Safety Science 110 (2018) 13–28

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Development of a methodology for systematic analysis of risk reduction by protective measures in tyre production machinery

M. Compare[a,b], E. Zio[a,b,c,d,*], E. Moroni[e], G. Portinari[f], T. Zanini[f]

[a] Dipartimento di Energia, Politecnico di Milano, Italy
[b] Aramis s.r.l., Italy
[c] Chair on System Science and the Energetic Challenge, Foundation Electricité de France, Ecole CentraleSupelec, France
[d] Department of Nuclear Engineering, College of Engineering, Kyung Hee University, Republic of Korea
[e] I.C.E.P.I. – Istituto Certificazione Europea Prodotti Industriali, Piacenza, Italy
[f] Pirelli Tyre S.p.a., Italy

ARTICLE INFO

Keywords:
Risk assessment
ISO 12100: 2010
ISO/TR 14121-2: 2012
Risk reduction
Protective measures

ABSTRACT

SO/TR 14121-2: 2012 considers three factors to describe the likelihood of the occurrence of an incident scenario: the frequency of exposure of persons to the hazard, the probability of occurrence of the hazardous event and the technical and human possibilities of avoiding harm. The assessment of these factors can be quite controversial, especially when it concerns the amount of risk removable by protective measures: their mapping onto the risk factors is not always clear and this can lead to non-conservative over-estimations of the risk reduction. We propose a methodological framework compliant with ISO 12100 to systemically carry out repeatable risk analyses in support to the design of industrial machinery in which protective measures can be introduced to reduce risk. The methodology first proposes a scheme for identifying the contribution of PMs to the reduction of risk in a machinery under design. Then, the methodology classifies the protective measures and builds a clear mapping between these classes and the risk factors they impact on. This helps decision makers to identify the protective measures guaranteeing that the residual risk is acceptable. The methodology is applied to a real case study concerning a curing machine for tyre vulcanization, where it has proven to be beneficial for the clarity of the analysis and its repeatability.

1. Introduction

ISO 0:1210, 2010 (ISO 0:1210, 2010) is the reference standard for carrying out risk analyses of machinery of different industrial fields. According to the engineering practice of many industries (Aven and Renn, 2009; Aven, 2012; Gauthier et al., 2012; Kaplan and Garrick, 1981; Nix et al., 2015), ISO 0:1210, 2010 defines risk as the combination of two attributes (acronyms are taken from ; ISO/TR 14121-2 (2012):

(a) *Severity* (Se), which is a rough quantification of the effect of the analyzed incident scenario. In the risk matrix in Appendix A, which is derived from ISO/TR 14121-2 (2012), this risk attribute is qualitatively expressed by integer numbers ranging from 1, for minor consequences, to 4, for severe consequences.
(b) *Likelihood* (Cl), which is a coarse estimation of the aleatory uncertainty regarding the occurrence of the incident scenario. ISO 12100: 2010 states that Cl is a function (e.g., the sum, product, etc.) of the following three sub-attributes:

(1) The frequency of exposure of persons to the hazard (Fr); in the risk matrix in Appendix A there are 5 exposure classes, which are assigned numerical values ranging from 1, in case of rare exposures with exposure time shorter than 10 min, to 5, for very frequent exposures.
(2) The probability of occurrence of the hazardous event (Pr); this is expressed by an integer numerical value between 1, for negligible probability, and 5, in case of very high probabilities.
(3) The technical and human possibilities of avoiding harm (Av); this attribute can take three possible values: 1, probable, 3, possible, and 5, impossible.

Once the risk of a scenario is assessed, i.e., the severity of its consequences and the probability of its occurrence have been estimated, it is checked against a pre-fixed risk matrix (e.g., Appendix A ISO 12100, 2010; ISO/TR 14121-2, 2012) to establish whether it is acceptable or not. If not, some risk reduction measures are suggested by risk analysts

---

* Corresponding author at: Dipartimento di Energia, Politecnico di Milano, campus Bovisa, via La Masa, 34, 20156 Milano, Italy.
E-mail address: enrico.zio@polimi.it (E. Zio).

https://doi.org/10.1016/j.ssci.2018.07.027
Received 23 April 2018; Received in revised form 12 July 2018; Accepted 23 July 2018
0925-7535/

Nomenclature

Acronyms

HZ	Hazardous Zone, i.e., any space within and/or around machinery in which a person can be exposed to a hazard (ISO 0:1210, 2010)
HS	Hazardous Situation, i.e., circumstance in which a person is exposed to at least one hazard. The exposure can immediately or over a period of time result in harm (ISO 0:1210, 2010)
LD	Limiting Device, i.e., device preventing a machine or hazardous machine conditions from exceeding a designed limit (ISO 0:1210, 2010)
MUP	Movable Upper Part, i.e., part of the machine that is opened for the green tyre loading and the cured tyre unloading; it is closed and locked during the curing process (EN 4:E1647, 2015)
PM	Protective Measure, i.e., measure intended to achieve risk reduction, implemented by either the machine designer or user (ISO 0:1210, 2010)
SPE	Sensitive Protective Equipment

Symbols

Cl	scenario likelihood. According to ISO 12100, Cl = f (Pr, Fr, Av). According to ISO/TR 14121-2: 2012, Cl = Pr + Fr + Av
Pr	probability of occurrence of the hazardous event
Se	scenario severity
Fr	frequency of exposure of persons to the hazard
Av	technical and human possibilities of avoiding harm
$\boldsymbol{Op^i}$	i-th operation performed by operators,$i = 1, \cdots, n$
$\boldsymbol{H^j}$	j-th hazard related to the machine operation,$j = 1, .., m$
$\boldsymbol{HS^{i,j}}$	Hazardous situation related to i-th operation and j-th hazard
$\boldsymbol{S_s^{i,j}}$	s-th scenario related to the i-th operation and j-th hazard,$s = 1, \cdots, s_{i,j}$
$\boldsymbol{E_s^{i,j}}$	Hazardous event $E_s^{i,j}$ of $S_s^{i,j}$,$s = 1, \cdots, s_{i,j}$
$\boldsymbol{Se_s^{i,j}}, \boldsymbol{Fr_s^{i,j}}, \boldsymbol{Pr_s^{i,j}}, \boldsymbol{Av_s^{i,j}}$	Risk factor scores for scenario $S_s^{i,j}$ before the protective measure introduction
$\overline{\boldsymbol{Se}}_s^{i,j}, \overline{\boldsymbol{Fr}}_s^{i,j}, \overline{\boldsymbol{Pr}}_s^{i,j}, \overline{\boldsymbol{Av}}_s^{i,j}$	Risk factor scores for scenario $S_s^{i,j}$ upon the protective measure introduction

and machine designers, and their effectiveness verified through a new iteration of the risk assessment process.

In spite of the wide use of ISO 12100: 2010 in industrial practice, risk analysts still encounter difficulties when the three-factor scheme is adopted for assessing the risk likelihood and the impact of risk reduction measures. In fact, although three parameters allow capturing the scenario characteristics better than when using a single factor (Gnoni and Bragatto, 2013), nonetheless their assessment becomes quite controversial in some cases, due to the inherent ambiguities of the analysis (Johansen and Rausand, 2015).

The main objective of this work is the development of a methodological framework in support to the reference standards, which provides a structured way for applying the three-factor scheme to the risk analysis of machinery.

In spite of the relevance of this issue for industry, to the authors' best knowledge it has been addressed in the light of ISO 12100: 2010 standard by a few works (e.g., Burlet-Vienny et al., 2015) in case of two risk factors, only.

Notice that risk reduction measures are referred to as safety barriers or controls in some industrial contexts (e.g., Oil&Gas (Petroleum Safety Authority Norway, 2013), Nuclear Energy (AIEA, 1996), Aerospace (NASA/SP-2010-580/Version 1.0, 2011)) and as Protective Measures (PMs) by ISO 12100: 2010, which is the reference standard of this work.

The remainder of the paper is organized as follows. Section 2 sketches the research method followed. Section 3 analyses the reference standardization framework. Section 4 provides a reasoning scheme to give more consistency to risk factor estimation and, on this basis, a methodology to systematically perform risk analysis. Section 5 proposes a classification of PMs. Section 6 outlines some considerations to map PM classes onto the risk factors. Section 7 proposes some procedures to estimate the impact of the PM classes onto the risk factors. Section 8 develops the risk modelling framework. Section 9 applies the proposed methodological framework to a case study. Section 10 analyses the results. Section 11 concludes the work.

2. Research method

The research method used in this work can be summarized as follows:

(a) Analysis of the standardization framework. This analysis allows better positioning our work in the reference standardization context.

(b) Design of the methodological framework. This is the outcome of a continuous interaction with expert risk analysts through which the proposed theoretical reasoning schemes have been iteratively checked against their practical applicability to industrial settings. These interactions have been structured as formal brainstorming sessions (e.g., ISO 31010, 2010), involving researchers as facilitators and engineers from Pirelli with a long experience in risk management as active participants. The outcomes of every brainstorming were synthetized by the researchers to form the basis for discussion for the next brainstorming session. The methodological framework is made up of the following steps:

1. Development of a reasoning scheme to unambiguously frame how the PMs enter the risk analysis.
2. Classification of the PMs. In industrial practice, there are a large number of possible devices and technical and organizational solutions that can be installed as PMs in different situations, scenarios, etc. However, to build the general risk modelling framework we are concerned with, it is fundamental to work with a limited number of possible alternatives. Thus, a preliminary grouping or classification of the PMs is required.
3. Mapping of PM classes onto risk factors. Every type of PM can reduce the scores of a subset of the risk factors, only. Then, at this step we select for each PM the corresponding factors that could be influenced.
4. Quantification of the impacts of PMs on risk factors. General considerations are drawn to support the analysts in estimating the score reduction that every PM yields on the affected risk factors.
5. Development of a risk-modelling framework to identify and model the risk scenarios originated from the set of operations carried out on the system under analysis.

(c) Case study. A team of 3 engineers from Pirelli with a sound experience in risk analysis were first trained by the Pirelli experts involved in step (b) on the developed methodological framework and, then, asked to apply it to the risk analysis of a tyre curing machine.

3. Analysis of the standardization framework

The primary objective of ISO 12100: 2010 is to provide an overall