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Adopting IOT Technologies to Control Risks in Confined Space: a Multi-criteria Decision Tool

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Work in confined spaces is still causing fatal accidents and injuries, despite the reinforcement of the worldwide regulatory and standards. Confined spaces are defined as limited or restricted areas not designed for continuous occupancy where employees enter and perform a specific task. Examples of confined spaces include, but are not limited to tanks, vessels, silos and pipelines. Several publications, reports and recent news demonstrate the great impact of such risks on the occupational safety level, showing high accident rates and multiple-fatality incidents.

This study aims to evaluate the potential contribution of Internet of Things (IOT) technologies to prevent and control the risks of confined space work. After a first legislative overview and a literature review on the topic, the authors conceptualize an AHP (Analytical Hierarchy process) model for analysing how critical factors affecting dangerous scenarios in confined spaces could affect the assessment of an IOT based device for preventing and managing confined spaces risks. The model aims to support both safety managers and risk analysts in reducing hazards in confined spaces. A case study in the chemical industry is proposed to validate the approach.

1. Introduction

Confined spaces are defined as limited or restricted areas not designed for continuous occupancy where workers enter and perform a specific task for a limited period of time. Confined space work is a high-risk activity, posing a serious dangerous hazard to the workers. Hazards in confined spaces are difficult to evaluate and manage, due to the complex characteristics of such particular work environments (Nano and Derudi, 2014). Both the features of the confined area and the characteristics of the performed task have direct impact on the overall risk level of a specific confined space activity. Despite international efforts in defining consistent procedures and recommendations for safe confined space work, the recent statistics show that fatal incidents still occur (Burlet-Vienney et al., 2014). Several accidents and injuries related to confined space work showed that workers access to confined areas without proper training and personal protective equipment, exposing themselves to high levels of hazards (Nano and Derudi, 2012). The lack of situation awareness is an underlying cause of human errors, especially when workers access to areas not designed for continuous occupancy as confined spaces. One potential contribution for preventing and reducing risks could be derived by the application of Internet of Things (IOT) technologies. IOT differ from other ICT technologies as they could increase context awareness of both workers inside and outside the confined space (Manca et al., 2012, Manca et al., 2014). This study proposes a multi-criteria model for assessing the most critical features requested to an IOT system for the management of the risks in confined spaces. The paper is organized as follows: at first, main factors influencing risk levels in confined space have been analyzed; the proposed multi-criteria model is described in in section 4, after a brief state of the art analysis about the adoption of IOT technologies for risk prevention. The effectiveness of the model is tested with a numerical test case in section 5. Finally, section 6 and section 7 discuss the results and conclusions.

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2. Analyzing confined space risks at process industries

Several industrial sectors face the risk of confined space work, i.e. confined areas characterize different processes in many industries, such as chemical industry (e.g. reaction vessels), food processing (e.g. above-ground storage silos) and utility sector (e.g. sewers and pipelines). Different factors contribute to increase the inherent complexity of confined space risks: multiple hazard sources, as electricity, lack of oxygen or inflammable atmosphere, are usually present, at the same time, during activities in confined spaces. In addition, the specific activity performed by confined space workers, (e.g. welding or cleaning), contribute to dynamically modify the risk level of the confined area (Andriulo et al, 2014). The current practice shows that many workplaces may become confined spaces when work is carried out, or during their construction or modification. The analysis of such "non-permanent" confined spaces shows that several of these locations are below ground level. Workers access to these underground areas by means of narrow stairs or ladders, to perform maintenance, inspection, testing, sampling and repairing activities. Workers inside and outside a "non-permanent" confined space should be informed about both the changing conditions and the emerging risks due to the changing conditions of the work environment. The past and recent statistics show that the activity performed within the confined space contribute to increase the risk level of the confined area, leading to the accident generation. A quantitative analysis of NIOSH data on confined space injuries and fatalities from 1985 to 2012 analyses the leading causes of accident due to confined space work (Botti et al. 2015). The study shows that asphyxiation, engulfment, poisoning, oxygen deficiency, drowning, explosion, and electrocution are the most frequent causes of accident in confined spaces. In particular, asphyxiation is the most frequent cause of death when an accident in confined space occurs. The same study shows that the total number of accident in the reference time period was 141, which caused 184 fatalities. The average fatality rate is about 1.3 fatalities per accident. Furthermore, NIOSH data highlight high risk of confined space accident in the food and agricultural industry. Typical examples of high-risk confined spaces in agriculture include but are not limited to silos, grain bins and manure pits. Similar results are outlined by analyzing accidents occurred from 2001 to 2015 in Italy: 20 accidents occured in the reference time period, which caused 51 fatalities. Consequently, the average fatality rate is higher in the Italian case and equal to about 2.25 fatalities per accident. Italian data show critical results in the food processing industry, with several accidents due to confined space work in storage tanks, grape presses, fermentation tanks, utility vaults and vessels.

3. State of the art analysis about the application of IOT for risk prevention and reduction in hazardous workplace

IOT technologies mainly refer to a paradigm where objects and people are interconnected and share information between each other and with the environment. Thus, IOT technologies are becoming widespread in our society in several industrial and service sectors (Atzori et al. 2010). Typically, an IOT application is based on three main categories of components (Borgia, 2014): collection devices, communication systems, and analysis applications. This structure represents the most innovative feature of an IOT system compared to a single ICT technology: IOT systems are capable to acquire, communicate and, more relevant, to analyze and provide effective feedbacks to their users. This capability will allow to widespread the application of these technologies in different field of application: one most promising is the risk prevention and control in hazardous workplace. Thus, an increasing, but still low compared to other fields, number of applications could be outlined in the scientific literature about the adoption of IOT technologies for supporting risk prevention and control in confined spaces. One main field of adoption is to support *emergency response activities* after an accident. Gelenbe and Wu (2013), Yang et al. (2013), Li et al. (2014) discussed potential impacts of IOT technologies for supporting emergency response operations to provide more efficient cooperation, to increase situational awareness of rescues and, finally, to provide complete visibility of resources during the emergency event. Qiuping et al. (2011) discussed main criticalities concerning the design of an IOT prototypal system to support safety and emergency management in mine sites. Two main topics have been discussed: main issues regarding the transmission phase, as it has to be developed in an harsh environment, and the actual compatibility of this technology with the working area, as wireless devices could contribute to increase risk levels (e.g. fire and/or explosion hazards). Liu and Zhu (2014) critically discussed the use of IOT technologies for supporting a specific emergency event, i.e. fire emergency operations. Another field of IOT technology application is on *risk control and supervision in confined space*. Yinghua et al. (2012) discussed the capability of IOT technologies to support safety supervision in a coalmine industry. Sun et al. (2012) described an IOT prototypal system for tailings dam monitoring and for pre-alerting workers.

Another field of application is to alert workers and safety managers about hazardous conditions that will occur in the workplace. Riaz et al. (2014) described 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.

4. The proposed multi-criteria model

The problem in analysis is to evaluate how factors influencing risk levels could also affect the design of an IOT system to be adopted in a confined space. A multi-criteria approach has been used, based on the well-known AHP (Analytical Hierarchical Process) method (Saaty, 1980). The AHP method has been widely adopted to support several decision making problems regarding risk analysis in the process industries (Sipahi and Timor , 2010; Gnoni et al., 2012). The AHP method divides the problem in three main elements: the *goal* – which represent the decision problem in analysis –, *alternatives* – which are the decision variable to be evaluated according to the goal – and, finally, different *levels of criteria*, which are organized in a hierarchical structure. Alternatives will be ranked quantitatively based on pairwise comparison carried out between criteria in the hierarchical structure, for each level. In the proposed model, the *goal* is to identify most critical features, which should characterize the IOT system adopted to prevent and control risk in a confined space. Results provided by the model will allow safety managers to evaluate the most effective IOT systems, based on the specific risk level and not only on the technological features. The model is depicted in Figure 1. Three technological requirements have been introduced as alternatives that characterize an IOT system:

- **Reliability** (A1): it focuses more on the service operations rather than the technical functionalities (Li et al, 2012). This requirement mainly refers to the capability of collecting data and providing effective feedbacks to workers for the confined space risk management. The aim is to evaluate the capability of the IOT system as a whole, i.e. this requirement do not refer to instrument precision values. Measurement performances characterizing each instrument or collection equipment are not considered under this requirement;
- **Responsiveness** (A2): this requirement refers to how the whole IOT system is able to collect information and provide feedbacks to the users in the workplace. One example is the capability of the IOT system to evaluate dynamic environment conditions and to provide pre-alarms to workers and/or rescue teams;
- **Agility (**A3): this requirement refers to how the IOT system interacts with the users and its level of usability, (e.g. manageability, automatic communication, etc.).

Three following first level criteria are based on the framework proposed by Botti et al. (2015) for the analysis of the risks in confined spaces:

- **Task factor** (C1): it refers to the contribution of the work activity to the risk level increase, due to the intrinsic hazardousness of the task performed in the confined space. Two second level criteria have been also added: **equipment (**C1.1) and **activity factors** (C1.2).
- **Area factors** (C2): this criterion refers to the contribution of the work environment to the risk level increase, due to specific features of the workplace where the task is carried out. Two second criteria have been also added such as **Geometric** (C2.1) and **Ambient Air Factors** (C2.2). Next, C2.1 criterion has been subdivided in two other criteria, such as **Access Limitation** (C2.1.1) and **Space Congestion** (C2.1.2); C2.2 criterion has been divided in two subsequent criteria, such as **Hazardous content** (C2.2.1) and **Restricted air flow** (C2.2.2)
- **Hazard characteristics** (C3): this criterion has been sub-divided based on the main risk categories that could affect the confined space activity: **Mechanical** (C3.1), **Electrical** (C3.2), **Chemical** (C3.3) and **Other Hazards** (C3.4).

5. The test case description

The test case proposed for validating the multi-criteria approach regards the hazardous tank cleaning for removing sludge or solids of an organic solvent in a chemical facility. Tanks are located underground. The activity is characterized by a high frequency; in addition, the total number of tanks to be periodically cleaned is relative high, i.e. it is equal to 11. Cleaning activities usually involve 3 workers. Thus, assessing and managing confined space risks requires a high effort for the company due to both its inherent complexity and its high frequency. The company is now evaluating if the adoption of IOT technologies could effectively prevent and control confined space risks during the repetitive cleaning activities. The multi-criteria model defined in the previous section has been adopted to provide feedbacks to the company. Each criterion defined in the hierarchy proposed in the previous section has been detailed as follows.

Hazard Characteristic: all the three second level criteria introduced in the hierarchy could be evaluated by referring to the activity developed in the underground task.

By evaluating the mechanical hazard criterion, three hazardous conditions have been outlined:

- falling into the vessel during the inspection of the hatch opening, leaning to the trapdoor margins could face an orthostatic problem, causing dizziness and / or light-headedness may result in a fall in the tank, related damage provided for the possibility of musculoskeletal trauma;
- falling during the entrance into the underground tank, after the step of opening the hatch and during the descent phase inside the tank could slip if the descent and safety devices do not have the appropriate characteristics, related damage provided for the possibility of musculoskeletal trauma;
- possibility of slipping into the vessel when the worker is in the tank to complete the cleaning operation, with even the presence of liquid and / or oily substances that may cause slippage, if the protective equipment is not used or if it does not have the appropriate features, related damage provided for the possibility of musculoskeletal trauma.

By evaluating the chemical hazard criterion, one critical condition is outlined. It refers to potential occurrence of dangerous atmospheres inside the tank due to the presence of VOCs and O2. The risk origins during the task execution due both to the stagnation of chemicals in the internal area and an initial mixing process occurred during the suction phase if there are some deficiencies and/or malfunctions in equipment.

By evaluating the electrical hazard criterion, one condition is outlined which refers to the occurrence of induced eddy currents, due to faults in the electrical protection system during the preliminary energy sources isolation process carried out before the task.

By evaluating the other hazard criterion, one outlined condition is the potential occurrence of an explosion due to the presence of saturated compounds which exceed the LEL (Level Explosion Limit) if not compliant equipment have been used during internal inspection and cleaning activities.

Task hazardousness factors: the activity to be carried out mainly consists of a cleaning process aiming to remove all lose materials inside the tank. Three main steps could be outlined: a preliminary activity developed through the opened manhole access, and, next, workers access the internal tank area to manually scarp residual materials. Finally, a sanitization activity is carried out. Specific equipment – as they have to be ATEX approved- used during these activities are sludge suction units, high pressure pumps, vacuum vents to maintain safe atmospheres in the tank.

Area hazardousness factors: the area in analysis is characterized by these two main hazardous features: restricted entrance for the tank inspection and underground location and the potential gas accumulation in the internal area of the tank which could lead to an explosive atmosphere. Furthermore, lack of oxygen could also occur due to the potential presence of VOCs (Volatile Organic Compounds) and O2.

In the next section, the quantitative application of the AHP method based on data regarding the test case is described in detail.

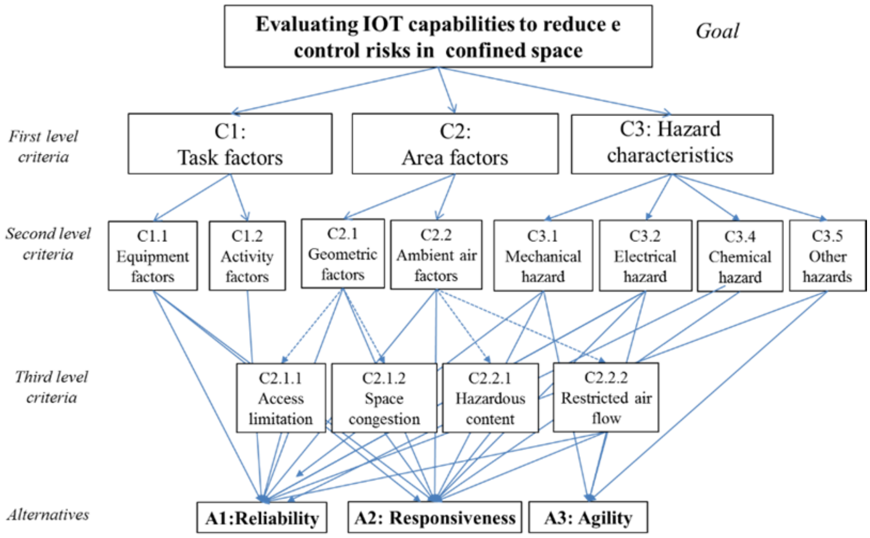

Figure 1. The proposed hierarchical structure

6. Results analysis

The AHP procedure has been carried out: the goal is to outline the critical characteristics of a potential IOT system to be applied for the risk reduction of cleaning activity in the underground tanks described in the previous section. Thus, based on the multi-criteria model proposed in section 3, the criteria assessment phase has been carried out: each criterion, at each level, has been compared pairwise with respect to the criteria in the immediate upper level. A quantitative 1-to-9 scale has been adopted to develop expert criteria comparisons. Experts in risk analysis and control have developed the pairwise judgment process: the geometric mean value - estimated based on each expert judgment carried out in each pairwise comparison – has been adopted for evaluating the overall ranking of alternatives. Before analyzing the final ranking, a validation analysis is carried out at each level of the AHP structure aiming to point out the possible inconstancy of such a single judgment. Saaty (1980) proposes to estimate a Consistency Index (CI), which characterizes the comparison (Saaty, 2000) matrix developed at the previous step; it is defined by (1):

$$CI = (kmax - n)/(n - 1) \tag{1}$$

where the kmax is the maximum eigenvalue characterizing the matrix and n is the matrix dimension. Analogously, the Consistency Ratio (CR) parameter could be estimated as in (2):

$$CR = CI/RI \tag{2}$$

where the RI parameter is defined by Saaty (1977) as the Random Index: it represents the average CI value estimated for 500 randomly filled matrices. Thus, if the estimated CR value is less than 10%, the current matrix could be characterized by an acceptable level of consistency (Saaty, 2000); otherwise, the decision makers should review and revise the pairwise comparisons. The estimated value for the test case is less than 10 % (i.e. about 8 %), thus all pairwise comparisons are proved to be consistent by the CR analysis. All scores estimated for each criterion for the proposed test case are reported in Table 1 together with the overall actual ranking of alternatives. Responsiveness is the most important technological requirement estimated for the test case with a final score of 37.6%; the estimated difference second and third alternative ranges from about 14% to 20%. Furthermore, scores estimated for each criterion at each level have been also evaluated: the most critical one for first level has been C2: this is in line with the real condition, where the task complexity is very low compared to the higher criticality characterizing the area where the task has to be developed.

Table 1: Estimated score values for each criterion and the three final alternatives

		Score [%]			Score [%]
First Level Criteria	C1: Task factors	0.143	FINAL RANKING	A1 Reliability	0.323
	C2: Area factors	0.571			
	C3:Hazard characteristics	0.286			
Second Level Criteria	C1.1 Activity factors	0.024		A2 Responsiveness	0.376
	C1.2 Equipment factors	0.119			
	C2.1 Ambient air factors	0.476			
	C2.2 Geometric factors	0.095			
	C3.1 Mechanical hazard	0.092			
	C3.2 Electrical hazard	0.035			
	C3.3 Chemical hazard	0.118			
	C3.4 other hazards	0.040			
Third level criteria	Access Limitation	0.133		A3 Agility	0.299
	Space congestion	0.033			
	Hazardous content	0.166			
	Restricted air flow	0.666			

7. Conclusions

The study proposes an application of a multi-criteria method for assessing quantitatively the most critical features required to IOT technologies to be adopted for preventing risks in confined spaces. Confined space risks are very complex to evaluate and manage as the risk level is affected by different factors depending to the hazardous level of activities developed as well as geometric burdens characterizing the confined space. Thus, the decision problem in analysis is to evaluate how different features requested to the IOT technologies could be more relevant based on the actual level of confined space risk. A test case regarding a repetitive cleaning activity developed in a chemical facility has been discussed aiming to validate by a numerical example the potentialities of the model. The model has revealed effective in outlining features which will be requested to an IOT system that will be developed based on results provided by the model.

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