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Design of a digital tool for the identification of confined spaces

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Abstract.

Statistics on accidents in confined spaces reveal that many workers are injured and killed each year while working in confined spaces. The main cause of accidents and fatalities due to work in confined spaces is related to the lack of awareness about the presence and the risks of such unconventional workplaces. A confined space hazard assessment and risk control program should be implemented prior to access a confined space, aiming to control the risks associated with working in a confined space. This paper introduces a structured procedure and a digital tool for mobile devices, which aim to increase workers' awareness about the risks of working in confined spaces.

The proposed tool investigates four different categories of confinement that characterize confined spaces: geometry, access, internal configuration, and atmosphere. After completing the procedure on the mobile application, the user, e.g. the employer or the company's safety professional, receives a list of potential issues that should be addressed before entering the space. Three case studies show the application of the proposed methodology to three suspected confined spaces.

Keywords. Confined space; identification; digital tool; risk assessment support; occupational health and safety.

1 Introduction

Work in confined spaces is a high-risk activity that poses a serious life-threatening hazard to workers who perform it. The risk factors related to work in confined spaces are due to both the characteristics of the confined area and the characteristics of the task to be performed (Botti et al., 2015). Activities such as cleaning, repairing and welding can create hazardous working conditions, when performed within a confined space. Past and recent statistics show that fatal incidents still occur, despite international efforts in defining consistent procedures and recommendations for safe confined space work (Burlet-Vienney et al., 2014).

The 29 CFR 1910.146 of the American Occupational Safety and Health Administration (OSHA) defines "confined space" a space that is large enough and configured that an employee can enter and perform work, has limited openings of entry or exit and is not designed for continuous occupancy (OSHA, 1993). Examples of confined spaces include silos, vessels, boilers, storage tanks, sewers and pipelines, but even unconventional confined spaces, such as the interior areas of machinery where operators access to perform maintenance tasks. The 29 CFR 1910.146, known as the Permit Required Confined Space (PRCS) standard, distinguishes between permit and non-permit required confined spaces, specifying the requirements for practices and procedures to protect employees in general industry from the hazards of entry into confined spaces (Ye, 2011). Such standard has not been extended to cover employees entering confined spaces while engaged in specific industries, as construction work or confined space workers in agriculture because of the unique characteristics of such worksites.

Safety procedures and guidelines for work in confined spaces are not internationally standardized. Industrialized countries adopt different approaches to address the risks of work in confined spaces (Botti et al., 2018). Despite the worldwide regulations, employers have difficulty distinguishing workspaces that fall under the definition of confined spaces. The lack of situational awareness is a causal factor in many confined space accidents (Lucia Botti et al., 2017b). A recent investigation on confined space fatalities revealed a rate of confined space deaths between 0.05 and 0.08 fatalities per 100,000 workers in similar industrialized countries, e.g. Australia, Canada and USA (Selman et al., 2018). Several accidents and injuries related to work in confined spaces showed that workers access confined areas without proper training and personal protective equipment (Nano and Derudi, 2012).

Rescue operations are hazardous activities, especially when performed in confined spaces. Emergency response is a low-frequency, unexpected and unplanned operation requiring high-risk activities in a short time. Statistics on accidents and fatalities in confined spaces show that many would-be rescuers perish in an attempt to rescue a victim after a confined space accident. Reports and investigations on confined space accidents refer to the *chain of solidarity* phenomenon when describing a chain of events that involved multiple workers who perished in an attempt to rescue a victim in a confined space (CSB, 2006; OSHA, 2017). Would-be rescuers deaths include trained fire-fighters and competent personnel who had years of experience. However, the atmosphere and the features of confined spaces may produce unexpected conditions that make rescue operations difficult and dangerous. The *chain of solidarity* among would-be rescuer deaths is a worldwide challenging issue.

Recent data on work-related confined space fatalities estimate a 17% of confined space deaths involving rescuers (Selman et al., 2018). The leading cause of accidents involving rescue personnel is the atmospheric condition, e.g. oxygen deficiency and toxic airborne contaminants (Selman et al., 2018). In 2006, a tragic accident involved two workers who remained asphyxiated inside a nitrogen filled vessel in a refinery in Delware (CSB, 2006). The results of the investigations suggested that one worker may have fallen into the vessel, or was overcome by the oxygen-depleted atmosphere directly above the opening. Seeing his co-worker lying on the tray five feet down inside the reactor, the second worker inserted a ladder through the opening and climbed inside. He too was overcome by the oxygen-depleted environment and also succumbed. This incident is one of many where would-be rescuers become casualties because they act on emotion rather than their training. The U.S. Chemical Safety Board reported that better hazard awareness training and proper confined space rescue actions might have avoided such fatalities. The hazards of an unsafe atmosphere may not be evident to a rescuer, i.e. a rescuer attempts a rescue if unconscious of the hazards of entry (Selman et al., 2018). These data reveal a lack of situation awareness about the presence of confined spaces and of the risks of confined space work (Burlet-Vienney et al., 2015a, 2014).

Confined spaces with limited geometric features are easily identifiable. The dimensions of the access are further conditions to verify when investigating the presence of a confined space. Limited or restricted means for entry or exit may characterize a confined space, regardless the size of the confined area. Specifically, restricted means for entry may hinder rescue operations in case of accident within the confined space.

In addition, the internal configuration (e.g. the presence of plants, machinery or bulk materials) and the atmospheric conditions within the confined area are important aspects to assess. The atmospheric conditions within a confined space may change rapidly, producing unexpected hazardous conditions, e.g. with high concentration of toxic substances or low oxygen levels.

Between 1992 and 2005, an average of nearly 38 deaths occurred per year in the United States due to poisoning or asphyxiation in confined spaces. Twenty percent of these events resulted in several deaths (Wilson et al., 2012). The American National Institute for Occupational Safety and Health (NIOSH) has published the Publication 80-106 (1979) outlining a classification system for confined spaces, with focus on the atmosphere characteristics. The NIOSH publication provides a checklist of factors to consider for the analysis of hazardous atmospheres, based on the content of oxygen, flammable substances and potential or toxic air contaminants. The presence of hazardous atmospheric conditions may lead dangerous events, as fires or explosions. Previous studies have investigated the presence of dangerous substances and hazardous atmospheric conditions associated with blasting and explosions in confined spaces (Chettouh et al., 2016; Harris and Mainiero, 2008; Kolbe et al., 2017; Salvado et al., 2017; Salzano, 2014). Salvado et al. (2017) proposed a mathematical model supporting the analysis of the destructive effects of detonations in confined industrial spaces. Harris and Mainiero (2008) investigated the means of preventing CO migration in underground enclosed areas, while Salzano (2014) examined the basic conditions for explosion and the critical safety parameters needed for the prediction, prevention, and mitigation of gas and dust explosions in confined spaces. Further researches focused on the oxygen deficiency hazard and the exposure of workers to the risk of asphyxiation (Hughes and Ferrett, 2008; Kletz, 2009; Lunn, 2017; Mejías et al., 2014; Stefana et al., 2015; Sundal et al., 2017).

Recent studies have focused on the development of tools and practical solutions for managing the risks associated with confined space interventions (Burlet-Vienney et al., 2015b). Such tools include frameworks and models, software applications (mobile and web applications), and Internet of Things (IOT) technologies, such as wireless sensors, cameras and atmosphere detectors.

1.1 Frameworks and models

Framework and models address the risks of work in confined spaces by suggesting a step-wise approach. For example, the OSHA has published the quick card, which is a document that summarizes the characteristics of PRCS and provides suggestions to reduce the likelihood of confined-space accidents and injuries (OSHA, 2018). Burlet-Vienney et al. (2015a) developed a five-step risk assessment tool for confined spaces based on risk management standards. The tool investigates and analyses the factors influencing the risks during an intervention in a confined space, categorizing interventions and rescue conditions by means of objective criteria. Garmer et al. (2015) proposed a three-step risk assessment method for the ship recycling sector. Aneziris et al. (2010) applied a workgroup occupational risk model to quantify the risk of work in a highway tunnel. More recently, Selman et al. (2019) focused on rescue operations, proposing a five-step procedure for safe confined space entry. Specifically, the procedure considers a hierarchy for protection (e.g. rescuers, bystanders, and casualties) and a hierarchy of the level of confined space rescue (e.g. self-rescue, non-entry rescue, and entry rescue). In these frameworks and models for risk assessment of confined spaces, the employer and the safety professionals set the input data for checklists. Such activity is performed during the plan of the intervention and it may be influenced by human perceptions, rather than the effective characteristics of the confined space and of the work to be performed.

1.2 Software applications

Software applications include mobile and web applications that support employers and site operators during the risk assessment and on site. The mobile application works in confined spaces, regardless the cell phone coverage or the Internet connection. The assessments performed with the mobile application are automatically uploaded on the web application as soon as the mobile device is online. Employers and workers can download the applications on their smartphones and/or tablets, and access customized inspection checklists for confined spaces. In addition, cloud functions allow the mobile applications to gather data through safety and health inspections and to store them in the cloud. For example, Qing-gui et al. (2012) designed an application software for risk management and safety countermeasures optimization in coal mine. The system includes a safety countermeasures database with several data for workers' unsafe behaviour control and risk control countermeasures. In case of emergency, the software sends a real-time alarm to the mobile phones of managers and site operators.

1.3 Internet of Things (IOT) technologies

IOT technologies for safe confined space work include commercial wireless sensors, cameras and atmosphere detectors. The main contribution of IOT technologies for the reduction of the risks of confined space work is due to an improved information flow between the confined space and the actors involved in confined space activity, whether they are workers or rescuers (Botti et al., 2015). In this context, IOT technologies provide a strong contribution to the improvement of the rescue operations and higher performances of the emergency interventions. These technologies have been widely adopted for confined space work in industry in the last decades (Botti et al., 2015; Yang et al., 2013). Riaz et al. (2014) proposed a prototype system based on IOT technologies for providing safety managers about temperature and oxygen concentration in construction sites where confined space risk is high. The system applies wireless sensor network to acquire data from the construction site and manage alarms to workers in specific areas.

This paper introduces the design process and the structure of a mobile application for the identification of confined spaces. The aim was to realize an effective tool to prevent workers entry into high-risk confined spaces. In collaboration with a panel of experts in engineering, occupational health and safety, occupational accident insurance, firefighting operations and employment contracts, an algorithm for the identification of confined spaces was conceptualized. The algorithm defined the conceptual structure of a procedure for the identification of confined spaces. A digital tool, i.e. a mobile application, for mobile devices based on the proposed procedure was developed to help employers, employees, practitioners and safety professionals during the identification of confined spaces. The Confined Space Alert (CSA) index is the result of the procedure on the mobile application. The CSA index quantifies the confinement characteristics of the investigated confined areas. In addition, the tool supports the mandatory risk assessment for confined spaces by alerting the user about the critical issues identified during the completion of the structured procedure.

In the following Section 2, the algorithm, the procedure and the digital tool for the identifications of confined spaces are introduced, together with the mathematical formulation for the CSA index. Section 3 describes the application of the digital tool to different suspected confined spaces. Finally, Section 4 and Section 5 introduce and discuss the results and the conclusions of this study.

2 Methods

This section introduces the proposed algorithm for the identification of confined spaces. A panel of experts in the field of Occupational Health and Safety (OHS) and work in confined spaces participated in the study. These experts include a professional engineer, an expert in occupational accident insurance, two firefighters, two labor inspectors, three academics (two full-time professors and a researcher) and six OHS specialists. The team met periodically to discuss the structure of the algorithm and share the results of the tests performed during their professional activities.

Following the structure of the methodology proposed by Botti, Mora, & Ferrari (2017), the algorithm described in this paper supports the investigation of suspected confined spaces, analyzing four categories of confinement that characterize such confined areas: geometry, access, internal configuration and atmosphere. A structured procedure, based on the introduced categories of confinement, drives the mobile application for the identification of confined spaces. The result of the procedure is the CSA index. The CSA index defines the risk of being in proximity to a confined space. In addition, the mobile application informs the user about the identified characteristics of confinement and other critical issues related to the presence of a confined space.

2.1 Definition of the parameters for the identification of confined spaces

The Occupational Safety and Health Administration (OSHA) of the United States promulgated the regulations on work in confined spaces, aiming to help employers and employees in recognizing these hazardous workplaces. Such regulations provide information on how to work safely in confines spaces, requiring companies and safety professional to develop a structured written program, issue entry permits, designate entrants (i.e. the workers allowed to enter the confined space), assign attendant(s) to supervise the entrants, and ensure safe means of rescue. The PRCS is a reference standard for companies, safety professionals and technicians that deal with work in confined spaces (Lucia Botti et al., 2017a). Such standard defines that a permit-required confined space contains or has potential to contain a hazardous atmosphere, contains a material that could potentially engulf the entrants, has an internal configuration that could trap or asphyxiate a worker, or presents any other serious, recognized hazard. Consequently, the design features of a confined space may determine whether it falls under the definition of PRCS or if it has potential to increase the risks for workers’ health and safety.

Following the structure of the methodology proposed by Botti, Mora, & Ferrari (2017), the tool described in this paper includes the PRCS definition for the identification of confined spaces. The investigation of a suspected confined space is based on the analysis of four categories of confinement that characterize confined spaces: geometry, access, internal configuration, and atmosphere.

2.1.1 Geometry

Restricted dimensions and a limited interior area characterize confined spaces. The OSHA's PRCS standard states that a confined space is large enough and so configured that an employee can bodily enter and perform assigned work. The concept of limitation of a dimension refers to the dimension of the human body, fully equipped to face the worst possible scenario. The minimum working area of a worker may be computed as the circumference drawn by his arm. Given the length of the arm of the 99th percentile man as equal to 800 mm (Tilley and Associates, 2002) and an additional increase due to the PPE (e.g., protective gloves) of 5 mm, the minimum working area of a worker is equal to a circumference with a ray of 805 mm. Therefore, a space is "geometrically confined" if the circumference with a diameter of 1,800 mm (ray 900 mm) and center at the intersection between the transverse plane and the longitudinal axis is not completely clear and free from obstructions (Figure 1A). Additional conditions that aggravate the geometric features of a confined space are the presence of hollowed areas below the walking surface, and extensions far from the entry (Figure 1B and 1C).

A B C

Fig. 1. Conditions of geometric confinement (A. Presence of at least one dimension of the space < 1800 mm; B. The space presents hollow areas, below the walking surface; C. The space is extended or branched in various areas, with hollow surfaces

2.1.2 Access

The international standards on anthropometric measures provide the dimensions of the human body (ISO, 2010; UNI Ente Italiano di Normazione, 2009a, 2009b, 2009c). Such standards allow determining the dimensions of the human body ellipse, which are 600 mm for the major axis (shoulder breadth) and 450 mm for the minor axis (body width). The access of a space is confined if the diameter or the shortest dimension of the entry is smaller than 600 mm (Figure 2A). The presence of a singular vertical or high lateral access (Figure 2B) and the need to use technical aids to access the space (Figure 2C) are aggravating conditions of the confined access.

A B C

Fig. 2. Conditions of access confinement (A. The diameter or the shortest dimension is < 600mm; B. The access is vertical/high lateral or technical aids are necessary; C. There is single access to the space)

2.1.3 Internal configuration

Internal configuration refers to the internal characteristics of the space. The internal configuration of a space is confined if the space is not designed for continuous occupancy. The presence of bulk materials that have the potential for engulfing the entrant or residuals from previous operations aggravate the conditions of the internal configuration, increasing the exposure of the worker to the risks of confined space work. Additional aggravating conditions are: the potential risk of slipping, stumbling and falling, the potential presence of unstable structures or materials, noise and vibration, interference in communication, liquid or gas infiltrations, adverse environmental conditions and other recognized threats for workers' safety and health.

2.1.4 Atmosphere

A space is atmospherically confined if it contains or has potential to contain a hazardous atmosphere. The presence of low or high oxygen levels, or the presence of toxic or explosive substances characterize spaces that are atmospherically confined. Aggravating conditions of atmospherically confined spaces include the absence of a natural or artificial efficient ventilation system that ensures proper ventilation in every accessible point, and the potential presence of residuals from previous activities.

Each confinement category (i.e. geometry, access, internal configuration and atmosphere) identifies a dimension of the confined space. Specifically, a space can be limited in one or more confinement dimensions, e.g. geometrically confined spaces as tanks or ship hulls may not have a confined atmosphere.

2.2 Algorithm for the identification of a confined space

The algorithm that drives the tool for the identification of confined spaces is based on the categories of confinement introduced in Section 2.1. Such categories outline a concise representation of the investigated confined space. Figure 3 describes the proposed algorithm for the identification of confined spaces.

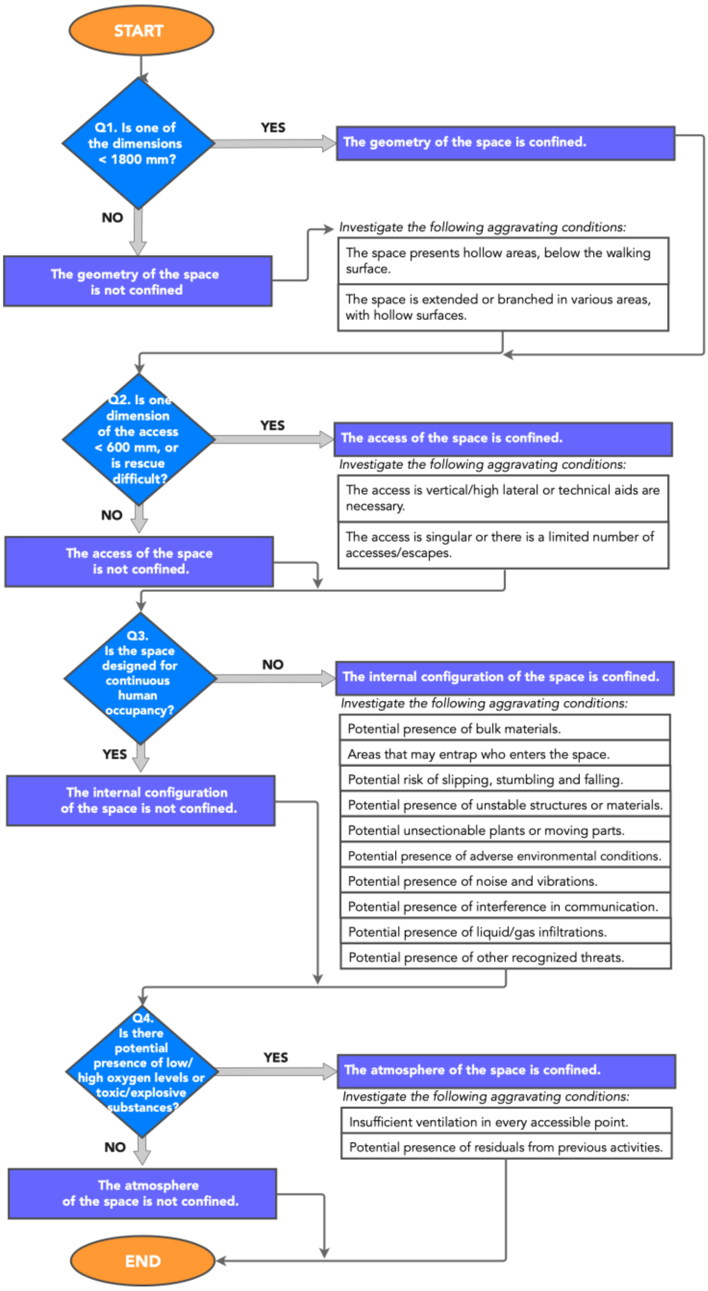


Fig. 3. Algorithm for the identification of confined spaces

The algorithm in Figure 3 guides employers, employees and safety professionals through the process for the identification of confined spaces, before entering a suspected confined area. A space can be confined in one or more categories of confinement. Then, the presence of a confined space is confirmed when one or more categories of confinement are verified. The four principal questions Q1, Q2, Q3 and Q4 investigate the presence of the necessary condition of confinement, for each category of confinement. The answer "YES" to at least one of the principal questions Q1, Q2 and Q4, or the answer "NO" to Q3, defines the presence of a confined space. The type of confinement refers to the specific categories for which the user (i.e. the employer or the safety professional who is in charge to perform the risk assessment) answers "YES". Aggravating conditions are investigated in case of answer "YES" to necessary conditions Q1, Q2 and Q4, or answer "NO" to necessary condition Q3. Based on the algorithm in Figure 3, Table 1 shows a checklist including both necessary and aggravating conditions, for each category of confinement.

Table 1. Checklist with necessary and aggravating conditions for the identification of confined spaces.

Conditions	YES	NO
Geometry		
A1. Presence of at least one dimension of the space < 1800 mm	☐	☐
A2. The space presents hollow areas, below the walking surface	☐	☐
A3. The space is extended or branched in various areas, with hollow surfaces	☐	☐
Access		
B1. The diameter or the shortest dimension is < 600mm or rescue is difficult	☐	☐
B2. The access is vertical/high lateral or technical aids are necessary	☐	☐
B3. There is single access to the space	☐	☐
Internal Configuration		
C1. Not designed for continuous human occupancy (answer YES is for a not conventional workplace)	☐	☐
C2. Potential presence of bulk materials which may cause engulfment, drowning or hit who enters the space	☐	☐
C3. The internal configuration has particular areas (bottlenecks, blind spots, etc.) which may entrap who enters the space, and/or closed circumscribed areas or cavities which may hinder rescue operations	☐	☐
C4. Potential presence of risk of slipping, stumbling and falling, potential presence of residuals which may hinder the access or the ability to walk inside the space, or use and/or storage of bulky and/or heavy material	☐	☐
C5. Potential presence of unstable and/or precarious structures or materials	☐	☐
C6. Potential presence of unsectionable plants or moving parts	☐	☐
C7. Potential presence of adverse environmental conditions (poor illumination and/or high/low temperature and/or humidity)	☐	☐
C8. Potential presence of noise and/or vibrations	☐	☐
C9. Potential presence of interference in communication	☐	☐
C10. Potential absence of isolation from liquid/gas infiltration	☐	☐
C11. Potential presence of other recognized threats to health and safety	☐	☐
Atmosphere		
D1. Potential presence of low or high oxygen levels and/or natural presence of toxic/explosive substances or induced by expected work activity	☐	☐
D2. Natural and/or artificial ventilation absent or not sufficient	☐	☐
D3. Potential presence of residuals from previous work activities.	☐	☐

Necessary conditions A1, B1, C1 and D1 in Table 1 refer to Q1, Q2, Q3 and Q4 in Figure 1. The user completes the checklist before entering a suspected confined space. However, the user may not be aware of the conditions inside the confined space prior to enter. For this reason, the statements in Table 1 refer to potential risk conditions that might be present. A mark is assigned to each condition concerning the situation in the suspected confined space. For example, the answer "YES" to conditions A1 and C1 define a geometrically confined space with a confined internal configuration (Table 1). Furthermore, aggravating conditions may determine the automatic mark on the necessary condition for their category of confinement. The following Section 2.3 describes the relationship between necessary and aggravating conditions for each category of confinement, together with the formulation for the CSA index.

2.3 The Confined Space Alert (CSA) index

The Confined Space Alert (CSA) index is a quantitative measure for the potential presence of a confined space. The marks in the checklist in Table 1 contribute to determine the CSA index.

A score is attributed to each marked condition. Specifically, the score for necessary conditions is equal to 1.1, while the value of aggravating conditions is set to 0.3. Such values were obtained from multiple tests of the algorithm in different case studies. The panel of experts involved in this study defined the values adopted in the algorithm, based on their professional experience and on the results of the test cases. Conditions without the mark have no score. The following Equation (1) defines the CSA index.

$$CSA = \alpha \cdot \left(\sum_{i=1}^{j} Ai\right) + \beta \cdot \left(\sum_{i=1}^{k} Bi\right) + \gamma \cdot \left(C \cdot \sum_{i=1}^{m} Ci\right) + \delta \cdot \left(D \cdot \sum_{i=1}^{n} Di\right) \quad (1)$$

where

$$C \begin{cases} 1, if\ C1, C2, C3, C5, C6, C7\ or\ C10\ is\ present \\ 0, otherwise \end{cases} \quad (2)$$

$$C1 \begin{cases} \neq 0, if\ C2, C3, C5, C6, C7\ or\ C10\ is\ present \\ 0, otherwise \end{cases} \quad (3)$$

$$D \begin{cases} 1, if\ D1, D2\ or\ D3\ is\ present \\ 0, otherwise \end{cases} \quad (4)$$

$$D1 \begin{cases} \neq 0, if\ D2\ or\ D3\ is\ present \\ 0, otherwise \end{cases} \quad (5)$$

Table 2. Notations for the computation of the CSA index.

Indices	*Description*	*Value*
i	Conditions index	From 1 to 11
j	Index for conditions in confinement category “geometry”	3
k	Index for conditions in confinement category “access”	3
m	Index for conditions in confinement category “internal configuration”	11
n	Index for conditions in confinement category “atmosphere”	3
Parameters	*Description*	*Value*
Ai	Condition *i* in confinement category “geometry”	$A1$ = 1.1; otherwise 0.3
Bi	Condition *i* in confinement category “access”	$B1$ = 1.1; otherwise 0.3
Ci	Condition *i* in confinement category “internal configuration”	$C1$ = 1.1; otherwise 0.3. See additional condition in (3)
Di	Condition *i* in confinement category “atmosphere”	$D1$ = 1.1; otherwise 0.3. See additional condition in (5)
C	Coefficient for the selection of necessary and aggravating conditions in confinement category “internal configuration”	See in (2)
D	Coefficient for the selection of necessary and aggravating conditions in confinement category “atmosphere”	See in (4)
α	Coefficient for confinement category “geometry”	1.8
β	Coefficient for confinement category “access”	3
γ	Coefficient for confinement category “internal configuration”	2
δ	Coefficient for confinement category “atmosphere”	5

Table 2 shows the indices and the parameters for the calculation of the CSA index. Specifically, the CSA index includes the contribution of necessary and aggravating conditions for each category of confinement. Four coefficients, α, β, γ, δ, weight the importance of each category of confinement to the risk of being in proximity to a confined space. Their values are in Table 2. Coefficient *C* ensures that category “internal configuration” is excluded from the CSA index calculation if *C1, C2, C3, C5, C6, C7* or *C10* are not verified (Equation 2). In addition, necessary condition *C1* is automatically included in the CSA index calculation if aggravating conditions *C2, C3, C5, C6, C7* or *C10* are present (Equation 3). Necessary condition *D1* is automatically included in the CSA index calculation if aggravating conditions *D2* or *D3* are present (Equation 4). Finally, the presence of at least an aggravating condition for confinement category “atmosphere”, i.e. *D2* or *D3*, determines the automatic inclusion of necessary condition *D1* in the CSA index calculation (Equation 5).

Table 3 shows the ranges for the CSA index.

Table 3. Ranges that define risk levels of being in proximity to a confined space.

CSA Index Value	Risk Level	Consequences	Alert color

0	No risk	No confined space. The space is not confined, no confinement conditions are present.
$0 < CSA < 3$	Low risk	Green alert: low probability of being in proximity to a confined space. Non-significant consequences.
$3 \leq CSA < 8$	Medium risk	Yellow alert: medium probability of being in proximity to a confined space. Improve the risk factors and adopt risk control measures.
$8 \leq CSA < 15$	Significant risk	Red alert: high probability of being in proximity to a confined space. Re-design the activities and/or the workplaces. Avoid entry if possible.
$15 \leq CSA \leq 25$	Very high risk	Violet alert: presence of a confined space! Avoid entry under the present conditions. Re-design the activities and/or the workplace.

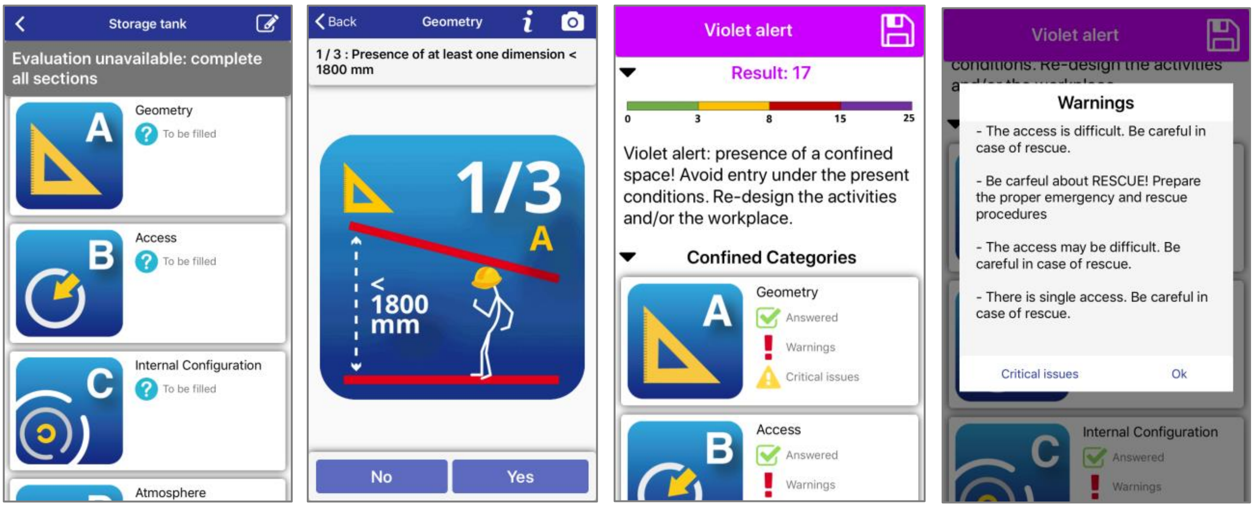
The CSA index is a number between 0 and 25. The computation of the CSA index is based on the answers provided by the user for each item in the checklist in Table 1. Hence, the result depends on the judgements provided by the user. The value of the CSA index is 0 if no condition for confinement is verified in the investigated space. The maximum value for the CSA index is 25 and it represents a confined space where all the necessary and aggravating conditions are present.

The user completes the checklist by means of a structured procedure on a digital tool, i.e. the mobile application (see Section 2.4). The procedure is based on the structure of the algorithm in Figure 1 and on the checklist in Table 1. The result is the CSA index for the suspected confined space. In addition, the mobile application informs the user about the identified characteristics of confinement, providing a set of warnings and critical issues related to the investigated space.

The value of the resulting CSA index is then compared with the ranges in Table 3, which define the corresponding risk level. In case of low risk of being about to enter a confined space, risk control measures as engineering controls, administrative controls and PPE should be taken. When the risk is high, workers should not enter the confined space. Tasks should be redesigned to avoid man entry and including the adoption of non-man entry technologies for work in confined spaces (L. Botti et al., 2017). A possible alternative is the redesign of the workplace to eliminate the necessary conditions concerning the identified confined space.

2.4 Design of the digital tool

A digital tool was developed to support safety practitioners and workers during the investigation of potential confined spaces. The digital tool is a mobile application compatible with both Android and iOS mobile operating systems. The algorithm in Figure 3 was transformed on the mobile application into the investigation process in Figure 4, as a visual representation of the proposed approach.



A B C D

Fig. 4. Mockup development of the mobile application: categories of confinement (A), investigation of the necessary condition for the category "Geometry" (B), result of the investigation (C), warnings after the completion of the category "Access" (D).

Three beta versions have been developed before defining the final wireframe of the mobile application. The mobile application contains graphical, verbal and numerical information. Pictures and symbols improve the user experience, supporting the browsing of the four categories of confinement (Figure 4A). A set of personal information about the user are required prior to the start of the procedure, e.g. name, role and years of experience. The consent to the use of geo-localization services on the device allows the application to store the information about the location of the space where the procedure is completed.

Investigation steps are based on the structure of the checklist in Table 1, i.e. the user browses the application by answering questions with regard to necessary and aggravating conditions, for each the category of confinement (Figure 4B). The user may take pictures with the camera, providing a graphical description for each answer provided in the application. The results of the investigation and the resulting CSA index appear on the screen after all the categories of confinement have been investigated (Figure 4C). At certain steps, a pop-up message appears on the screen. The message informs the user on critical issues detected during the investigation. By touching the exclamation mark and the triangular icon at the end of the investigation, the user gets additional information on warnings and critical issues about the investigated space (Figure 4D).

Personal credentials are generated at the first start of the application. The user can save the investigations performed with the mobile application on the mobile device. A synchronizing option is available to save the investigations on an online server. All the synchronized investigations are accessible online using the personal credentials on a dedicated website. The digital tool is available for smartphones and tablets on the major stores for mobile applications. Users may register or log in before using the tool on their personal devices. There is no maximum number of investigations that the user can save both on the mobile application and on the server. Date and time of the investigation performed with the mobile application define a unique ID for each investigation. Finally, the employer or the safety professional has access to the online server, from which it is possible to obtain a personal QR-code. The activation of the mobile application on the mobile devices is performed by means of the QR-code associated with the personal account in the server. The employer accesses and tracks the evaluations performed by employees with the company account using the personal credentials to access the web portal (https://confinedspaceapp.it/login). Each evaluation in the web portal includes the information provided by the user, e.g. the name of the user, the location of the confined space on the map and the pictures caught with the camera during the use of the application.

3 Case studies

This section introduces the application of the procedure in previous Section 2 to three suspected confined spaces.

The first case study concerns the investigation of the flour storage silo in Figure 5.

Fig. 5. Flour storage silo in a pork breeding farm.

The silo is situated in a pork breeding farm. The height of the silo is 3000 mm and the internal diameter is 1500 mm. A single access is present on the upper surface of the silo, with a manhole of 600 mm in diameter. Workers access the silo to perform cleaning activities and to manually unclog flour clusters from the walls, with a shovel and a flashlight. Such activities are dangerous due to the release of materials that may entrap the workers and the possible presence of gases.

In the second case study, a dairy tank in a cheese factory is investigated (Figure 6). The tank is 5000 mm height and 1500 mm in diameter. The access is singular, at the bottom of the tank. Specifically, the manhole in Figure 6 is a 600 x 400 mm ellipse. Workers access the tank to perform cleaning activities.

Fig. 6. Dairy tank in a cheese factory.

Both the employers of the pork breeding farm and from the cheese factory completed the procedure with the digital tool introduced in Section 2. The mobile application was downloaded on their personal smartphones prior to the investigation. A personal account to access the functionalities of the application was created for each company. Two workers who usually perform the cleaning activities were invited to complete the same procedure on their personal smartphone. The workers are full-time employees in the pork breeding farm and in the cheese factory.

Finally, the third case study concerns the investigation of the ship double hull in Figure 7.

Fig. 7. Double hull

The double hull is the space between the double layers of the ship hull. This structure reduces potential marine pollution in case of damage to the ship skin, and prevents water from penetrating in the ship failures. The cavity is a honeycomb structure made of metal sheets spaced at 600 mm intervals. The vertical distance between the bottom and the upper layers varies between 1000 – 1800 mm. The access to the double hull is a singular manhole measuring 400 x 600 mm. The space is dark and no openings are present for lighting. Workers enter the double hull with a flashlight and with the proper equipment for performing inspections and maintenance. Inspections aim to identify corrosions and any damage to the metal structures. Maintenance tasks frequently include welding operations and repairing interventions. A safety inspector from the Italian Local Health Authority of Ravenna completed the procedure for the investigation of the double hull with the mobile application on his personal smartphone. The results of the evaluation are in the following Section 4.

4 Results and discussion

4.1 Case study 1: Flour storage silo

The employer and the worker (employee) completed the procedure separately. Specifically, the employer is the owner of the pork breeding farm. The employee is a skilled worker with 11 years of experience in silo cleaning. The results were not shared until they both finished the procedure. Table 4 shows the answers provided in each evaluation.

Table 4. Answers in the evaluations related to the flour storage silo, for the employer and for the worker of the pork breeding farm.

Conditions	Employer		Worker	
Geometry	*YES*	*NO*	*YES*	*NO*
A1.		*x*		*x*
A2.	*x*		*x*	
A3.		*x*	*x*	
Access	*YES*	*NO*	*YES*	*NO*
B1.	*x*		*x*	
B2.	*x*		*x*	
B3.	*x*		*x*	
Internal Configuration	*YES*	*NO*	*YES*	*NO*
C1.	*x*			*x*
C2.	*x*		*x*	
C3.	*x*		*x*	
C4.	*x*		*x*	
C5.	*x*		*x*	
C6.		*x*		*x*
C7.	*x*		*x*	
C8.		*x*	*x*	
C9.	*x*			*x*
C10.		*x*	*x*	
C11.		*x*	*x*	
Atmosphere	*YES*	*NO*	*YES*	*NO*
D1.	*x*		*x*	
D2.	*x*		*x*	
D3.	*x*		*x*	
Results				
CSA index	19.9		21.7	
Alert (risk range)	Violet		Violet	

Following the checklist in Table 1, the evaluation in Table 4 shows that both the employer and the worker agreed that the necessary condition A1 is not present, i.e. no dimensions below 1800 mm are present. The answers for the aggravating conditions in category "Geometry" are partially different. The presence of all the conditions for category "Access" are confirmed in both the evaluations. Some discrepancies are present in category "Internal configuration". The employer confirmed the presence of the necessary condition C1, while the answer provided by the worker is clearly mistaken, as the silo was not designed for continuous occupancy. Such mistake may be due to excessive haste during the investigation. Both the employer and the worker agreed that all the conditions are present in category “Atmosphere”. The resulting CSA indices confirm the same risk range in both the evaluations, i.e. the alert is violet and the presence of the confined space is confirmed. The mobile application invites the users to avoid entry under the present conditions and to re-design the activities and/or the workplace. Finally, these findings suggest that the access, the internal configuration and the atmosphere of the flour storage silo are confined.

4.2 Case study 2: Dairy tank

The employer in this case study is the owner of the cheese factory where the dairy tank is situated. The worker has been an employee of the cheese factory for two years at the time of the evaluation. They completed the procedure separately on their personal smartphones. The results were not shared until both the employer and the worker finished the procedure. Table 5 shows the answers provided in each evaluation.

Table 5. Answers in the evaluations related to the dairy tank, for the employer and for the worker of the cheese factory.

Conditions	Employer		Worker	
Geometry	*YES*	*NO*	*YES*	*NO*
A1.	*x*		*x*	
A2.		*x*		*x*
A3.		*x*		*x*
Access	*YES*	*NO*	*YES*	*NO*
B1.	*x*		*x*	
B2.	*x*		*x*	
B3.	*x*		*x*	
Internal Configuration	*YES*	*NO*	*YES*	*NO*
C1.	*x*		*x*	
C2.	*x*			*x*
C3.	*x*			*x*
C4.	*x*			*x*
C5.	*x*		*x*	
C6.	*x*		*x*	
C7.	*x*		*x*	
C8.		*x*	*x*	
C9.	*x*		*x*	
C10.		*x*	*x*	
C11.		*x*	*x*	
Atmosphere	*YES*	*NO*	*YES*	*NO*
D1.		*x*	*x*	
D2.		*x*	*x*	
D3.		*x*	*x*	
Results				
CSA INDEX	13.5		22.0	
Alert (risk range)	Red		Violet	

The evaluations in Table 5 show that both the employer and the worker agreed about the conditions in the categories “Geometry” and “Access”, i.e. both the geometry and the access of the dairy tank are confined. The necessary condition C1 for the category “Internal Configuration” is confirmed in each evaluation, i.e. the internal configuration is confined, but some discrepancies are present for the aggravating conditions. Finally, opposite answers are present for category “Atmosphere”. Particularly, the evaluation performed by the employer reports no conditions in such category, while the employee confirmed the necessary condition D1 and both the aggravating conditions.

The results show a red alert for the evaluation performed by the employer, suggesting high probability of being in proximity to a confined space. The mobile application invited the employer to re-design the activities and/or the workplace, and to avoid entry if possible. The evaluation performed by the worker reveals a violet alert and the presence of a confined space.

The worker stated that he provided multiple "YES" to the conditions in the checklist because of his limited knowledge and awareness about the conditions inside the tank. Finally, the worker revealed that, after a second reading of the conditions in the checklist, he would edit multiple answers.

4.3 Case study 3: Double hull

The safety inspector used the digital tool for the identification of confined spaces during the investigation of a ship at the Port of Ravenna, in Italy. The mobile application was activated on his personal smartphone. Table 6 shows the answers provided during the evaluation of the double hall.

Table 6. Answers provided by the safety inspector during the evaluation of the double hull.

Conditions	Safety inspector	
Geometry	*YES*	*NO*
A1.	*x*	
A2.		*x*
A3.	*x*	
Access	*YES*	*NO*
B1.	*x*	
B2.	*x*	
B3.	*x*	
Internal Configuration	*YES*	*NO*
C1.	*x*	
C2.		*x*
C3.	*x*	
C4.	*x*	
C5.		*x*
C6.		*x*
C7.	*x*	
C8.	*x*	
C9.	*x*	
C10.		*x*
C11.		*x*
Atmosphere	*YES*	*NO*
D1.	*x*	
D2.	*x*	
D3.	*x*	
Results		
CSA index	18.5	
Alert (risk range)	Violet	

The evaluation in Table 6 shows that all the necessary conditions are present, i.e. the geometry, the access, the internal configuration and the atmosphere of the double hull are confined. All the aggravating conditions are present for categories "Access" and "Atmosphere". Specifically, the access is singular, technical aids are necessary in case of rescue and the internal atmosphere may not be safe. Further aggravating conditions are related to the cavities that may hinder rescue operations, the potential risk of stumbling and the falling, the poor illumination and the potential presence of noise, vibrations and interference to the communication during the work activity. The resulting CSA index is equal to 18.5, defining very high probability of being close to a confined space. Finally, the tool suggests to avoid entry under the present conditions and to re-design the activities and/or the workplace.

4.4 Other case studies

In this section a brief list of suspected confined spaces is provided, together with the results from the evaluations with the procedure in the mobile application.

Table 7. Examples of suspected confined spaces investigated with the procedure in the mobile application and results of the evaluation.

Suspected confined space	*A1 Geometry*	*B1 Access*	*C1 Internal configuraton*	*D1 Atmosphere*	*CSA INDEX*	*Alert*
Switch cabinets room					1.0	Green
Basement			x		4.8	Yellow
Aircraft	x		x		6.0	Yellow
Wind turbine nacelle		x	x		7.9	Yellow
Crawl space	x		x		8.6	Red
Automated warehouse			x	x	9.4	Red
Open-air technical well			x	x	10.0	Red
Depuration tank			x		10.7	Red
Underground room for machinery			x	x	11.0	Red
Bulk carrier hold			x	x	11.3	Red
Underground space below the cabinets			x	x	14.0	Red
Depuration tank			x	x	15.0	Violet
Sewer tunnel	x		x		16.8	Violet
Swimming pool	x		x	x	16.8	Violet
Construction pit	x	x	x		17.0	Violet
Ship crate	x	x	x	x	19.6	Violet
Laboratory false ceiling	x	x	x		20.0	Violet
Underground well	x	x	x	x	23.0	Violet

Table 7 shows the results of the test of the procedure with various suspected confined spaces in several industries, e.g. construction, manufacturing and power generation industry. For example, the investigation of a wind turbine nacelle revealed that the access and the internal configuration of such space are confined. Practice shows that wind turbine nacelle are not conventionally considered confined spaces. However, emergency and rescue operations require careful planning and proper equipment as would be for conventional confined space as tanks, silos and pipelines.

Similarly, the investigation of a swimming pool revealed high risk for the presence of confined space. Swimming pools are unconventional confined spaces, as their dimensions are large enough and so configured that workers can bodily enter and perform assigned work (OSHA, 2004). However, work activities in empty swimming pools, as cleaning and maintenance operations, require the use of chemicals and substances that may create the potential presence of low or high oxygen levels and the presence of toxic substances induced by the expected work activity. Furthermore, cleaning and maintenance operations in swimming pools may require workers to enter enclosed spaces such as filter vessels. This activity should be performed after a comprehensive assessment of the dangers associated with this work, and following the regulations on confined spaces (HSE, 2013).

These results are related to the specific confined spaces that were investigated with the procedure. The information introduced in Tables from 4 to 7 do not generalize the CSA INDEX values and the alerts for suspected confined spaces that may be similar to the introduced case studies. A new investigation with the introduced digital tool should be performed whenever it is required to perform work in a suspected confined space.

5 Conclusions

This paper has introduced an innovative methodology based on an algorithm and a structured procedure for the identification of confined spaces. The algorithm investigates a set of critical parameters that define four categories of confinement: geometry, access, internal configuration and atmosphere. The procedure was developed to support the user during the investigation of such parameters on a digital tool, i.e. a mobile application. The result of the procedure is the Confined Space Alert (CSA) index, which measures the probability of being in proximity to a confined space. The digital tool is available for smartphones and tablets on the major stores for mobile applications. The download of the tool is free. Users may register or log in before using the tool on their personal devices. A web portal was developed to collect the evaluations performed by the users. Registered users, as employers and safety professionals, may use the web portal to allow the installation of the tool on the personal devices belonging to their employees.

Each evaluation in the web portal includes the information provided by the user, e.g. the name of the user, the location of the confined space on the map (the geolocation of the mobile device is required for this function) and the pictures caught with the camera during the use of the application. Such data are useful information for the preparation of rescue plans prior to a confined space entry. Sharing the information collected in the evaluations with emergency and rescue teams may improve the effectiveness of rescue operations, allowing shorter intervention time and improved awareness about the risks of the confined space.

A limitation of the digital tool is related with the consistency of the values for the CSA index, i.e. the answers provided for the investigations of the confined spaces with the proposed tool are based on the user judgments. The test of the digital tool with multiple users and case studies revealed that some discrepancies may appear in the results of the evaluations operated by different users for the same suspected confined space. Such differences may be the result of different levels of experience with confined space work and limited awareness of non-operative users about the potential conditions inside confined spaces. Hence, employers, employees and company's safety professionals should collaborate during the investigation of a suspected confined space with the proposed digital tool. Excessive confidence of some users with multiple years of experience with work in confined spaces resulted in hasty answers with limited time for reading the conditions in the procedure. To address such issue, a 5-second timer was set before the user can select the answer for each condition. The choice of the time-lapse was based on the assumption that 5 seconds is the minimum time required to read each condition in the procedure.

Finally, the collection of the evaluations on the web portal and on the online server provides a framework for the distribution and the characteristics of confined spaces, offering a critical support to emergency and rescue operations.

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