A Multiple Criteria Decision-Making framework for evaluating Oxygen Reduction Systems' use

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Abstract: Warehouses and storages, data centers, server rooms, museums and heritage buildings, bank vaults, automatic parking systems are frequently mentioned applications of Oxygen Reduction Systems (ORSs) for fire prevention. These systems represent a relevant fire prevention technology and seem to be a recent application able to achieve fire safety objectives. ORSs keep the indoor oxygen concentration in a protected volume permanently below the ignition threshold to inhibit any combustion process of the different stored or present materials and substances. However, multidisciplinary analyses reveal a lack of consensus about technology advantages and some critical issues (e.g. Oxygen Deficiency Hazard). To the best of our knowledge, one of the main gaps about ORSs regards the absence of a complete assessment of all the criteria and elements that a decision-maker should consider for choosing this fire protection technology, also in comparison to others currently available. For this reason, the aim of this paper is to propose criteria relevant for evaluating ORSs' application, organising them into a preliminary Multiple Criteria Decision-Making (MCDM) framework. To achieve this aim, we conducted a review of available scientific literature, legislative acts, and technical standards on ORSs' requirements published by European countries and/or International organisations. We collected information and details through interviews and contacts with ORSs' manufacturers and potential users, and experts belonging to fire protection associations, insurance companies, and medical commissions. The developed MCDM framework may provide support to health and safety managers for assessing if an ORS should be the appropriate and effective solution for their own specific needs.

Keywords: Fire prevention; Fire Protection; Oxygen concentration; Normobaric hypoxic atmosphere; Occupational health and safety.

1. Introduction

The recent publication of relevant standards (e.g. CEN, 2017) and technical reports (e.g. van Hees et al., 2018) has motivated a renewed interest in Oxygen Reduction Systems (ORSs), although they have been installed and in operation for more than 20 years (Daniault and Siedler, 2017). An ORS, also called "hypoxic air technology for fire prevention" and/or "hypoxic (air) fire prevention system", is a fixed firefighting and fire prevention system (CEN, 2017; DGUV, 2013; van Hees et al., 2018). The term "fire prevention" refers to "measures to prevent the outbreak of a fire and/or to limit its effects" (ISO, 1987). Consequently, the primary purpose of such technology is to prevent or inhibit fire initiation, development, and spread (Cancelliere and Gasser, 2018; DGUV, 2013; van Hees et al., 2018), and not to extinguish fires (Berg and Lindgren, 2004; Cancelliere and Gasser, 2018; CEN, 2017; VdS, 2018). For achieving this purpose, an atmosphere with a permanent oxygen (O_2) concentration lower than natural (i.e. normoxic) air is created in a volume (Cancelliere and Gasser, 2018; CEN, 2017; van Hees et al., 2018). Such an atmosphere is achieved supplying O_2-reduced air, i.e. inert gas (typically nitrogen) enriched air. This O_2-reduced air is determined defining a design concentration based on the ignition threshold of materials stored or present in the protected volume. Design concentration is the maximum O_2 concentration which cannot be exceeded in any time (CEN, 2017). Ignition threshold is the maximum O_2 concentration in a mixture of a combustible material with air and inert gas, at which there can be no ignition, determined under established test conditions (CEN, 2017; VdS, 2018). According to PAS 95:2011 (BSI, 2011), ignition-limiting O_2 threshold is O_2 concentration required for limiting ignition and preventing sustained flaming combustion of materials.

In the opinion of many authors (e.g. Barowy and Creighton, 2016; Cancelliere and Gasser, 2018; Clauss, 2014; Jensen, 2006; Jensen and Nygaard, 2013; Madsen et al., 2005; Mueller, 2017; Nilsson and van Hees, 2014; van Hees et al., 2018; Zhou et al., 2018), the adoption of an ORS can lead to several benefits, for instance:

- continuous operation, ignition prevention, and monitoring;

- prevention from backdraught;
- avoidance of potential damage to products, processes, assets, and equipment from extinguishing agents, smoke, fire, heat, particles, water, gas, aerosol, or mechanical impact;
- no secondary damage and environmental risks; no toxic or residue;
- no loss of production, storage and/or building capacity, maintaining of operational business processes and ensuring of availability of key resources;
- no running empty, re-filling of extinguishing agent, transport or resetting issues following incidents;
- no nozzles, pipes, equipment, fixed or non-reversible invasive installations required within the protected area(s) (if already existing air conditioning systems are employed), demanding minimum of space, and few design limitations within the protected areas;
- applicable to areas of all sizes and to irregular-shaped compartments;
- minimal re-adjustment of the system to accommodate changes in requirements and contents, and variations of occupancy and fire load;
- beneficial for processes where water is not a feasible fire extinguishing agent, (non-)thermal damage is unacceptable, and/or commodity is stacked so that options such as in-rack sprinklers are impractical.

Several authors (e.g. Barowy and Creighton, 2016; CEN, 2017; Jensen, 2006; Madsen et al., 2005; Nilsson and van Hees, 2014; van Hees et al., 2018) state that there are some limitations to ORSs' use in spaces where there are:

- materials that can provide O_2, or non-generic materials and products with unknown ignition properties;
- processes demanding normoxic air or biological ones thriving by nitrogen;
- fuels requiring suppression mode and evacuation;
- highly flammable or explosives materials requiring an extremely low O_2 concentration for fire prevention;
- possibilities of entering fuels or particular good having ignition threshold less than the design concentration;
- and/or employees that have to perform hot works.

A wide range of topics about ORSs, highlighted by the same authors, need additional research: ignition threshold of non-generic materials, smouldering combustion in O_2-reduced environment, system and components' reliability, exposure parameters and health and safety issues. About the last point, several aspects require further attention: the most significant parameters affecting the human health and exposure time before negative effects occur in normobaric hypoxic environment, reconciliation with existing health and safety regulations, acceptable O_2 level, and lack of medical data. In addition, the actual O_2 design concentrations for ORS's use in real applications have to be examined in comparison to values recommended by existing standards due to different test conditions (Zhou et al., 2018). Moreover, in the case of storage of hazardous chemicals that could evolve gases, the airborne pollutants' concentrations may increase beyond the threshold limit values because of the lack of air exchange inside the protected volume.

To the best of our knowledge, one of the main gaps about ORSs regards the lack of a complete framework of all the criteria and attributes that a decision-maker should consider to evaluate the possible adoption of this fire prevention system. For this reason, the aim of this paper is to propose criteria and attributes relevant for evaluating ORSs' application, organising them into a preliminary Multiple Criteria Decision-Making (MCDM) framework. This framework allows the decision-maker to comprehend if an ORS is the most suitable firefighting system for a specific working environment, in comparison to other fire solutions currently available or (if admissible) to not adopting any prevention/protection technologies.

2. Methods

We carried out a review of available scientific literature and technical reports related to ORSs' features and functioning principles. We selected Scopus, ScienceDirect, Web of Science, and Google Scholar as relevant databases. We used as keywords terms belonging to the set of fire protection measures, fixed firefighting systems, and the effects of O_2 reduction in enclosed spaces (e.g. fire prevention, normobaric hypoxic atmosphere). The search was extended to documents written in European languages, and studies were included in the review when their abstracts and full texts were considered relevant for our purpose. Their reference lists were checked to find additional interesting studies. We manually browsed standards catalogues currently available. International standards about ORSs have not yet been published: Draft ISO/DIS 20338.2 is at present under development and, once it will be published, will cover design, installation, planning, and maintenance requirements and specifications of ORSs for fire prevention. European Committee for Standardization has recently published EN 16750:2017 (CEN, 2017), then adopted by all national standards bodies that are CEN members. Some European national institutions (both members of CEN and not) have also proposed other standards: Table 1 shows an overview of these existing standards. In US, the UL 67377:2016 outline (UL, 2016) defines requirements for ORS units intended for design, installation, operation, and maintenance, in accordance with European standard. In addition to standards, we studied legislative references about occupational health and safety, and firefighting systems.

We discussed with experts in the field of fire risk assessment (academic researchers and fire protection associations), and insurance companies. Technical descriptions were gathered from face-to-face interviews with system designers, manufacturers, and installers participating to conferences about fire topics and workshops related to this technology.

Table 1: Overview of existing European national standards other than EN 16750:2017 adoption (chronological order)

Country	Standard	References
Austria	TRVB 155/08 (S)	ÖBFV (2008)
Netherlands	BRL-K21017/01	Kiwa (2009)
Austria	ÖNORM F 3007	ASI (2009)
Austria	ÖNORM F 3008	ASI (2010a)
Austria	ÖNORM F 3073	ASI (2010b)
UK	PAS 95	BSI (2011)
Germany	VdS 3527	VdS (2018)

Some organisations relevant in logistics field put us into contact with designers of warehouses and storages (frequently mentioned ORSs' applications) to acquire information about the typical aspects and data that have to be taken into consideration during the study and selection of specific fire solutions and measures. The contacts with these designers were undertaken through face-to-face and/or telephone interviews for reaching a greater number of professionals. Each interview was completed in about two hours. These contacts and interviews permitted to organise some site visits in warehouses using an ORS to understand more deeply the operating principles and the technical requirements. The opinions of some lawyers engaged in consulting activities related to health and safety issues helped us to clarify the obligations and liability of the several stakeholders involved in design and use of this technology (e.g. designers, manufacturers, and employers), mainly in terms of safety and risk assessment. Judgments from commissions and organisations in the field of high-altitude medicine provided interesting assessments of exposure to environments with decreased O_2 availability due to reduced pressure (hypobaric hypoxia). The correspondence with lawyers and high-altitude medicine experts was principally managed through mail.

Finally, a literature review about MCDM techniques and approaches in scientific publications and books indexed in electronic databases (e.g. Scopus and ScienceDirect) was carried out. We focused on those MCDM techniques that have been or could be applied to support the comparison of alternative fire systems. An interesting review of these methods is provided by Mardani et al. (2015).

3. Results and discussion

The main result of our study is the MCDM framework for evaluating ORSs' use and is shown in Figure 1 with the indication of the goal, strategic criteria, and criteria. In this graph each strategic criterion and each criterion has also an acronym, to which we refer in the rest of the paper. The goal of our framework is to assess the suitability of an ORS in a working environment with respect to other fire solutions currently available or (if admissible) to not using any prevention/protection technologies. Four strategic criteria are analysed. Such strategic criteria include several aspects that a decision-maker/assessor should simultaneously consider for performing a complete, structured, and multidisciplinary examination of this fire prevention system. Each strategic criterion is decomposed into criteria, and each criterion is defined through a set of attributes and elements.

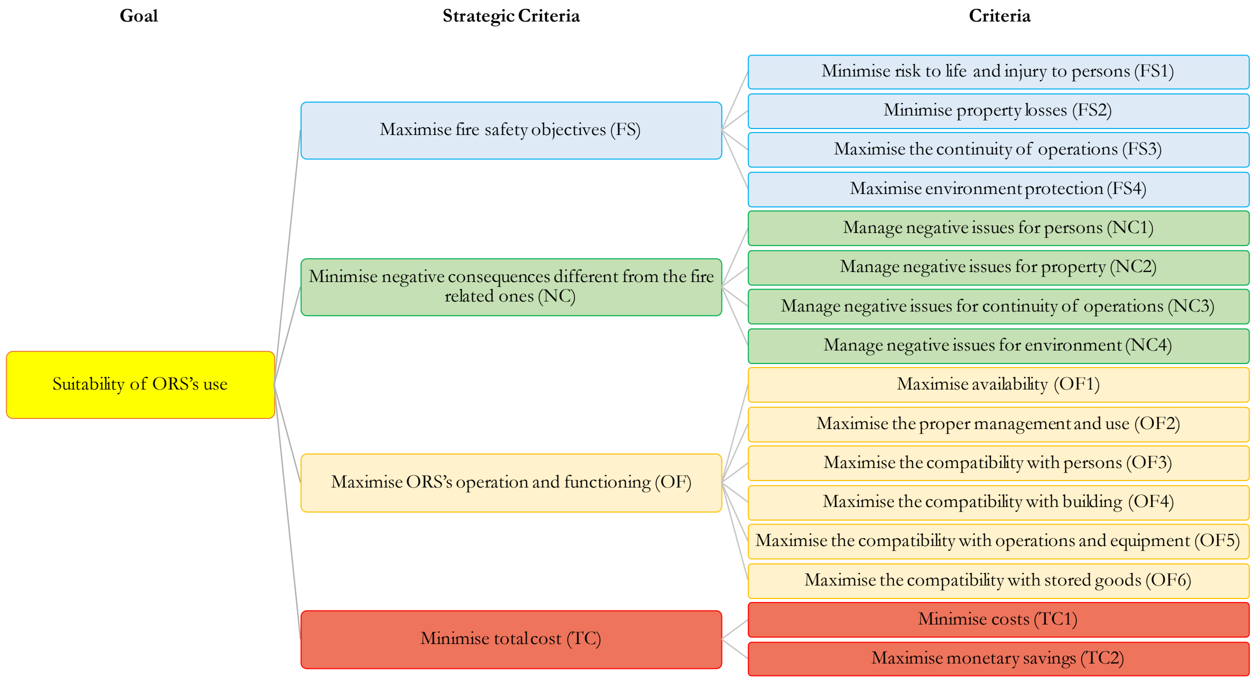

Figure 1: MCDM framework for the evaluation of ORSs' use

In the characterisation of the several criteria, we take into account the different targets of the assessment, i.e. involved persons, property, building, activities, equipment, and stored goods. For our purposes, the involved persons are workers entering the protected volumes for normal operation/maintenance services, emergency rescuers, and others (e.g. visitors in a museum, external companies' staff in a warehouse).

The strategic criteria are explained in the following paragraphs. For length constraints, we omit a detailed description of each criterion and of the related attributes and elements.

3.1 Maximise fire safety objectives (FS)

Fire safety objectives are the "desired outcome with respect to the probability of an unwanted fire, relative to essential aspects of the built environment", and include the issues of life safety, conservation of property, continuity of operations, protection of the environment, and preservation of heritage (ISO, 2017). In this group, we include criteria and attributes related to ability of the ORS to avoid and/or limit damages from potential fire, and to limit the consequences of a fire if it occurs despite its presence, considering characteristics of building, occupants, activities, equipment, and stored goods. Table 2 reports the defined attributes and elements for each criterion considered for achieving fire safety objectives.

3.2 Minimise negative consequences different from the fire related ones (NC)

This strategic criterion focuses on the possible negative consequences and/or side-effects (different from the fire-related ones) on occupants, property, operations, and environment, deriving from the ORS's use. From workers' health and safety point of view, their presence and carrying out operations in O_2-reduced atmospheres could expose them to severe asphyxiation risk and cause several adverse human physiological effects and thus should be properly assessed (e.g. Stefana et al. 2016, 2017). These negative effects should be minimised thanks to the adoption of different organisational measures and risk controls, considering regulatory and legislative requirements (included in Table 3). Stefana et al. (2015) emphasise the lack of consensus about the minimum safe level of O_2 well tolerated by healthy persons. Angerer and Nowak (2003) give a detailed analysis on working in permanent normobaric hypoxia for fire protection, highlighting and associating health effects, exposure durations, measures and precautions. BSI (2011), CEN (2017), Clauss (2014), DGUV (2013), and Mueller (2017) report some safety measures to be implemented based on risk classes defined considering four ranges of O_2 concentration. According to DGUV (2013), the O_2 design concentration should be defined as high as possible, which means only as low as it is absolutely necessary for fire protection reasons.

Table 2: Criteria, attributes, and elements for the maximisation of fire safety objectives

		Attributes and elements
Criteria	FS1	Loss of life of occupants, entering workers, rescuers, and/or other persons that should enter the volume Damage from fire (e.g. burns) and breathing toxic fire products Smoke hazards Emergency measures Provision of accessible means of escape Regulatory and legislative prescription related to training of First on Place (FOP) rescuers Rescuer's individual characteristics: physical fitness; psychological conditions; pre-existing health diseases Need for training to right use of rescue devices and defining procedures for First Aid and Rescue Operations
	FS2	Alteration, damage, or destroying to buildings Alteration, damage, or destroying to stored goods by smoke, fire, and extinguishing agents Loss, alteration, damage, or destroying to process equipment and systems Power shut-off consequences in case of fire (e.g. emergency power shut down) Inability to meet obligations to customers including a ripple effect up and down to supply chain Damage to public image Legal liability exposure Property damage due to fire spread and its potential chain reactions
	FS3	Business operation interruption, disruption and/or downtime, and loss of profits in the event of a fire Specific measures for any special substance that may burn at O_2 level below the design O_2 concentration Need for detection and alarm systems Other fire protection systems and/or extinguishing agents need for managing residual fire risk Possibility to confine fire
	FS4	Damage of building in the immediate vicinity Environmental risks due to hazardous fire products and impact of extinguisher agents use Environmental impacts due to fire spread and its potential chain reactions Residual disposal of waste from fire and firefighting operations Replacing chemical extinguishing agents with natural gases generated from the ambient air

Table 3: Criteria, attributes, and elements for the minimisation of possible negative consequences and/or side-effects

		Attributes and elements
Criteria	NC1	Worktime breaks to reoxygenate blood after hypoxic atmosphere exposure General measures due to O_2-reduced atmosphere (e.g. O_2 level detection, audible alarm; warning signs) Measures to prevent uncontrolled access by any unauthorised person O_2 level monitoring in workplaces near openings Workers’ medical screening and checks Risk assessment; instructions; procedures and workers’ training PPEs/rescue devices and training for correct use; First Aid Rescue Squad training and verification of effectiveness Regulatory and legislative limitations about O_2-reduced atmosphere for access and works in such areas Information of other persons that should enter the volume Creation of new risks in surrounding area(s)/other internal area(s)
	NC2	Sensitivity of the stored goods in respect to potential extinguishing agents Accidental and undesired impacts to surrounding area(s)/other internal area(s)
	NC3	Prevent fires without leaving any residue behind on stored goods (fire products) Interruption of critical activities that cannot be stopped
	NC4	Energy consumption Use of potential extinguishing agents posing any environmental risks Production of residues of potential extinguishing agents

Table 4: Criteria, attributes, and elements for the maximisation of ORS’ operation and functioning (continued on next page)

		Attributes and elements
Criteria	OF1	Effectiveness (e.g. in terms of time to reach the design O_2 concentration and possibilities to maintain it) Reliability Maintainability Ability to detect and report potential failures, and to continuously monitor critical parameters (e.g. O_2 level) Maintenance plan: frequency; need of periodic inspections; trained personnel; definition of procedures Durability and expected lifetime
	OF2	Training; Instructions Definition of specific procedures
	OF3	Familiarity with the building Number and occupancy pattern of both entering workers and other persons that should enter the volume Persons that work in workplaces near warehouse openings Worker’s individual characteristics: physical fitness; psychological conditions; pre-existing health diseases Abilities and training to leave the protected space at any time, and to perform rescue operations if needed
	OF4	Local conditions and environment: altitude; air quality (e.g. dust, humidity, temperature); yearly average wind speed New or existing building/part of it - volume(s) to be protected Technical area(s) as entire building versus only a part of the entire building Type of building (or its part) structure Type of protected volume structure versus expected total leakage (retention time) Geometrical configuration: layout; shape; dimensions; net volume; functional and physical compartmentation Openings: number functional to the activity (e.g. roller conveyors); characteristics (e.g. type, size); frequency Characteristics, size, and number of levels/lanes of shelfs in the warehouse Presence of: elevators, shuttles; electrical systems/apparatus; mechanical systems/machines Ignition sources and energy; duration of ignition source(s) (consider the material with the lowest ignition threshold) Mandatory and voluntary requirements Architectural or aesthetic impacts Compatibility with: the typical uses and applications of the entire building; existing fire protection measures Presence of particular systems and/or substances that can interfere with functioning of fire systems Consequences and effects of possible combustion processes Production and logistic constraints introduced by the fire system Obstacles and/or irregularities that can hinder the homogeneous O_2 inside the whole volume(s) protected Building tightness and air permeability Presence of: openings; infiltration; inward and/or structural leakage; air locks; sluices; O_2 sources Control of openings and air leakage Risk assessment of the building and of each volume to be protected; existence of particular risks (e.g. radioactivity) Presence of explosive mixtures, reactive metals, and chemicals capable of auto-thermal decomposition

Table 4 (continued)

		Attributes and elements
Criteria	OF5	Intended use of the area(s) Number of workers employed Duration and frequency of each activity Severity of physical works to be performed; Psycho-mental burden Use of particular equipment (e.g. marine ladder) or request for specific activities (e.g. work at height) Number of logistic movements Requirements of door and window openings (e.g. time, frequency) Compatibility with: process equipment; used substances; requested PPEs for new risks due to the fire system Frequency of accesses Request for continuous employee occupancy and presence of permanent workstations in area(s) to be protected
	OF6	Stored goods characteristics: quantity; type; shape, geometry, dimensions; mass; packaging; combustibility features Storage of substances that could evolve gases or oxidizing agents that have the potential to reduce O_2 Stored goods load units closed or open (displacement of low O_2 indoor air volumes externally and vice versa) Economic value attributed to stored goods (valuable items' presence) and their importance on business continuity Compatibility with extinguishing agents (inert gases) Time trend of quantities, sizes, and percentage of volume occupancy Presence of: hazardous substances; combustible materials; items in particular geometric configurations; O_2 Protection, conservation, and presentation requirements Volume of the gas (air) contained in combustible materials (hollow parts, densely packed storage items)

Table 5: Criteria, attributes, and elements for the minimisation of total cost

		Attributes and elements
Criteria	TC1	Cost of whole system, including design, administrative, components' and installation costs Running, operating (power consumption and consumables), and maintenance costs Retrofitting cost Costs for new safety measures to be adopted
	TC2	Insurance premiums Re-use of existing equipment (e.g. ventilation system(s)) Energy recovery

3.3 Maximise ORS's operation and functioning (OF)

The maximisation of the ORS' operation and functioning is achievable through the criteria related to reliability and proper functioning of the ORS, considering characteristics of building, occupants, activities, and stored goods. Table 4 provides the details of the different defined attributes and elements. This strategic criterion includes the greatest number of attributes because characteristics of the building and stored goods, compatibility with planned activities, existing systems and equipment, openings' presence and features are relevant elements to be evaluated in ORS's design and use.

3.4 Minimise total cost (TC)

Total cost is estimated through the balance between all the costs associated with the fire prevention system and the monetary savings achievable through ORS's adoption. Regarding components' cost, typical part of ORS (e.g. nitrogen production unit, control panel, and O_2 sensors) should be considered. Additionally, since the ORS functioning could be expensive, operating costs should be carefully taken into account in the total cost estimation. In Table 5 we point out the several elements of this strategic criterion.

4. Conclusions

Despite common fire protection systems, an ORS allows to prevent ignition and consequent damages to persons, property, and environment. For this reason, it represents a suitable fire system if it is able at the same time to maximise fire safety objectives and ORS's operation, and minimise negative consequences and total cost. However, scientific and technical literature highlights ongoing debate about benefits, negative features, and needs of further research efforts. This paper provides a preliminary MCDM framework for describing a wide set of different types of criteria, attributes, and elements that a decision-maker/assessor should consider during the evaluation of an ORS's use, in comparison to other fire solutions currently available or (if admissible) to not adopting any prevention/protection technologies. Criteria that require particular attention should be the provision of adequate measures to reduce hypoxia risks for any person entering the volume to be protected, and the assessment of building features and compatibility with planned activities. The developed MCDM framework may guide health and safety managers for assessing if an ORS should be the appropriate and effective solution for proper managing fire risks in a specific working environment, containing other negative consequences and costs. A future interesting work could focus on the application of our preliminary framework in real case studies in order to test the completeness and the effectiveness of the identified criteria and attributes.

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