Advances in Reliability, Safety and Security, Part 7 – Kołowrocki, Magryta-Mut (eds.)
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Advances in Reliability, Safety and Security

ESREL 2024
Monograph Book Series

DyPASI And REWI Procedures Applied To Steel And Aluminum Manufacturing Sites Using Hydrogen

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Abstract

The rise of global temperatures as a result of greenhouse gases is forcing countries and governments to push for more environmentally friendlier options. Hydrogen is shaping up to be a valid alternative fuel that is capable of performing well in energy intensive processes.

The HyInHeat project funded under Horizon Europe seeks to aid the green transition of the aluminum and steel manufacturing processes by realizing the implementation of efficient hydrogen combustion systems that decarbonize the heating and melting processes. In order to secure a successful and smooth implementation of the main deliverables of the project, safety analyses that can determine the likely hazards, their consequences and means to prevent or minimize their effects are necessary.

This study aims to conduct a hazard identification of potential risks present within the steel and aluminum process manufacturing industry. The DyPASI (Dynamic Procedure of Atypical Scenarios Identification) method is used to incorporate known causes and consequences of catastrophic failures within the industries that are normally overlooked in bow tie diagrams obtained using the MIMAH (Methodology for the Identification of Major Accident Hazards) method. As part of the safety barriers that aim to prevent or mitigate the risks found, the REWI (Resilience based Early Warning Indicator) method will be presented as a potential proactive safety barrier that can help in increasing the safety level of both routine activities as well as maintenance work.

The results of this paper can be used towards creating safety training material as well as direct future research avenues.

Keywords: aluminium, hydrogen, DyPASI, REWI, steel

1. Introduction

In recent years, in response to changing public perception concerning environmental related issues, governments have started adopting more policies that aim to facilitate the green transition. While the development of the petroleum industry has aided in ushering in many of the positive aspects of the modern world, its side effects can no longer be ignored. In order to tackle the current climate crisis, all greenhouse gas emitting sectors have to be looked into. While a lot of attention has been given in recent years to mobile applications, heavy industry should not be forgotten as it has a substantial contribution to the overall problem. Steel represents the backbone of modern societies while aluminum is used in almost all sectors from transportation, construction to electrical equipment. Overall steel can contribute as much as 25% (Lei et al., 2023) of global industrial CO_2 emissions, while aluminum is responsible for 3% (“Aluminium,” 2023). The HyInHeat project funded through Horizon Europe aims to make both industries greener through the use of hydrogen in the furnaces that currently run on a natural gas, oxygen or air mixture (“Hydrogen technologies for decarbonization of industrial heating processes | HyInHeat Project | Fact Sheet | HORIZON,” 2024). As a result of its physicochemical properties, hydrogen can meet the energy requirements of both mobile applications as well as energy intensive ones, ultimately presenting itself as a viable all-round alternative fuel. Regretfully, it also presents certain disadvantages, most notably tied to safety. As such robust and dependable safety measures need to be enacted.

To that effect in order to ascertain the threats posed and in consequence the potential mitigation methods, dynamic risk analysis and resilience methods can be used.

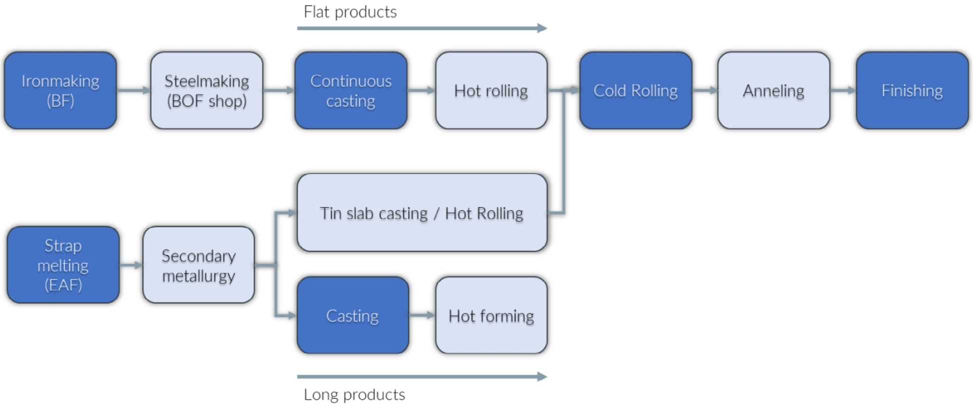

Fig. 1. Equipment in a steel manufacturing plant.

The introduction section will continue with a presentation of the steel and aluminum manufacturing processes and mention the equipment that is set to be retrofitted through the HyInHeat project that was launched in 2023. It will conclude with a presentation of the dangerous substances used in the furnaces that are the focus of the project.

In the Methodology section, the methodologies used for running risk analysis will be presented. This will include the MIMAH (Methodology for the Identification of Major Accident Hazards) as well as the DyPASI (Dynamic Procedure of Atypical Scenarios Identification) and REWI (Resilience based Early Warning Indicator) methods and an overall presentation on the types of safety barriers.

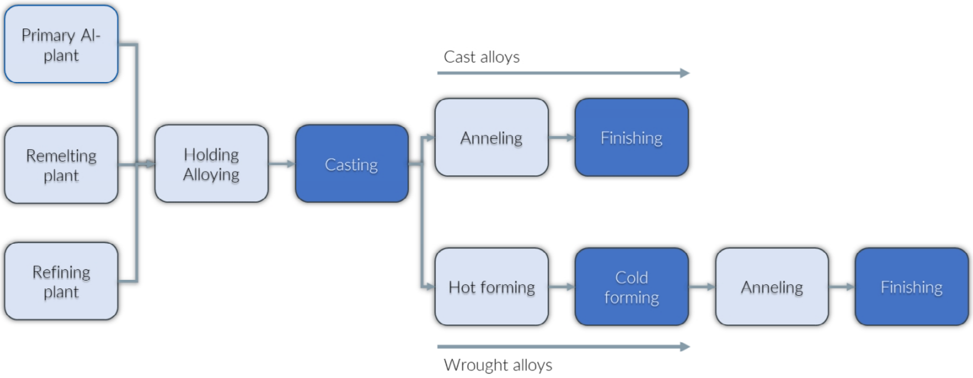

Fig. 2. Equipment in an aluminum manufacturing plant.

The Results and Discussion section will include the results and observations made while applying the MIMAH, DyPASI and REWI methodologies. Lastly, the Conclusion section will sum up the findings of the present study.

1.1. Equipment in a steel manufacturing plant

Fig. 1 presents a schematic representation of the steel manufacturing process for long and flat steel products that incorporates the use of a basic oxygen furnaces (BOF) as well as an electric arc furnace (EAF).

BOF use oxygen blown into molten iron to diminish the content of carbon present from 4% to under 0.5%. Scrap steel is added to control the temperature. The steel obtained is tapped from the furnace vessel into a ladle that is ready for casting. Depending on the end use of the steel, the melt can be treated in order to adjust its chemical composition. In the continuous caster, the steel will pass through a mold and a sequence of segments to become a horizontal path that will be cut into semi-finished products. In the hot rolling section the semi-finished products are heated above the steel's recrystallisation temperature of 1200ºC to make them easier to form. The cold rolling stage involves pickling in heated acid which aids in providing better surface characteristics and precise dimensions. In the annealing stage the alloy is heated past its recrystallization temperature, maintained for an amount of time and then cooled in order to increase the ductility and reduce the hardness of the alloy (Haro et al., 1999). In the final stage, aesthetics and environmental protection is provided to the alloys (Scrinzi and Rossi, 2010).

Table 1. Hazardous substances present at the sites (Langhorst et al., 2023).

Compound	Hydrogen	Oxygen	Methane
Pictograms			
Risk Phrases	R12	R8	R12
Hazards statements	H220	H272	H220
Precautionary statements	P202, P210, P271, P377, P381, P403	P220, P244, P370+P376, P403	P210
NFPA 704			

An electric arc furnace uses steel that has reached the end of its life, scrap, to create long products. To bring the steel to its designated properties, it will undergo steps that aim to nullify its previously had characteristics. Upon being melted down, it will go through secondary metallurgy processes that include deoxidation, desulfurization, degassing, decarburization, alloying and trimming additions, heating and temperature adjustments so as to determine and adjust the final composition and properties of the new steel alloys (Holappa, 2014). In the tin slab casting/hot rolling segment, liquid steel is molded to the caster. Here complete through thickness solidification will take place. The cast strand will at the end of the caster be cut into slabs. The hot thin slab will be directly hot rolled after it was homogenized in a tunnel furnace (Klinkenberg et al., 2017).

As part of the HyInHeat project the following processes are set to be retrofitted: the ladle preheater that is part of the steelmaking (BOF shop) and second metallurgy stage, the walking beam furnace that is used for reheating during the hot rolling and hot forming sections, the pilot radiant tubes that are used for heating during the thin slab casting/hot rolling section, the tunnel furnace that is located between the continuous casting and rolling section and the annealing furnace used in the annealing stage.

1.2. Equipment in an aluminum manufacturing plant

The aluminum manufacturing process presented in Fig. 2 uses scrap aluminum made out of manufacturing scrap or old aluminum that has reached its end use. To create new products, it is first sorted based on the alloy type, grade and impurity level and subsequently bailed, shredded and crushed as part of the pretreatment processes completed prior to being melted down and subsequently recast.

Depending on the type of scrap processed, different types of furnaces are used: reverberatory gas fired furnaces, rotary melting furnace. (Langhorst et al., 2023) As the scrap melts, fluxes are added. This enables the binding and absorption of impurities that will be scrapped off as dross. Degassing removes any dissolved hydrogen, whereas solid impurities and inclusions can be removed through chemical filtration. The resulted molten aluminum can then be cast into solid form. The method used will heavily depend on the subsequent processing and envisioned end use of the alloy.

Throughout the HyInHeat project the following equipment is scheduled to be retrofitted and made hydrogen compatible: the preheat station, the rotary furnace, the reverb melting furnace, the holding furnace and the pusher reheating furnace.

1.3. Hazardous substances present

Hydrogen, oxygen and natural gas represent the hazardous substances present on site and used to run the furnaces in the two manufacturing processes (Langhorst et al., 2023).

As seen in Table 1, both hydrogen and natural gas are classified as an extremely flammable gas, having the risk phrase R12 as well as being designated H220, while oxygen is listed with a R8 risk phrase and H272, as a result of its oxidizing property that can cause/intensify a fire (Council, 1977).

In the NFPA 704 fire diamond diagram, both hydrogen and natural gas register a "4" for flammability, namely they will rapidly and completely vaporize at normal atmospheric pressure and temperature, while oxygen having a "0" (zero) does not burn under typical fire conditions. Hydrogen and oxygen have a "0" (zero) in the health section, which signifies that it does not present any health hazard, while natural gas is a "2" (two) means that an intense or continued not chronic exposure can temporarily give an incapacitation or residual injury. In the instability reactivity section, both hydrogen and methane register a "0" (zero) as they are normally stable even under fire exposure conditions and not reactive with water, while oxygen has a "1" (one) which means that it is normally stable but can become instable at elevated temperatures and pressures. Lastly, in the special notice category, hydrogen has no special notice, while natural gas lists a "SA", meaning it is an asphyxiant gas. Lastly, oxygen has an "OX" for oxidizer, meaning it permits chemicals to burn without an air supply ("NFPA 704 Standard Development," 2024).

2. Methodologies

The methodology section presents the methods used towards identifying the risks existing within the aluminum and steel manufacturing industries, namely MIMAH, DyPASI and REWI.

2.1. MIMAH methodology

The MIMAH methodology created during the "Accidental Risk Assessment Methodology for Industries" (ARAMIS) project("Accidental risk assessment methodology for industries | ARAMIS Project | Fact Sheet | FP5," 2024), in the context of the SEVECO II directive (Wettig and Porter, 1999), is comprised of 7 steps that together assist the creation of bow tie diagrams (Delvosalle et al., 2006):

- In step "1", the needed information related to the studied site is gathered: This can include a plant layout, brief description of the process equipment and pipes available (Delvosalle et al., 2006).
- In step "2", the potentially hazardous equipment present on site is identified. This will include the substances considered dangerous and their respective risk phrases (Delvosalle et al., 2006).
- In step "3", the relevant hazardous equipment is identified. For this, the following data is necessary: equipment name, type, substance handled and physical state among others (Delvosalle et al., 2006).
- In the next step, "4", for each selected equipment the associated critical event is determined. To do this the STAT-EQ matrix is used. It takes into account the phase of the dangerous substances and the general purpose of the equipment analyzed. Multiple critical events can be obtained (Delvosalle et al., 2006).
- In step "5", a fault tree will be built for each critical event (CE)(Delvosalle et al., 2006).
- In step "6", for each CE an event tree that takes into account the risk phrases of the substances is built. Here, the potential secondary critical events (SCE), tertiary critical events (TCE) and dangerous phenomena (DP) are listed. The secondary critical events are obtained using the CE-STAT-SCE matrix, while for the tertiary critical events the SCE-TCE matrix is used. Lastly, the TCE-DP matrix is used to obtain the dangerous phenomena (Delvosalle et al., 2006).
- In the final step, "7", the fault trees created in step 5 are merged with the relevant event trees obtained in step 6 in order to obtain the bow-tie diagrams. (Delvosalle et al., 2006)

2.2. Safety barriers

Safety barriers are defined by the Norwegian Petroleum Safety Authority as technical, operational, and organizational elements that are individually or collectively meant to reduce the possibility of a certain error/hazard/accident from occurring or limit its consequences. Coincidentally, in many cases all three elements are necessary to realize the role of a barrier or a barrier function. Technical barrier systems refer to engineering elements that meet one or more barrier functions. Operational barrier elements encompasses tasks done by either a single operator or a team, whereas organizational barrier elements refer to personnel that are either responsible or should complete a specific barrier function.(Johansen and Rausand, 2015)

Based on their purpose, safety barriers can fall in one of the following categories:

- Proactive barriers. Their role is to prevent or reduce the likelihood of a hazardous event and includes elements related to process design of the plant, the use of PPE, basic process control systems, process alarms, operator procedures as well as safety critical process alarms and safety instrumental systems(Rausand and Haugen, 2020).

- Reactive barriers. They are used to avoid or reduce the effects of a hazardous event and include: pressure release valves, rupture disks, physical barriers, sprinklers systems, gas detectors, alarms, plant emergency and community emergency response(Rausand and Haugen, 2020).

Safety barriers can generally be introduced into a bow tie diagram using the MIRAS (Methodology for the identification of reference accident scenarios) methodology that was also created during the ARAMIS project. (Delvosalle et al., 2006)

Table 2. EQ-CE matrix.

		CE1 Decomposition	CE2 Explosion	CE3 Materials set in Motion (entrainment by air)	CE4 Materials set in motion (entrainment by a liquid)	CE5 Start of a fire (LPI)	CE6 Breach on the shell in vapor phase	CE7 Breach on the shell in liquid phase	CE8 Leak from liquid pipe	CE9 Leak from gas pipe	CE10 catastrophic rupture	CE11 Vessel	CE12 Collapse of the roof
Equipment designated for energy production and supply	EQ14					X	X	X	X	X	X		
Gas/Liquid	STAT4					X	X			X	X		
Results						X	X			X	X		

2.3. DyPASI methodology

The DyPASI (Dynamic Procedure for Atypical Scenarios Identification) (Paltrinieri et al., 2013) method was created during the European Commission FP7 iNTeg-Risk project(“Early Recognition, Monitoring and Integrated Management of Emerging, New Technology Related Risks | INTEG-RISK Project | Fact Sheet | FP7,” 2024). It is a method that can be incorporated into the HAZID process. It utilizes information from past accidents and incidents to highlight potential uncommon chain of events as a result of the substances and equipment used(Paltrinieri et al., 2011). This can enable more comprehensive analyses. The method was built upon the MIMAH bow-tie analysis developed during the ARAMIS project.

The DyPASI method consists of 5 main steps (Paltrinieri et al., 2013):

In the first step that is generally referred to as “0”, the bow tie technique is used to highlight poignant critical events that can occur in the process that is the focus of the research. Bow tie diagrams can be created following either the conventional guidelines presented by the Centre for Chemical Process Safety (CCPS 2008) or the MIMAH tool (Paltrinieri et al., 2013).

In the next step, “1” (one), a search is done to locate pertinent information tied to the process. This focuses on undetected possible hazards and accident scenarios that haven’t been included in classic bow-tie analyses. The step can be further split into 3 stages, namely the elaboration of the information necessary and selection of places where the search is to take place, the creation of the query to be searched and lastly the assessment of the results obtained. The location of the industrial site, the process investigated, the equipment that makes up the process, the substances used can all be seen as potential search boundaries (Paltrinieri et al., 2013).

In the third step, “2”, the information previously gathered is assessed in order to determine if it is relevant enough to trigger more action and the start of a risk assessment. In order to make this stage easier, it is possible to tabulate the risk notions gathered in step “1” and attribute their relevant importance and impact. Possible consequences can be determined as well as a ranking scale that shows the level of severity namely: 1-near miss, 2-mishap, 3-incident, 4-accident, and 5-disaster (Paltrinieri et al., 2013).

The 4th step, “3”, sees the incorporation of the atypical scenario into the bow-tie diagram. To do this, the potential chain of events is isolated from the early warnings that have been gathered and a cause consequence chain that follows the layout of a bow-tie diagram is created (Paltrinieri et al., 2013).

Lastly, in the final step “4”, safety measures can be introduced into the bow-tie diagram(Paltrinieri et al., 2013).

Table 3: Events listed in HIAD2.0 and MHIDAS.

Source	No	Location	Date	Industry	Details	Injured	Fatalities
HIAD2.0	206	UK	08.11.2001	Metallurgy	H_2O and hot molten materials mixed in the lower part of the blast furnace	12	1

HIAD2.0	217	US	02.02.2001	Metallurgy	during demolition of a furnace, gas from the line came in contact with flames	5	2
HIAD2.0	558	Belgium	19.10.1982	Metallurgy	H_2O from preceding days' rain came in contact with slag and cinders in the pit	0	0
HIAD2.0	673	US	28.10.1996	Electrical components production	H_2 still present in furnace while welding was being done during maintenance	1	0
HIAD2.0	718	US	05.12.1998	Chemical industry	the purge procedure for H_2 was not followed correctly	2	0
MHIDAS	6889	France	24.03.1986	Metallurgy (Al)	lighting struck foundry and created a fine Al spray that gave an explosive chain reaction with air	25	4
MHIDAS	9775	Australia	15.04.1979	Metallurgy (Al)	Al smelting factory explosion	3	1

2.4. REWI methodology

The REWI method which stands for Resilience based Early Warning Indicators, was developed at Sintef and IFE throughout multiple research projects, namely ReSMaM (Resilience based safety management and monitoring for petroleum exploration and production in the Arctic)("Resilience based Safety Management and Monitoring for petroleum exploration and production in the Arctic - Prosjektbanken," 2024), Building safety (Building safety in petroleum exploration and production in the Northern Regions)("Building Safety in Petroleum Exploration and Production in the Northern Regions - Prosjektbanken," 2024) and iNTeg-Risk (Early recognition, Monitoring and Integrated Management in Emerging, New Technologies). The method aims to identify, select, implement and use resilience-based indicators(Øien et al., 2012).

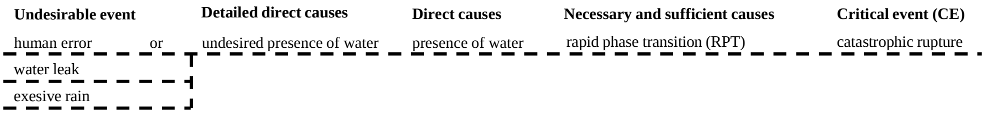

Fig. 3. Fault tree branch incorporating DyPASI findings.

The REWI method is comprised of 5 main steps, with the second step being further divisible into an additional 5 sub-steps(Øien et al., 2012).

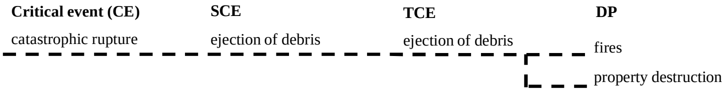

Fig. 4. Event tree branch incorporating DyPASI findings/

The first main step will see the establishment of organizational arrangements and includes the appointment of a project manager, the set-up of the implementation team and convening the team(Øien et al., 2012).

Step 2 is used for identifying and selecting the indicators. The sub steps that comprise this section will see: the review of the general issues namely, the predefined issues and the putting up of additional issues, assessing the importance of the general issues, reviewing the candidate's indicators for the most important general issues, reviewing predefined indicators and proposing new more specific or relevant indicators, selecting a manageable set of indicators, specifying the selected set of indicators(Øien et al., 2012).

In step 3, the implementation of the indicators and interpretation of the data will be done. This will entail the collection, review, and interpretation of the data. The results obtained are to be presented in reports and meetings where the future actions required by the system will be decided(Øien et al., 2012).

Step 4 covers the review and update of the indicator system regularly. Here, the review of the set of indicators and evaluation of the need for change or updates of the indicator system will be completed(Øien et al., 2012).

Lastly, in the final step, REWI indicators can be integrated with other self-assessment initiatives. The findings or actions are to be merged into already existing corrective action plans(Øien et al., 2012).

3. Results and Discussion

3.1. MIMAH

As all the demonstrators included in the project aim to provide heat necessary for creating new aluminum or steel, the particularities of each unit were disregarded, as they presented no added value. In consequence, the general "furnace" unit was retained for the purpose of creating the bow tie diagrams. Furnaces correspond to EQ14, equipment devoted for energy production and supply. As a result of the working conditions in the furnaces, the physical state of the substances is Vapor Gas, namely STAT4. The risk phrases of the 3 gases are: R12 for Hydrogen, R8 for Oxygen and R12 for methane.

Using the EQ-CE matrix, Table 2, it is possible to determine the situations that are most likely to occur given the equipment and substances used. They are CE5 Start of a Fire, CE6 Breach on the shell in vapor phase, CE9 Leak from gas pipe and CE10 catastrophic rupture.

For each critical event, independent fault trees were built. Event trees that take into account the risk phrases and the respective critical event were also made and subsequently added to the previously mentioned in order to give rise to the bow tie diagrams. A total of 8 bow tie graphs can be made, namely: CE5 Start of a fire, CE6 Large breach on the shell in vapor phase, CE6 Medium breach on the shell in vapor phase, CE6 Small breach on the shell in vapor phase, CE9 Large leak from gas pipe, CE9 Medium leak from gas pipe, CE9 Small leak from gas pipe, CE10 catastrophic rupture.

3.2. DyPASI

In accordance with the steps of the DyPASI method, in step 0 the creation of the bow tie diagrams was done using the MIMAH procedure.

In step one, the selection of keywords to be used in the search for past events pertinent to the manufacturing of aluminum and steel was done. The keywords considered as being the most representative were "furnace", "steel" and "aluminum". The databases selected for the search were HIAD2.0 (Hydrogen Incidents and Accidents Database)("HIAD 2.0 – free access to the renewed hydrogen incident and accident database – HySafe," 2018; "Safety of Hydrogen as an Energy Carrier (HYSAFE) | HYSAFE Project | Fact Sheet | FP6," 2024) and MHIDAS (Major Hazard Incident Data Service)("Major Hazard Incident Data Service - Big Chemical Encyclopedia," 2023).

In accordance with step "2", the entries previously found were assessed in order to determine their relevance and see if they could be used to improve the previously made bow tie diagrams. The criteria used to determine if the incidents were relevant was the general application of the technology where the furnaces were used. The HIAD2.0 database gave 5 entries, while MHIDAS presented 2 entries. Their details including location, date, industry, accident details, number of injured and fatalities can be found in Table 3. Based on the DyPASI method's ranking for severity, due to the presence of fatalities and injuries all should be awarded the highest level.

Given the nature of the incidents found, it can be stated that an addition to the bow tie charts obtained using the MIMAH method can be done. namely to the chart that deals with CE10, catastrophic rupture.

On top of identifying potential CE that are the result of improperly followed maintenance procedures, DyPASI can also assist in including in bow tie diagrams well know causes of CE that would normally be overlooked in a standard MIMAH bowtie, namely RPT explosions when molten metal comes in contact with water. As seen through the entries obtained from HIAD2.0 and MHIDAS as well as the Annual Summary Report on molten Metal Incidents for 2020 (Annual Summary Report on Molten Metal Incidents for 2020, 2021) this can occur when molten metal is placed in a pit that has leftover rain from previous days or when wet scrap might be placed in the furnace. RPT explosions of this nature also present the likelihood of having molten metal pour out onto the pit floor (Hubbard and Pierce, 2003). This can lead to fires, injury and death to personnel, debris being ejected. The latter, due to their high temperature can cause fires, destruction of property, injury and death to people located in the vicinity of the affected plant.

Using Fig. 3 and Fig. 4 that presents possible chain of events that can occur during daily activities, safety barriers that aim to prevent or mitigate a catastrophic rupture can be enacted. As part of plant's emergency response, a reactive barrier, the most effective approach is immediately evacuating the vicinity of the furnace. Epoxy coatings can be used as a proactive barrier to prevent fires erupting from the molten metal splattered onto the pit floor(Richter et al., 1997). Moreso, the REWI method can be used to minimize the chances of errors being done during maintenance work as well as in daily activities. Lastly, with respect to the danger posed by lighting, anti-lighting equipment can be installed in equipment deemed to be at risk.

Table 4: REWI indicators.

CSF detailed level	General Issue	Indicator
Risk understanding	System knowledge	1. Average no. of years' experience with such systems
		2. Average no. of years' experience with this particular system
		3. Portion of operating personnel receiving system training last 3 months
		4. Portion of operating personnel familiar with design assumptions
		5. Turnover of operating personnel last 6 months
	Information about risk	6. Portion of operating personnel taking risk courses last 12 months
		7. Portion of operating personnel informed about risk analyses last 3 months
		8. No. of tool-box meetings last month
		9. No of violations to assumptions/limitations in the risk analysis (QRA)
	Reporting of incidents, near-misses and accidents	10. No of accidents, incidents and near misses
	Information about the quality of barriers (technical safety)	11. No. of overrides of safety systems last month
		12. No. of procedures not up to date
		13. No. of feedback on procedures (tracked in the management system)
		14. No. of internal audits/inspections covering operational safety last 6 months
		15. Fraction of internal operational audits behind schedule during last 6 months
	Discussion of HSE issues/ status in regular meetings	16. No. of meetings discussing the status on safety performance indicators
	Communicating risk/ resilience at all levels of the organization	17. No. of risk issues communicated to the entire organization each month
		18. Portion of company actively using the risk register
Anticipation	Risk/hazard identification (HAZID, etc)	19. Portion of operating personnel participated in (general) HAZID
		20. Portion of affected personnel participated in HAZID for specific operation
		21. Fraction of operational procedures that have been risk assessed
	Learn from own and other's experience & accidents	22. Fraction of internal and external past events considered in safety report review
Attention	Bypass of control and safety functions	23. Maximum no. of control and safety functions in bypass during last month
		24. Maximum no. of control and safety functions in bypass to the next shift
		25. No. of unauthorized bypasses/overrides during last 3 months
	Activity level/ simultaneous operations	26. Total no. of hot work permits issued last month
		27. No of instances where hot work permissions have been checked against QRA
	Trends in reported events and quality of barriers	28. Evolution of events and effectiveness of safety barriers
Resourcefulness/rapidity	Adequate resource allocation and staffing	29. Amount of overtime worked

3.3. REWI

As a result of the incidents found, the implementation of the REWI method within industrial sites can be suggested as a potential proactive safety barrier. It can be used to make safer daily procedures as well as maintenance work. Table 4 presents suggested indicators that aim to cover the aforementioned situations to be done in step 2 of the REWI method after the establishment of organizational arrangements.

With the exception of the No.26 and No.27 that are strictly applicable to maintenance work that involves the use of hot work, all the other indicators are relevant for both running repairs as well as daily activities. The years of experience of workers in the field No.1, No.2, the training they received No.3, how often refresher courses are done as well as if the aforementioned courses undergo a periodic update can all play an important role. It is also worth noting that personnel should understand the design and function of the equipment they are working with as well as the risk factors they can be exposed to No.6, No.7. The number of new personnel on the job No.5, their level of training, presence in the team of more experienced teammates that can use their knowledge towards preventing a critical event can play a substantial role.

With respect to maintenance work as well as routine operations, it is important to note the amount of backlog work and to account for realistic scenarios that might see corners being cut as a result of deadlines No.29, No.23, No.24, No.25. Regretfully, such scenarios can lead to safety functions being by-passed, which can include properly checking that no water or organic material is present in places where molten metal is to be poured or that scrap meant for the furnaces is properly dry. Overall, procedures should be regarded as living documents that should periodically be updated to encompass the newest safety recommendations for a system No.12, including lessons learn from incidents occurring on-site as well as in other companies that utilize the same technology No.22. Hot work should be done following all the latest safety recommendations. Also, the input provided by workers concerning routine tasks as well as maintenance work should be taken into account including the feedback issued following the enactment of new procedures No.13.

4. Further works

Building upon the work completed during this study, a first potential avenue for future research could be to look into alternative RPT generating chain of events that involve water and molten metals. While this study presents typical technological scenarios, it is also possible to have water that is the result of natural events taking part in critical events, more specifically Natech accidents.

Secondly, understanding the physics and chemistry behind the explosions that can occur within the smelting industry, more specifically under which conditions they are triggered, can aid in creating better training material for personnel as they would enable the inclusion of more accurate safety distances as well as scientifically backed procedures that can be followed in case of an emergency.

Lastly, as it was seen through this study, the DyPASI method can enable the inclusion of known causes and consequences of critical events into existing bow-tie diagrams that would otherwise be overlooked when applying the MIMAH procedure. This aspect can prove beneficial as in the following years, given the push for alternative fuels, more technologies are likely to undergo retrofitting studies to make them suitable for greener fuels. As it is imperative that new, greener technologies are rolled out as soon as possible, the creation of a tool build upon the DyPASI method could assist with the identification of overlooked threats, consequences as well as fast tracking the creation of safety related material.

5. Conclusions

As it was seen through this study, both DyPASI and REWI have the potential to provide assistance towards the implementation of hydrogen in the aluminum and steel manufacturing processes. Both methods already count several articles that prove their utility. The DyPASI method has been used to analyze LNG tanks(Paltrinieri et al., 2011), as well as to showcase its ability in identifying risk factors relevant for the Hoehanaes accident(Paltrinieri et al., 2014), while the REWI method was used to analyze the Buncefield accident(Soares, 2011) as well as to showcase its potential contribution towards increasing the safety of operations that involve autonomous marine systems(Thieme and Utne, 2017).

Firstly, the DyPASI method, through its technical, reactive viewpoint has provided a route towards incorporating well known hazards in the industry into bow tie diagrams, that in consequence can assist in highlighting the subject matter that should be included in safety training courses. While the chain of events is not directly tied to the use of hydrogen, they are still relevant, more so as the new furnaces will be tied to supply lines and in consequence tanks containing hydrogen. The aforementioned supply lines and tanks, in the case of an RPT, could magnify the amplitude of SCE, TCE and DP. Secondly, the REWI method through its very nature of providing a proactive, organizational viewpoint, aids in showcasing the importance of having properly trained personnel on site and of maintaining the procedures used for both daily tasks as well as maintenance work up to date as it can assist in preventing the occurrence of critical events, like a catastrophic rupture. It also presents the added advantage of incorporating observations made by personnel on site into the procedures as well as learning from internal and external past events, the method itself acting like a proactive safety barrier.

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