glass Industry

Introduction

The transition toward sustainable and clean energy production has been among the most discussed topics since the beginning of the 21st century. Achieving the goals set by the Paris Agreement is this century's main challenge: global CO_2 emissions should reach net zero by 2050. The world needs to be decarbonised to reverse the current trend of emissions. Different sectors, such as electricity generation, transportation, heating and cooling, and industrial manufacturing, are responsible for CO_2 emissions. The electricity sector shows the fastest and most significant reductions in global emissions, registering an estimated drop by nearly 60% in the period to 2030 (IEA, 2021). Conversely, energy-intensive sectors, such as the manufacturing industry, are laid behind the target above. In fact, they are highly cost-competitive and sensitive to product quality (Bataille et al., 2018). Among these is the production of aluminium, steel, cement, and glass.

Glass production requires a substantial amount of energy primarily used to achieve the high temperatures essential for melting the raw materials. Reaching temperatures above 1500 °C led the main subsectors of the glass industry (container glass, flat glass, fibre glass, domestic glass, and special glass) to be responsible for 18 Mt CO2e in 2020 (EEA, 2020).

As recognised by the European Economic and Social Committee (EESC, 2009), the glass industries have reached existing physical limits in the state of current knowledge, and the best available technologies are widespread. Glass manufacturers are currently financing extensive research programs to get to a new break-through and overcome current technological barriers to reducing energy consumption and CO2 emissions.

Hence, a radical transformation is pressing, and hydrogen can play a pivotal role if used as an alternative to natural gas in glass furnaces. This substitution alone is insufficient to achieve the decarbonisation target: hydrogen production is the other challenge. Many energy sources (coal, oil, natural gas, biomass, renewables, and nuclear) through different technologies (reforming, gasification, pyrolysis, electrolysis, etc.) can contribute to hydrogen production, but clean production should remain the ultimate goal. A promising solution is *green hydrogen*, obtained mainly through water electrolysis with electricity coming from renewable energies (i.e. wind power or solar power); no harmful greenhouse emissions are released in the atmosphere. Research efforts are moving in this direction: the Horizon Europe project H2GLASS - advancing Hydrogen (H_2) technologies and smart production systems TO decarbonise the GLass and Aluminium SectorS – is an example of this.

However, introducing hydrogen in new sectors is challenging due to its peculiar properties. Hydrogen is the lightest existing substance, with a density of 0.0899 kg/m3 at 0 °C and 1 atm (Hassan et al., 2021). It has an excellent gravimetric energy density with a lower heating value (LHV) of 118.8 MJ/kg (Mazloomi and Gomes, 2012), but it possesses a very low volumetric energy density of approximately 10.7 kJ/L (Mazloomi and Gomes, 2012) at ambient conditions (temperature and pressure of 20 °C and 1 atm, respectively), leading to require special storage methods.

Hydrogen is classified as a hazardous substance. The flammability and detonability range is wide, 4 – 75 %vol and 13 – 59 %vol, respectively (Nicoletti et al., 2015). Its minimum ignition energy is 0.02 mJ, meaning that any undesirable ignition sources should always be avoided. In addition, detecting hydrogen leak is challenging, since the gas is colourless, odourless, and tasteless; its flame is also undetectable with the naked eye.

Furthermore, the ability to permeate and embrittle metallic materials is no less critical. Hydrogen is absorbed by most metals and alloys commonly used in industrial applications. It, therefore, accumulates in internal defects and voids, representing a severe concern. Preserving the physical integrity of components exposed to hydrogen environment is essential and gives much importance to maintenance and inspection activities.

The profitability of a business is intricately linked to how available and reliable its equipment is, while the quality of its products dramatically relies on the condition of that equipment (Manzini et al., 2010). For maintenance engineers, the main challenge is implementing a maintenance strategy that maximises equipment availability and efficiency, regulates the rate of equipment deterioration, ensures safe and environmentally friendly operations, and minimises overall operational costs. Over the last decades, maintenance management techniques have undergone significant changes, transitioning from focusing on periodic overhauls to incorporating practices like condition monitoring, reliability-centred maintenance, and expert systems. The corrective approach is turning into a predictive one.

The evolution of maintenance strategies is essential when it comes to hydrogen technologies. In this case, adopting a corrective maintenance approach, besides affecting the equipment's reliability, is dangerous since any loss of integrity can lead to undesirable events with grave consequences, given the peculiarity of hydrogen in terms of safety. Interest in maintenance activities arises from analysing what has happened in the past. Among the incidents reported in the HIAD 2.0 database, most events caused by hydrogen-induced damage could have been prevented through proper maintenance operations (Campari et al., 2023b). In addition, maintenance is critical: it can trigger new undesired events and expose people to extra risks. Many events occurred during maintenance activities. A significant example of a hydrogen-related incident due to maintenance error is the explosion in the Sodeguara refinery in Japan on October 16th, 1992 (Okoh and Haugen, 2013); on this occasion, more than one error contributed to the disaster. Therefore, efficient management of maintenance activities is even essential in hydrogen technologies.

Most recently, Risk-Based Maintenance (RBM) methodologies started to emerge in many industrial sectors, leading to several benefits; hence, the idea to study their applicability for new hydrogen systems.

This paper is structured as follows. Firstly, a sub-section is dedicated to an overview of maintenance strategies. A section is dedicated to the European project behind this study. The "Methodology" chapter presents the procedure adopted in this work; firstly, the questionnaire spread among the project participants is presented; then, the RBM methodology is investigated. The "Results and Discussion" section shows the survey results and gives an overview of the RBM strategy, highlighting the adaptation for hydrogen systems. Finally, the "Conclusion" section summarises the main outcomes of this study.

Maintenance management

During the last decades, significant progress has been made in maintenance management, with academic researchers and industrial practitioners developing various standards, techniques, and methodologies for planning and managing maintenance activities in production systems. The advancements have improved equipment reliability, reduced downtime, and optimised maintenance processes.

The most common maintenance strategies according to the standard EN 13306-2001 (European Standard, 2001) are presented in Figure 1.

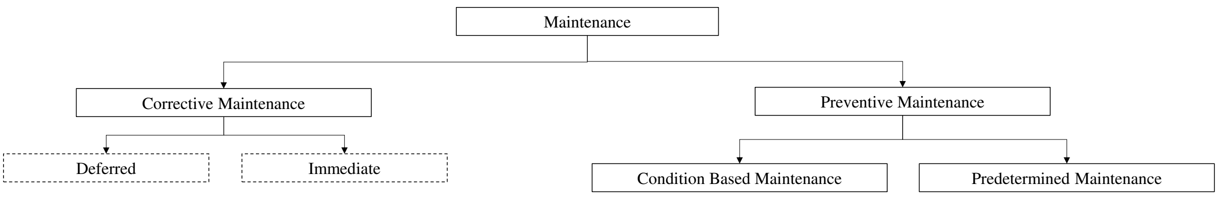

Figure 1 - Maintenance strategies from EN13306:2001 (European Standard, 2001).

The different strategies are briefly described in the following.

Corrective maintenance is performed when a production system or equipment stops functioning correctly, disrupting operations. In this strategy, maintenance actions are taken in response to failures based on known operating conditions, and there is no proactive planning for optimising maintenance activities or supporting management decisions. Deferred maintenance is not immediately carried out after a fault detection but is delayed following given maintenance rules. Immediate maintenance is conducted directly after fault detection to avoid unacceptable consequences.

Preventive maintenance is carried out at predetermined intervals or according to prescribed criteria and aims at reducing the probability of failure or the degradation of the functioning of an item. This strategy can be performed if there is enough knowledge of system operating conditions. Several models and methods to support managers in planning and scheduling preventive maintenance activities have been presented in the literature. Predetermined (or time-based) maintenance and condition-based maintenance are two widely used approaches to this preventive maintenance planning strategy. According to the first approach, maintenance tasks are scheduled at regular intervals, regardless of the actual operating condition of the equipment. This strategy assumes that specific components or systems will experience wear and tear over time, and maintenance aims to replace or refurbish these components before failures occur. The advantages of predetermined maintenance are simplicity in scheduling and planning and the potential to extend the lifespan of the equipment. However, it may result in unnecessary maintenance if components are still functional and may not capture sudden changes in equipment condition. The second approach relies on real-time data and monitoring to determine when maintenance is needed. Sensors and monitoring systems continuously track the health and performance of equipment. Maintenance actions are triggered when specific conditions or performance thresholds are met, meaning maintenance is necessary. The choice between these approaches depends on factors such as the criticality of equipment, the availability of monitoring technology, the accuracy of condition assessments, and the overall goals of the maintenance program. Many organisations combine these approaches or use advanced techniques to determine the most appropriate maintenance schedule and minimise operational risks while optimising maintenance efforts.

In the last decade, several research efforts have focused on another maintenance strategy, namely **predictive maintenance** (Zonta et al., 2020). Predictive maintenance is based on maintenance actions on a system following the forecast derived from analysing and evaluating significant parameters, as described in the following, based on the choice of the three different main approaches (Zonta et al., 2020). The *physics-based* approach employs mathematical modelling that considers the component's condition, requiring the precision of the condition and statistical methods. The *knowledge-based approach* is less complex than the first one, and it is often coupled with expert systems or fuzzy logic. Lastly, the most popular is the *data-driven approach*, which is based on statistics, pattern recognition, artificial intelligence, or machine learning algorithms.

Hydrogen and the Glass Industry

As a heavy industry (Sutherland, 2020), the glass industry should be decarbonised. Since the lifetime of a glass furnace is between 12 and 15 years, urgent action is required to achieve the goal of net zero emissions by 2050. There are many alternative solutions to reduce the energy consumption of a glass plant and curb CO_2 emissions, and several efforts have been made over the last decades. However, the only way to cut emissions and achieve this goal in less than 30 years seems to be to revolutionise this sector and redesign the furnaces, converting them into full electric melters or fuelled by biogas or green hydrogen (Zier et al., 2021). In this context, the Horizon Europe project H2GLASS – advancing Hydrogen (H2) technologies and smart production systems TO decarbonise the GLass and Aluminium SectorS – was launched at the beginning of 2023 and will last four years (H2GLASS, 2023).

The glass industry is highly different and can be categorised following the European Reference Document on Best Available Techniques in the Glass Manufacturing Industry (Scalet et al., 2013).

Container glass refers to the fabrication of glass packaging products as bottles and jars, mainly for food and drinks but also for cosmetics, perfumes, pharmaceuticals, and technical products.

Flat glass comprises the sheet glass products used in the construction and automotive industry and for solar applications.

Domestic glass covers the production of glass tableware, cookware, and decorative items.

Fibre glass is mainly used to reinforce polymer composite materials.

Special glass refers to a wide range of high-value products, such as laboratory and technical glassware, lightning applications, and optical and quartz glass.

Each subsector requires different considerations in terms of processes and melting systems. For this reason, the H2GLASS project includes five industrial demonstrators (IDs) from this sector to maximise the impact of the outcomes and guarantee the replicability of the developed solutions.

The container and flat glass industries are the predominant CO_2 emitters, 48 % and 32 % of the total glass industry, respectively (Zier et al., 2021). For this reason, three out of five produce container glass, an industrial demonstrator produces flat glass, and the last makes fibre glass, a subsector responsible for 3 % of the total glass industry's emissions (Zier et al., 2021).

Among the mentioned possibilities for revolutionising the glass sector, H2GLASS aims to substitute hydrogen to natural gas for combustion, specifically targeting *green* hydrogen. The goal is to develop the technology stack that will enable the use of hydrogen in the glass furnace, validating the technology through application in an industrial context. The vision is to supply to the furnace burners the hydrogen produced by a portable electrolyser at location. Proving the economic and environmental viability of this technology compared to fossil fuel will raise public understanding of hydrogen technology as a solution for decarbonising industrial processes. Efforts to implement these changes must be geared towards ensuring the quality of the final product: an IT architecture for automatic control and management will be developed, and, not least, the safety issue of this new industrial perspective will be addressed. The current study contributed to this last goal, approaching the development of a maintenance plan based on risk evaluation of the glass plant.

Methodology

Two pillars can describe the methodology adopted for this study as Figure 2 shows: firstly, the glass industry's maintenance policy within the project's boundaries is investigated; secondly, after briefly highlighting the advantages and disadvantages of the most commonly used maintenance techniques, attention is addressed to risk-based maintenance.

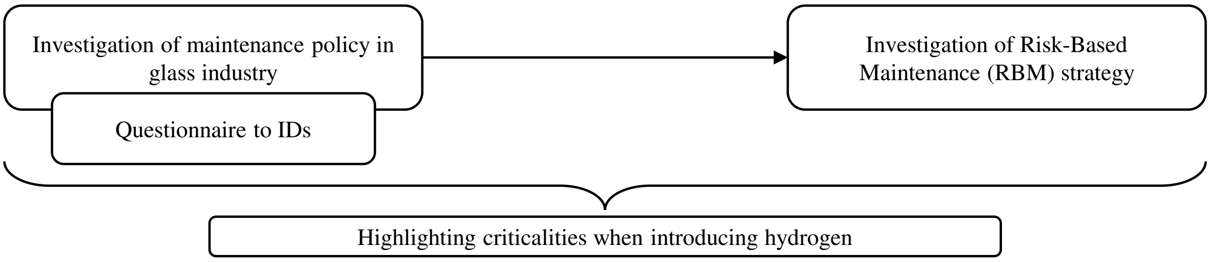

Figure 2 - Schematic methodology of this study.

Maintenance strategy investigation

In the project's initial phase, tasks independent of this study included a comprehensive analysis to gain a thorough understanding of the five industrial demonstrators. The maintenance approach was investigated, among others.

Table 1 sums up the approach for collecting maintenance data. Selected questions relevant to this study are reported in the first column. In the case of closed-ended questions, the possible options are in the second column; otherwise, the required answer is open-ended.

Table 1 - Questionnaire about maintenance policy.

Questions	**Options**
Indicate the main maintenance strategy used	Corrective maintenance Predetermined/time-based maintenance Condition-based maintenance Predictive maintenance
In the case of Corrective Maintenance, why is it applied and how are the failures identified?	
In the case of Predetermined Maintenance, why is it applied and what is the maintenance frequency?	
In the case of Condition-Based and Predictive Maintenance, what sensor, technologies or machine data are used (e.g. thermal imaging for condition monitoring) and what parameters are monitored for maintenance?	
What parameters for maintenance are applied?	Mean Time To Failure (MTTF) Remaining Useful Life (RUL) Time to First Failure (TFF) Other
For Predictive Maintenance, what are the models and methods used?	Artificial Neural Network Deep Learning Machine Learning Other
What are the ISO maintenance standards followed?	
In case of unscheduled maintenance due to deviation from optimal conditions, based on what priority do you take action?	Production Quality Safety Other

Risk-Based Maintenance

Risk-Based Maintenance (RBM) methodology is investigated, and a dedicated approach for hydrogen technologies is preliminarily suggested. A collection of articles from the Web of Science Core Collection (WoS CC) database is selected to underline the interest in this strategy among the researchers. Table 2 shows the queries and filters chosen to highlight the attention this topic has attracted over the years. This collection is dated July 20th, 2023.

Table 2 - Queries and filters selected in Web of Science Core Collection.

Type	Option selected
Queries	[“risk-based maintenance” OR (“risk-based inspection” AND “maintenance”] AND [“application” OR “case study”]
Analysis field	Topic
Document type	Articles, Review Articles. Conference Proceedings
Language	English

Results and discussion

The results of this study are presented in this section: firstly, the survey results in Table 1 are shown and discussed; then, Risk-Based Maintenance is described, and some adaptation to hydrogen systems are suggested.

The industrial survey

The survey shows that the most common strategy among industrial demonstrators is *corrective* maintenance. All five respondents indicated using this strategy. Two industrial demonstrators provided more details: in each department of the plant, an automatic supervisory system or manual monitoring signals any problems to the maintenance department, asking for intervention after evaluating if it is urgent or not. In the case of non-urgency, an optimal time for fixing is set (deferred maintenance).

Corrective is the most simple and classic type of maintenance: it is appropriate for less critical assets, mainly when repairing is less expensive after the failure. This can be the case for some sections of a glass plant. However, the willingness to introduce hydrogen into the feed line to the furnace burners implies some risks. Adopting the corrective maintenance strategy in this part of the plant might be dangerous. For instance, an accident in 2010 in the USA caused seven fatalities: a seal broke due to a high-temperature hydrogen attack, leading to an explosion and an intense fire (CSB, 2013). This was a typical case in which preventive maintenance against material degradation could have helped (Campari et al., 2023b).

Three out of five IDs stated they also apply predetermined maintenance. They justified the use to prevent failure; the frequency depends on the section of the plant, and it relies on the maintenance manual by the supplier in terms of modality and timing. Mean Time To Failure is the favoured parameter. Still, three IDs also adopt Remaining Useful Life and Time To First Failure to improve their maintenance strategies, adopting a proactive attitude that helps them prevent problems, reduce unscheduled downtime and optimise asset performance and lifetime. Condition-based maintenance is employed to the same extent as the prior maintenance method among those who responded to the questionnaire. It is assumed that all the equipment has normal working parameters included in a specific range. If the monitored parameters exceed that range, the system gives an alarm. Rotation, current absorption, temperature, flow, ratio, and vibration are the typical parameters controlled by the sensors and all their deviation from the set point active alarms. In general, preventive maintenance should reduce the frequency and complexity of maintenance while ensuring maximum equipment utilisation under safe conditions.

On the other hand, both time-based and condition-based maintenance have some drawbacks: the first can lead to unnecessary operations that can introduce risks besides increasing costs. Indeed, maintenance activities are critical and can also be the triggered event, as shown in the Sodeguara refinery disaster in 1992, when a maintenance error provoked a vapour cloud explosion (Okoh and Haugen, 2013). Condition-based requires high training for technicians, which can be ambitious when implementing hydrogen in a new environment. The necessity of sensors and monitoring equipment is also an issue since the fitness of the equipment in contact with hydrogen is challenging to detect continuously.

Predictive maintenance is also frequently cited, although limited detailed data is available on it.

The only maintenance standard cited by an industrial test case is ISO 9001, which focuses on quality management system requirements.

When unplanned maintenance arises due to conditions straying from the ideal, one respondent indicated that their decision-making process prioritises safety first, followed by production, and then quality. This approach is reasonable and commendable, particularly when considering the introduction of hydrogen into this new context.

The industrial demonstrators involved in the H2GLASS project currently use natural gas as fuel in the furnace to melt the glass. Its upper flammability limit is five times lower than hydrogen, while the flammable energy in air is one order of magnitude higher (Nicoletti et al., 2015). With a hydrogen-based technological setup, the warning threshold and safety measures implemented in the plant will certainly have to increase. Furthermore, hydrogen might affect material integrity: hydrogen-induced damage of metals long-known phenomena in material science (Ustolin et al., 2020). They represent the degradations that result from the action of hydrogen exposure and uptake into the materials. In the past, they have been responsible for the failure of components, leading to accidents. The HIAD 2.0 database, which represents the most comprehensive online database, reports 24 accidents due to hydrogen-induced damage of metal (Campari et al., 2023b). Among those, hydrogen embrittlement was responsible for 14 undesired events, while high-temperature hydrogen attacks caused six accidents. These accidents could have possibly been prevented by thorough inspection and maintenance plan.

Risk-Based Maintenance strategy

In the 1990s, Risk-Based Maintenance emerged and gained popularity beyond the 2000s: combining maintenance and safety is a suitable way to maximise the plant capacity, as safety and maintenance can work effectively together. Over the years, this methodology has been increasingly investigated and applied in various fields, such as onshore chemical and petrochemical industries, offshore, and energy industries. Figure 3 shows interest in this approach has skyrocketed in the last five years.

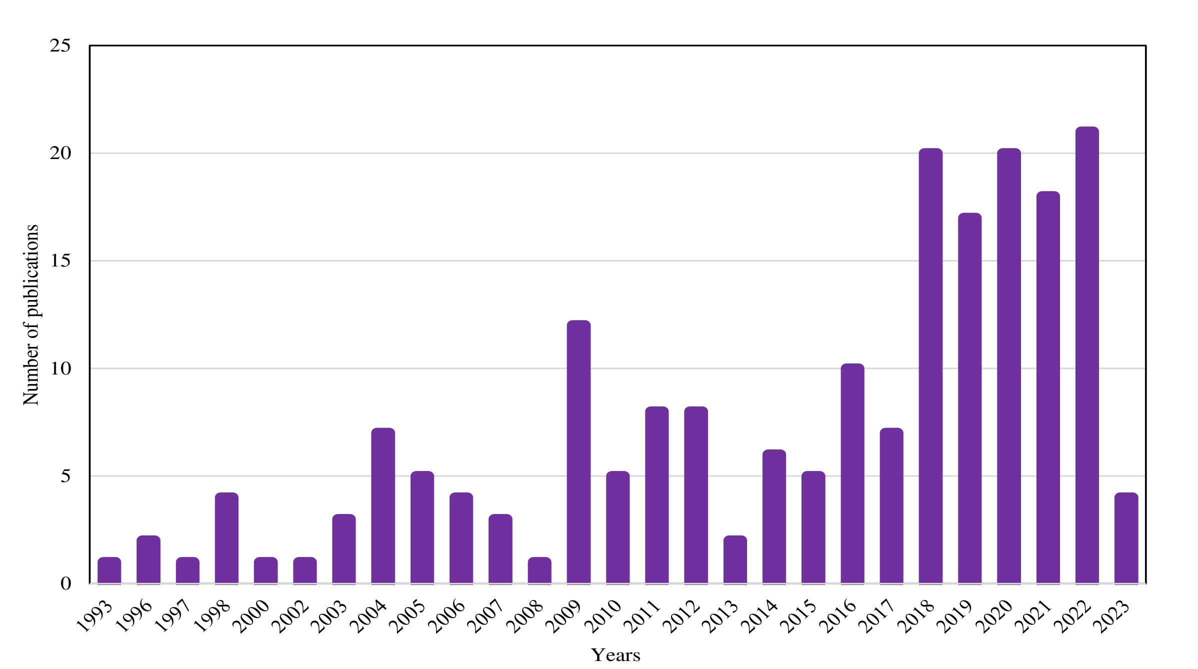

Figure 3 - Publication years of papers on RBM (WoS CC, 2023).

This approach relies on the assumption that in most plants, a significant percentage of the total risk is associated with a relatively small number of items. The main aim of this methodology is to lower the overall risk stemming from unforeseen failures in operating facilities. Inspection and maintenance tasks are prioritised based on quantified risk caused by the failure of the components so that the total risk can be minimised. The parts with higher risk levels typically undergo more frequent and comprehensive inspections and maintenance to meet acceptable risk standards. This methodology involves breaking the system down into units and consists of three main blocks:

- risk assessment consists of risk identification and estimation through hazard identification, probabilistic failure analysis and consequence assessment;
- risk evaluation consists of comparing the assessed risk against the acceptable criteria previously selected;
- maintenance planning involves developing a plan to reduce the unacceptable risk to an acceptable level.

This methodology can be considered as a follow-up of the Risk-Based Inspection (RBI) approach, which arose when the American Society of Mechanical Engineering recognised the need for risk-based inspection management methods (Krishnasamy et al., 2005) and published a series of reports as an inspection guideline in several applications (ASME, 1991). The American Petroleum Institute contributed to the development of risk-based inspection by providing a flow diagram (API, 2016a) and tables, algorithms, equations and models to carry out the planning (API, 2016b). Combining the approaches proposed for offshore oil and gas facilities (Khan and Haddara, 2004), for a natural gas regulating and metering station (Leoni et al., 2019) and for an oil refinery (Bertolini et al., 2009), with the need and criticalities of hydrogen systems, the recommended methodology is illustrated in Figure 4 through a simplified flow diagram. The process starts by collecting data and information about the whole system and dividing it into manageable units. Each unit undergoes three sections highlighted in bold in the figure.

The first module calculates the risk by combining the probability of failure $P_f(t,I_E)$ with its consequences C_f:

$$R_f(t, I_E) = P_f(t, I_E) \cdot C_f \quad (1)$$

The consequence of a loss of containment is determined through well-established consequence analysis techniques and is expressed as an affected impact area or in financial terms. Impact areas from event outcomes such as pool fires, flash fires, jet fires, fireballs, and vapour cloud explosions are assessed based on the effects of thermal radiation and overpressure on surrounding equipment and personnel. Cloud dispersion analysis methods quantify the magnitude of flammable releases and determine the extent and duration of personnel exposure to toxic releases.

The probability of failure is calculated as the product of a generic failure frequency (g_{ff}), a damage factor (D_f) and a management system factor (F_{MS}):

$$P_f(t, I_E) = g_{ff} \cdot D_f(t, I_E) \cdot F_{MS} \quad (2)$$

The generic failure frequency is intended to be the failure frequency before any specific damage occurs from exposure to the operating environment, and it is defined as the number of failures per year of a particular type of equipment and relies on statistical analyses of historical data. The management system factor is an adjustment factor that accounts for the probability that accumulating damage that may result in a loss of containment will be detected before the failure occurrence. The damage factor modifies the failure frequency, making it specific to the component under evaluation by considering the amount of damage that may be present as a function of time in service and the effectiveness of the inspection activity. American Petroleum Institute provides methods for determining damage factors for some damage mechanisms: thinning (both general and local), component lining damage, external damage, stress corrosion cracking (SCC), high-temperature hydrogen attack (HTHA), mechanical fatigue (piping only), brittle fracture (API, 2016b). However, hydrogen embrittlement should be considered a relevant damage mechanism for equipment in contact with hydrogen since it is the primary active degrading mechanism in equipment exposed to a hydrogenated environment. For this reason, an additional factor should be included when applying the RBM methodology to hydrogen systems. A preliminary study (Campari et al., 2023a) was recently proposed to fill this gap in the API standards.

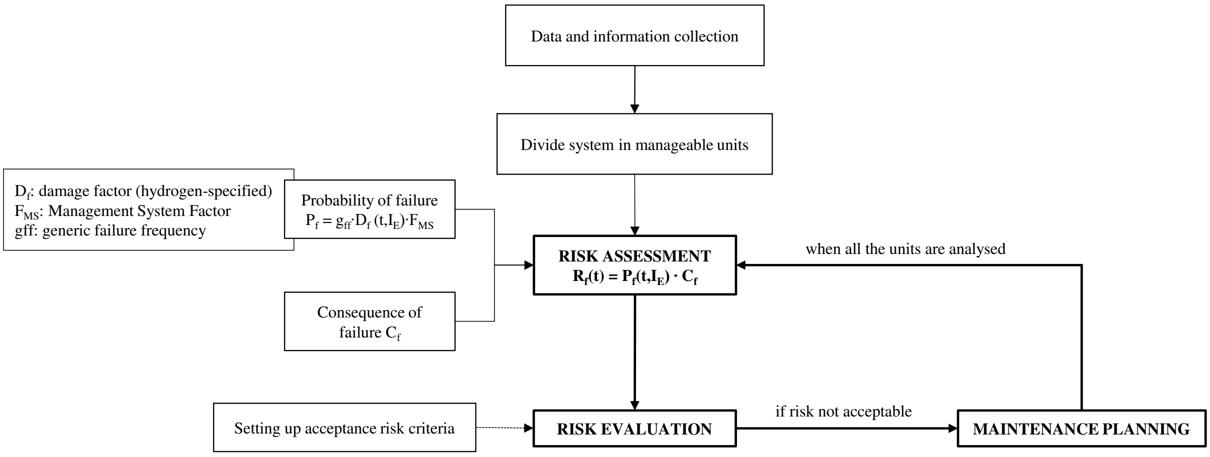

Figure 4 - Risk-Based Maintenance approach for hydrogen technologies.

The second module in Figure 4, evaluates the risk assessed in the previous section and compares it with a selected criterion. The user establishes risk acceptance criteria based on the study's scope, the system's criticality, and the organisation's strategy or policy. ALARP (As Low As Reasonably Possible) criteria, HSE land use planning criteria, and Dutch criteria are commonly used risk criteria. If the outcome of the first module satisfies the acceptance criteria, the procedure continues with the following unit; otherwise, the unit undergoes maintenance planning.

The third module investigates the marked units from the previous section that do not respect the acceptance criteria. The output of this section is the maintenance time for the component under study to reduce the risk and satisfy the acceptance criterion, setting up a target risk. All the units of the whole system go under this procedure. After evaluating the adequate maintenance time for each component, the risk assessment is repeated to verify that the maintenance plan developed will produce an accepted risk level for the complete system. If the revised risk is acceptable, developing the maintenance plan containing all the maintenance time is possible; otherwise, the target risk should be updated.

Applying this methodology is of the utmost importance when the goal is to keep the risk of the operations low. Indeed, this strategy minimises the possibility of asset failure, increasing asset availability and reducing the likelihood of undesired events. In addition, it can help in enhancing efficiency in maintenance management, reducing the overall costs.

From the analysis of past incidents related to hydrogen, pipelines are the most affected, but tanks, joints, valves and pressure regulators are also involved in many incidents. The new design of the glass plants will include the implementation of an electrolyser, many pipelines bringing hydrogen from the battery limits to the furnace, different flanges and some pressure regulators since hydrogen is stored at high pressure and the furnace works at atmospheric conditions. These remarks make the necessity of implementing an effective maintenance strategy even more attractive.

Conclusion

The urgency to decarbonise energy-intensive industries within 2050 made hydrogen a key player in many projects. H2GLASS aims to replace natural gas with hydrogen in glass and aluminium furnaces. Besides developing the technology stack, the safety issue is addressed due to the hazardous properties of this substance. The introduction of hydrogen in new scenarios leads to emerging risks to be handled. Maintenance is among the different safety measures implementable in a plant. For this reason, this study investigated the maintenance strategies spread across the project's industrial demonstrators who will test this new technology in their glass furnaces after implementing adequate plant modifications.

The conventional maintenance strategies showed some criticalities when introducing hydrogen into the system. Corrective maintenance allows the failure to happen, leading to possible hydrogen leakages that can be extremely dangerous. A time-based strategy threatens to introduce unnecessary maintenance operations, increasing the likelihood of errors that can trigger undesired events. Condition-based maintenance is difficult to apply since the interaction of hydrogen with metals changes the mechanical properties of the materials that can not be monitored continuously.

In this context, adopting the Risk-Based Maintenance methodology could be the solution. The growth of interest, measured in the number of publications on the topic, has increased in recent years, driven by the advantageous features of this strategy, which allows maintenance activities to be prioritised for higher-risk components. Before applying this methodology to hydrogen systems, a more thorough analysis of the probability of failure is required: hydrogen embrittlement should be considered among the damage factors, and a procedure to calculate it should be developed and included in the next edition of RBI standards.

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