Confined space risk management in steel industry: towards the adoption of Industry 4.0 technologies

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Abstract: Confined spaces are high-risk industrial working areas, since serious and fatal injuries occur with a certain frequency and repetitive scenarios. Although these spaces are "ubiquitous throughout industry", steel industry represents an interesting field of investigation because performing maintenance and manufacturing activities in confined spaces is one of the most common causes of accidents, also fatal, in this industry. In addition, steel plants are characterised by a significant number of confined spaces, quite varied in terms of features, types, and risks. However, to the best of our knowledge, scientific papers focusing on the risk management in confined spaces in the steel industry are not available in the literature. For this reason, the objectives of this paper are to: (1) identify the confined spaces that are typically present in a steel company, (2) provide guidelines on how to assess and manage risks in these spaces, and (3) propose some possible Industry 4.0 technologies to effectively reduce and control the risks. To achieve these objectives, we conducted in-depth case studies in 3 Italian steel firms. We gathered data thanks to an ad hoc questionnaire, detailed audits, and instrumental tests in identified confined spaces. Finally, a focus group was organised for reviewing and discussing collected data, comparing the obtained findings, and developing guidelines for risk management.

Keywords: Steel plant; Confined spaces; Risk assessment; Occupational health and safety; Industry 4.0.

1. Introduction

A wide range of confined space definitions can be found in the literature. Indeed, as well underlined by Brophy (2011), "a universal definition of a confined space is elusive". One of the main definitions is provided by OSHA (2011), according to which confined space is "a space that: (1) is large enough and so configured that an employee can bodily enter and perform assigned work; and (2) has limited or restricted means for entry or exit (for example, tanks, vessels, silos, storage bins, hoppers, vaults, and pits are spaces that may have limited means of entry); and (3) is not designed for continuous employee occupancy".

McManus (2010) states that the term "confined space" is similar to a zipped computer file for pointing out the potential contemporary presence of multiple hazardous conditions and risks. Furthermore, the conditions can be transient and change rapidly from innocuous to life-threatening (McManus, 1998, 2010). McManus (1998) also introduces the terms "confined space/confined atmosphere/confined energy" for putting the emphasis on the need for a broader recognition of the hazards that can exist, occur, or develop inside. Additionally, confined spaces "are ubiquitous throughout industry", and "occur across the spectrum of industry" (McManus, 1998, 2011).

In the last few years, this particular working area is capturing more and more attention due to the occurrence of many serious and fatal injuries. In confined spaces, accidents are common (Chinniah et al., 2017), and typically are more severe than those taking place in other working environments (McManus, 1998). For instance, one of the most recent (January 2018) and serious Italian accidents in confined spaces took place in a steel company in Milan. In particular, during maintenance activities inside a heating furnace, four workers died due to asphyxiation caused by an accidental argon release, the failure to use adequate respiratory devices, and the lack of awareness about hazardous situation by other workers and rescuers.

This event provides further confirmation of an aspect put in evidence by the International Labour Organization: working in confined spaces represents one of the most common causes of injury in steel industry (ILO, 2005). Recently, World Steel Association (WSA, 2015) has reinforced that one of five most common causes of incidents is working in confined space, due to risk of asphyxiation. Indeed, in steel plants, carrying out maintenance and manufacturing activities inside confined spaces may rapidly lead to multiple-fatality accidents. In addition, steel industry is an interesting field of investigation also for the significant number of confined spaces, which are quite varied in terms of features, types, and risks. However, to the best of our knowledge, there are no available scientific literature and/or technical reports about confined space risk management in steel industry.

Moreover, although Industry 4.0 technologies are recently being proposed as appropriate measures implementable to control, reduce, and manage several types of risks (e.g. Cocca et al., 2016; Grahn et al., 2016), also in confined spaces (e.g. Botti et al., 2015), there are no specific indications for the steel industry.

For these reasons, our study is intended to provide steel safety managers with a useful support during all steps of confined space risk assessment and management. This study is also an attempt to overcome the gap underlined by Chinniah et al. (2017): "the main confined space risk analysis tools suggested in the literature (e.g., checklists, risk matrices) are often incomplete". In particular, the objectives of this paper are to:

1. identify the confined spaces typically present in a steel company, capturing their peculiarities (also in terms of the working activities that must be done inside them);
2. provide guidelines on how to assess and manage risks in these spaces, developing a list of potential risks and preventive or mitigating measures associated with each type of confined space previously identified;
3. propose some possible applications of Industry 4.0 technologies to effectively reduce and control the risks.

2. Methods

In order to achieve the objectives of our study, we carried out a literature review of scientific papers, standards, guidelines, technical reports, and regulations concerning confined space risk management. This literature review was completed by reliance upon electronic databases (ScienceDirect, Scopus, and Web of Science), specialised or general search engines (e.g. Google and Google Scholar), and website of organisations relevant in the field of health and safety at work or of the steel production.

In addition, we contacted several academic experts in the field and conducted in-depth case studies in 3 Italian steel firms. These case studies represented the opportunity to interface with safety managers of several steel companies and to collaborate in the definition of shared and actually applicable guidelines for risk management. For this purpose, we gathered data through an ad hoc questionnaire, detailed audits, and instrumental tests in identified confined spaces.

Our questionnaire, developed according to guidelines provided by Lavrakas (2008), and Rea and Parker (2014), is composed by both closed-ended and open-ended questions. We introduced some open-ended questions to encourage a wide and detailed range of answers (e.g. lists of confined spaces, risks, and control measures) and additional explanations about the reasons for the answer to closed-ended questions. Regarding closed-ended questions, we minimised the use of "other" response questions only to strictly necessary cases and we clearly stated when more than one response was acceptable.

For reducing the time requested for completing the entire questionnaire, we submitted a cover letter (for informing the respondents about the study's purpose and the procedures to be followed) and the list of questions previous of the interviews. The questionnaire was administered on a single occasion for each steel firm.

The questionnaire is a summary document that merges information about the latest confined space risk assessments, practices, and procedures carried out and developed in the company. It is structured into five sections and categories of questions: (1) introductory and general information on the organisation and respondent(s); (2) information related to the topic of confined spaces, legislative and technical references for identifying confined spaces and conducting the risk assessment, and past accidents and near misses occurred in the company; (3) assessment (i.e. identification, analysis, and evaluation) of confined spaces in each production area of the firm, explaining the tasks that may be performed, the content (e.g. substances and equipment), the risks and their causes, and the likelihood of damage and the severity of consequences in the best and in the worst cases; (4) risk treatment, including preventive, protective, and emergency measures specifically adopted (also in terms of Industry 4.0 technologies), and procedures implemented for monitoring and review the risk management process; and (5) any other comments and/or opinions that pertain to the subject matter of the questionnaire not addressed before. This order follows the steps of the risk assessment and management processes, as proposed by ISO 31000 (ISO, 2018a) and IEC/ISO 31010 (IEC/ISO, 2009) standards. Details about the number of questions composing each section are reported in Table 1.

We filled in the questionnaires through face-to-face interviews with steel safety managers for minimising nonresponse rates and maximising the quality of the collected data. Indeed, in-person interviews allowed to guide respondents during the long and detailed compilation of the questionnaire itself, to improve comprehension, to clarify some questions, and to probe for more complete responses when necessary. The main instructions for completing the questionnaire are repeated at the beginning of each interview. The time required for completing the questionnaire was about 1 ÷ 2 hours.

In addition to questionnaire, we conducted site visits (including unstructured interviews with managers and workers of the different production areas), measurements of space and access dimensions, and instrumental tests for acquiring data about atmospheric parameters. All the gathered data were summarised into a Microsoft® Excel spreadsheet. The results and the most interesting aspects highlighted by this data elaboration represented the main and the starting point of discussion during a focus group.

Table 1: Number of questions in the questionnaire

Section	Closed-ended questions	Open-ended questions	Combined questions	Total
1	4	2	0	6
2	4	3	10	17
3	17	21	11	49
4	13	2	5	20
5	0	1	0	1
Total	38	29	26	93

This focus group was organised in an only occasion involving seven participants, which were the interviewed safety managers and collaborators of the three steel companies visited and analysed. After a brief overview of the subject matter, the discussion rules, and the introduction of each participant, the discussion was conducted over a period of two hours. The following main topics were dealt with:

- the data collected during the interviews, also checking their reliability and enriching them if necessary;
- the obtained findings, comparing them and highlighting their similarities and differences;
- the development of shared guidelines for risk management.

We had the role of moderators for balancing the various contributions of participants and keeping the discussion on track. In particular, one of us guided the conversation and another made sure that all desired topics were covered and took notes.

3. Results and discussion

The main results of our study consist on a list of confined spaces typically identified in steel industry, some guidelines for risk assessment and management, and several proposals of Industry 4.0 technologies to reduce and control the risks.

For length constraints, we omit data and details about the characterisation of confined spaces, Personal Protective Equipment (PPE), and emergency measures.

3.1 Confined spaces identification

As suggested by ANSI/ASSE (2016), the first step of the confined space risk assessment regards an initial survey and analysis of the premises or operations (or both) to identify the critical areas into a steel company. An example of methodology for the confined space identification in industry is proposed by Botti et al. (2017b), who consider geometric features, access, internal configuration, and atmosphere and environment.

In steel companies, the following sixteen types of confined spaces (in alphabetical order) can be identified:

1. areas above furnace;
2. box: e.g. electrical systems;
3. chimney: e.g. emissions, industrial fumes, steam, dust;
4. heat treatment furnace;
5. heating furnace;
6. hopper: e.g. cast iron;
7. inspection chamber: e.g. ventilation systems, emission systems, industrial fumes, turbine, rotor, lime and alloys, filters, continuous casting, conveyor belt;
8. internal furnace;
9. ladle;
10. pipe, conduit, and sewer: e.g. cooling water, dust, emission systems, industrial fumes;
11. pit and manhole: e.g. casting, slag, furnace, ladle furnace, water;
12. silo: e.g. coal, lime, activated carbons;
13. tank (including settling tank and collection tank): e.g. water, service plants of rolling mill, wastewater treatment, steel chip, rainwater;
14. tank/cistern: e.g. sand filter;
15. tunnel: e.g. service plants of rolling equipment, dust and emission collection equipment, electrical system, cables and panels, cooling of (semi-)finished products, bag filter;
16. vacuum degasser tank.

The numbers in the previous list represent the ID of each type of confined space reported in Table 2 and Table 3.

Note that we differentiate between tank and tank/cistern. We use the former word for indicating a large container mainly for liquids, while the latter for describing a metal container (with a significant height) also for solids.

Each identified confined space is characterised and analysed in terms of:

- relative production area or department (e.g. melting, casting, rolling, heat treatment, utilities and services);
- equipment to use;
- entrance features (e.g. number, dimensions, shape, presence of barriers, vertical/horizontal access);
- spatial configuration (e.g. internal shape, dimensions, past content of the space, installed equipment and plants, presence of obstacles and/or obstructions);
- presence/absence of natural ventilation and lighting;
- outside environment (e.g. changeable conditions, weather information, presence of chemicals nearby).

In addition, relevant information also concerns the work assignments, the operators authorised for entry, the duration and frequency of access(es) and interventions. In the confined spaces that are typical of the steel industry, workers have to carry out routine, non-routine, non-production, and/or intermittent activities. For instance, maintenance personnel usually perform biweekly or monthly inspection of components and equipment in tunnels and tanks, and/or waste cleaning in pits. Both these activities are executed simultaneously by at least two company workers. On the contrary, rehabilitation of internal refractory material is typically subcontracted to external specialised operators that enter daily (for an entire shift) furnaces and/or ladles.

3.2 Guidelines for risk assessment and management

In order to better support safety managers during the risk assessment and mitigation in confined spaces, we formulate guidelines about the main risks, related factors influencing these risks, and some appropriate controls and measures for properly decreasing potential worker exposures.

With these guidelines, each risk of every space can be assessed in terms of likelihood of occurrence and consequence severity. The likelihood of occurrence depends on the length of time the activity takes, the exposure to hazard (e.g. total duration of work, length of use of certain devices, number of exposed workers and entry frequency), the likelihood of occurrence of hazardous event (e.g. historical accidents), and the possibility of avoiding or limiting harm (e.g. physical ability, aptitude to work in a restrictive space). With respect to the consequence severity, the most severe harm that could result should be evaluated. Both parameters are composed by four levels and then are combined into a risk matrix. This estimation produces a risk rating that allows the identification of scenarios requiring controls and of risk reduction measures.

The implementation of appropriate measures and controls permits to estimate residual risks and to evaluate whether these are acceptable. In order to define the most effective risk reduction measures, our guidelines are based on the following hierarchy, proposed by ISO 45001 (ISO, 2018b) and ANSI/ASSE Z117.1 (ANSI/ASSE, 2016) standards:

1. elimination of hazards where practicable;
2. substitution;
3. engineering controls;
4. signage/warnings and/or administrative controls for avoiding hazards and reducing the exposure frequency;
5. PPE for attenuating the severity of injury or exposure.

Following the hierarchy, safety managers should consider any options for eliminating the need for entry into confined spaces. Placing the elements requiring intervention outside the space, adapting the design so the work activities can be carried out outside, and/or making the elements in the space accessible and manoeuvrable from outside the space are some examples of methods that prevent the access into these areas (Burlet-Vienney et al., 2014). In addition, risk assessors can consider the use of self-cleaning or vibratory devices in hoppers and silos for avoiding the phenomenon of material bridges and, consequently, for undertaking tasks outside the space.

If the entry cannot be avoided in any way, definition of written operating procedures and recommendations to address activities, development of training programmes, and posting of warning signs could be common measures to all risks of each confined space because they are low-cost and non-technical. Furthermore, administrative procedures such as reducing time spent in the spaces and worker rotation can be other interesting low-cost safe practices.

In all identified confined spaces, safety managers should provide each entrant with the most adequate PPE. For example, in spaces that could have or develop a hazardous atmosphere, workers should wear respiratory protection devices; in areas where heat stress and thermal issues can arise, protective clothing should be used.

A relevant risk reduction measure is represented by a written permit (or authorisation for entry), whose objectives are to "provide a systematic review of hazards, communicate this information to all those involved and provide an approval process for permit space entry" (ANSI/ASSE, 2016). OSHA (2011) defines a Permit-Required Confined Space (PRCS) as a "confined space that has one or more of the following characteristics: (1) contains or has a potential to contain a hazardous atmosphere; (2) contains a material that has the potential for engulfing an entrant; (3) has an internal configuration such that an entrant could be trapped or asphyxiated by inwardly converging walls or by a floor which slopes downward and tapers to a smaller cross-section; or (4) contains any other recognized serious safety or health hazard". Consequently, entry into spaces where there could be an oxygen deficient atmosphere (Stefana et al., 2015, 2016, 2017) requires the preparation of this permit.

In all PRCSs, risk managers should assign at least one attendant outside the space itself in order to constantly monitor processes and operations inside, communicate with entrants, and provide support in a timely manner. In confined spaces with relevant length (such as pipes and conduits), the attendant can be supplemented by remote means for communication (e.g. radio devices). Note that in non-permit confined spaces, the provision of an attendant is optional.

Finally, our guidelines tackle emergency measures and rescue procedures. All identified confined spaces involve both atmospheric and non-atmospheric hazardous conditions. Therefore, as underlined by McManus (1998), rescuers should give particular attention to accident conditions, recognise the hazards, and react safely.

Table 2 provides an overview of the types of confined spaces, the related risks, the main traditional risk reduction measures, and the recognition of PRCS. The risks and the main traditional measures are listed in alphabetical order.

3.3 Proposals of Industry 4.0 technologies

In addition to traditional reduction measures, risk assessors can adopt some of available Industry 4.0 technologies for improving risk prevention and mitigation. Some papers in the literature and online databases contain examples of solutions that can be suited to operations to be performed in steel companies' confined spaces. In Table 3 we report some Industry 4.0 technologies (in alphabetical order) and we indicate in which confined spaces can be particularly appropriate to face confined spaces' hazardousness in steel companies.

According to the risk reduction hierarchy, reported in the previous paragraph, safety managers should try to eliminate risks at the source. In this sense, non-man entry technologies represent the best risk treatment solutions because allow to eliminate the need to enter the space. Several examples of such technologies can be found in Botti et al. (2017a). For instance, steel companies can consider the adoption of semi-movable devices for applying internal lining material, robots for cleaning, emptying, and performing inspection of tanks and containers, acoustic systems for analysing the tank content, and video cameras for checking cistern, tank, and pipe surfaces to individuate any anomaly.

Table 2: Types of confined spaces in steel companies, related risks, reduction measures, and request for entry permit

		Types of confined spaces (ID)															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Risks	Asphyxiation due to oxygen deficiency			×	×	×	×	×		×	×		×		×		×
	Awkward movement			×						×							
	Contact with and injection of high-pressure fluids						×	×				×				×	
	Contact with and/or inhalation of irritant gases, chemical products, and metallic compounds	×		×			×	×	×	×	×	×	×			×	
	Contact with electrical parts		×													×	
	Contact with hot surfaces								×	×		×					×
	Contact with moving parts							×								×	
	Drowning											×		×			
	Electrocution		×													×	
	Engulfment						×						×		×		
	Fall from heights	×		×			×	×	×	×		×	×	×	×	×	×
	Falling objects						×	×	×	×		×		×	×		×
	Fire/explosion		×		×	×						×				×	
	Heat stress				×	×			×	×	×	×		×		×	×
	Noise					×		×									
	Physical exertion									×							
	Poor body posture			×						×							
	Poor body posture due to limited means of access/egress						×						×		×		
	Reduced visibility/Inadequate lighting		×	×		×		×			×		×		×	×	
	Slip/trip	×	×	×	×				×	×		×		×		×	×
	Vibration							×									
Main traditional risk reduction measures	Atmosphere monitoring/testing	×		×	×	×	×	×		×	×	×	×		×	×	×
	Closure of valves						×	×				×				×	
	Implementation of purging practices		×		×	×						×				×	
	Installation of entry barriers															×	
	Installation of extraction systems								×	×							×
	Installation of railings	×						×				×		×			
	Installation of safeguards around electrical components		×													×	
	Installation of safeguards around mechanical components							×								×	
	Installation of vertical ladders with safety cage						×										
	Installation of vibrators, air purgers, and/or rotating flail devices						×						×				
	Interruption of crane movement								×								
	Isolation of piping systems						×	×				×		×		×	
	Lockout/tagout of equipment							×				×					
	Measurement of internal temperature											×					
	Placement of adequate platforms	×							×								×
	Plant shutdown							×									
	Provision of fall protection anchor points built into the structure	×							×			×					×
	Provision of ventilation				×	×							×				
	Removal of residues and previous contents						×							×	×		
	Use of ATEX equipment and protective systems		×		×							×				×	
	Use of gas detectors	×		×	×	×	×	×		×	×				×		×
	Use of portable light			×		×		×			×		×			×	
PRCS				×	×	×	×	×	×	×	×		×		×		×

Table 3: Industry 4.0 technologies suitable for confined spaces in steel companies

Industry 4.0 technologies	Types of confined spaces (ID)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3D mapping measurement technologies												×	×	×		
Acoustic systems						×						×	×	×		
Augmented reality systems				×			×			×	×	×		×		
Industrial robots				×	×	×		×	×		×	×	×	×	×	×
IoT wearable devices				×	×	×		×			×	×		×	×	
Semi-movable devices				×				×	×							×
Solutions for (online) monitoring				×	×			×	×	×	×		×	×		×
Systems for lone workers	×		×	×	×	×	×			×					×	
Technologies for automatic gas detection			×	×	×	×	×		×	×		×		×		×
Video cameras			×		×	×				×		×	×	×		
Video surveillance systems	×	×	×	×	×		×								×	
Virtual reality systems	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

Industrial robots can be particularly useful tools during some extraordinary maintenance operations in steel confined spaces, such as the release of the obstructed material and the refurbishment of structures. Indeed, these instruments permit to replace human for performing dangerous tasks and during an emergency. For example, the mobile robot with an electronic nose described by Razak et al. (2016) can be used in steel furnaces and tanks.

In many confined spaces typically present in a steel company, workers can rely on IoT wearable devices that improve information flows among workers, safety managers, and rescuers, and to provide support during the risk control and supervision (Botti et al., 2015; Botti et al., 2016; Zhou et al., 2017). For example, the system described by Riaz et al. (2014) facilitates intelligent and real-time monitoring of confined spaces, and manages alarms to workers in specific areas thanks to the acquisition of oxygen level and air temperature data in the site.

Further safety improvements can also be achieved using virtual reality. It allows the user to simulate and interactively explore the confined space, and therefore to improve training related to the carrying out of risky activities and emergency and rescue management.

The risk and activity supervision and the emergency management can be further supported thanks to a video surveillance system made available to workers outside confined spaces. It may be helpful both when using industrial robots and when operators are in the space.

More effective performance during repair or replacement of components in furnaces, conduits, and tunnels, and cleaning of hoppers and chimneys can be obtained through different systems available on the market for lone workers. These systems support lone workers operating in confined spaces constantly via periodic status check, individuate them (through a real-time GPS location), and direct rescuers in the fastest possible time in case of emergency. The presence of motion sensors and of Worker Down function in the device gives the possibility to react promptly to alarms during falls and/or incidents. As a matter of fact, systems for lone workers also facilitate emergency and rescue coordination, and accident investigation. For instance, the wearable automated safety suit suggested by Aleksy and Rissanen (2014) includes several sensors (e.g. oxygen level and temperature meters), alerts the different supervisors in case of dangerous situation, and is able to send warning (e.g. audio and/or vibro-tactile) messages.

Technologies for automatic gas detection can be applied in confined spaces where workers can be exposed to asphyxiation due to oxygen deficiency, and/or to atmospheres containing toxic and/or flammable contaminants. Such tools allow to give hazard transparency about environment conditions and (pre-)alert operators and assessors about hazards. Additionally, they could give information about overexposure of operators, and where, when, and why this exposure occurs.

For increasing context awareness of workers both inside and outside the confined space during repair or replacement of components in chambers and/or maintenance operations in silos, safety managers can choose augmented reality systems providing real-time information and visualisations of components and equipment. Besides these devices, the analysis of anomalies and inspections in several steel confined spaces can be conducted more safely thanks to the adoption of 3D mapping measurement technology and solutions for (online) monitoring. These solutions are particularly indicated also for inspection of refractories at high temperatures in furnaces and vacuum degasser tanks, and for analysing de-slagging and gas flow purging.

4. Conclusions

Although numerous regulations and technical documents deal with the topic of confined spaces, there are no available structured approaches for the risk management into these critical areas in steel industry. Our paper provides a first list of confined spaces that are typically present in a steel company, and some guidelines for assessing and managing risks in these spaces. In particular, this study can help steel safety managers to identify confined spaces, assess the related risks, and select the main traditional risk reduction measures. In addition to these typical measures, our study suggests several Industry 4.0 technologies for improving risk prevention and mitigation during some hazardous operations to be typically performed in steel companies' confined spaces. Future works may include testing the effectiveness of these identified Industry 4.0 alternatives in some steel companies, and defining a concise index for each confined space that summarises the entire risk assessment process and other relevant aggravating factors (e.g. emergency measures).

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