AHP-based methodology for selecting safety devices of industrial machinery

Antonio C. Caputo,*, Pacifico M. Pelagagge, Paolo Salini

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Abstract
Safe machines make a major contribution to personnel safety on the workplace. Safety of machines is often guaranteed or enhanced by safety devices. The choice of a safety device involves multiple criteria decision making and a ranking of alternatives according to often contrasting performance measures. In this paper, a systematic methodology for selecting safety measures aimed at reducing mechanical hazards of industrial machinery is presented. The method at first includes a classification of mechanical hazards and applicable safety devices, then introduces an exhaustive list of 15 factors useful to judge the suitability of safety devices for comparison purposes. A comparison of relative importance between the rating criteria is then carried out in the framework of the Analytic Hierarchy Process decision making approach, based on expert opinion, allowing unambiguous prioritization of the above decision making factors. This allows a rapid ranking of alternatives and the selection of the most suitable device for a given machine that suits the mission requirements and the preferences of the decision maker. An application example is included to demonstrate the utilization of the method.

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1. Introduction

Workers are killed or injured as a result of hazardous contact with machinery and equipment. According to NIOSH data, from 1980 to 1998 in the USA occupational injury from machinery was ranked third after motor vehicle and homicide as cause of death, accounting fatalities for approximately 13% of the total. The industry sectors that ranked the highest in injury due to machinery were: agriculture, mining, manufacturing and construction. Similar data are reported even for the other industrialized countries.

Some of the leading injuries experienced in these industries were: struck by or against an object, caught in or compressed by equipment, and caught in or crushed in collapsing materials.

Safe machines are, therefore, a prerequisite to ensure personnel safety on the workplace. Safety of machines is often guaranteed or enhanced by safety devices. Strict regulations have been enforced in most Countries dictating specific safety requirements to be satisfied by newly built machines or older ones which are to be maintained in service.

According to European Union Directives 2006/42/EC and 98/37/EC (superseding previous Directive 89/392/EC) machinery needs to satisfy a number of so called Essential Health and Safety Requirements (EHSRs) contained in Annex I of the Directive. To certify satisfaction of EHSRs, a conformity assessment must be carried out, a “Declaration of Conformity” must be given and the CE marking must be affixed. It is an offence to supply and use machinery not complying with the Directives. This applies to the supply and utilization of new and used machinery and other equipment including safety components.

Compliance to Directive can be accomplished by utilizing a hierarchy of methods, namely inherently safe design (to prevent any hazards if possible), adoption of proper safety devices (i.e. Additional Protection Devices, APD), or resorting to Personal Protective Equipment and/or training to contain any residual risk which cannot be dealt with by the above methods. In most cases APDs are adopted given that most operations performed by industrial machinery to process materials are hazardous, unavoidable, and can harm the operator in case he enters in contact with moving parts and working tools.

Then the problem of selecting the right safety device arises and involves a number of parties, namely designers and manufacturers of new machines, sellers, renters, buyers and users of new as well as old machines, those modifying a machine to adapt it to new purposes and those upgrading, refurbishing and reconditioning used machines. The EU certification process involves specific penal responsibilities in charge of those issuing the certification. So that the selection of safety device has relevant effects either on workers safety, and on all peoples involved in the machinery acquisition, installation and certification process.

Provided that the selection of proper safety devices for industrial machinery is often left to designers of new machines or users

* Corresponding author. Tel.: +39 0657331546.
E-mail addresses: acaputo@uniroma3.it (A.C. Caputo), pacifico.pelagagge@univaq.it (P.M. Pelagagge), paolo.salini@univaq.it (P. Salini).

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of the older ones, the choice is hard given that a vast array of alternative safety devices is available on the market, that many machines are one-of-a-kind and custom-built so that standard choices are often not allowable, and that the installation of an unsuitable device increases risk to workers. This also means that the designer or user can be held liable of any damage caused by an improper selection of safety devices (Baram, 2007).

The choice of a safety device, on the other hand, is influenced by many factors, such as cost, reliability, effectiveness, risk of neutralization or new hazards creation, work interference potential and so on. As a consequence, the selection of a safety device involves a multiple criteria decision making and a ranking of competing devices according to often contrasting performance measures.

As a contribution to solving this problem in this paper an AHP based approach is thus developed to allow ranking of alternative safety devices, to be used as a decision making tool when selecting the most suitable device for a given machine.

The paper is organized as follows. At first the relevance of machine-related injuries is highlighted by presenting statistical data. Then the critical role of design in providing safe machines is outlined. Subsequently a classification of mechanical hazards and risk factors from machinery is provided. Available approaches to risk assessment are then reviewed. A classification of available safety devices is thus carried out to help in screening the set of safety devices in order to define a subset of alternatives to be ranked. Afterwards, the parameters able to characterize any safety devices are also discussed and a set of decision making criteria is defined. Subsequently the AHP methodology for safety devices selection is described. Finally, a numerical example is presented to practically show the capabilities of the method, and a discussion of results concludes the paper.

2. Relevance of machine-related injuries

According to the European Commission (2009) from 1995 to 2005 the fatal accident rate per 100,000 workers year fell from 4 to about 2.5 in the manufacturing sector while a reduction of about 20% was observed in the non fatal accident rate respect 1995 values. Of fatal accidents at work from 2003 to 2005, 399 involved loss of control of machine, means of transport or handling equipment, 260 being caught or carried away by something or by momentum, and 249 were caused by loss of control of machine (including unwanted start-up) or the material being worked by the machine.

In the UK, according to the Health and Safety Executive statistics (HSE, 2011), 171 workers were killed at work in 2010/11 with a rate of 0.6 fatalities per 100,000 workers, and 115,379 injuries were reported leading to a rate of 462.1 per 100,000 employees; 4.4 million work days were lost due to workplace injury (and 22.1 million due to work-related ill health), while workplace illness and injuries cost society £ 14 billion in 2009/10.

According to Bailler et al. (2003) approximately 6000 US workers died each year between 1980 and 1995 due to occupational fatal injuries, while non-fatal injuries are order of magnitudes larger than fatal occupational injury counts. In manufacturing industry they report a rate of 3.8 fatal injuries per 100,000 workers years in the 1983–1994 period. Machinery accidents were found to be the top external cause with a rate of 0.647 per 100,000 workers year. However, machinery-related industry-specific rates were 6.3 for agriculture, forestry and fishing, 6 in the mining industry, 1.9 in construction, 0.7 in manufacturing, 0.6 in transportation, 0.4 in wholesale trade, and 0.1 in retail trade.

Machinery related fatalities in the USA were analyzed by Pratt et al. (1996). They found that between 1980 and 1989 these incidents resulted in 8505 civilian worker deaths and an average annual fatality rate of 0.8 per 100,000 workers. The highest industry-specific rate was noted in agriculture, forestry, and fishing (7.47). Hakkinen and Silvennoinen (1998) carried out similar analyses in the European scenario. Etherton et al. (2001), while citing US Bureau of Labor Statistics data, report that 464 occupational fatalities occurred in the US between 1966 and 1998 resulting from being caught-in-running-machinery (costing $122 million). In the 1995–1997 period instead 92,932 nonfatal injuries of this type occurred of which 65% were in manufacturing industries. In 1996 the total nonfatal injuries incidence rate for the manufacturing industry was 238.3 per 100,000 workers and the rate for machinery injury in manufacturing was 27.7 (11% of the manufacturing rate). Of the approximately 5700 workers fatally injured in the US in 2005 about 18% were injured by contact with objects and equipment, the second leading cause of occupational fatalities after transportation incidents, while contact with equipment caused 38% of deaths among workers in production occupations (Bulzacchelli et al., 2008).

The case of mechanical equipment injuries in small manufacturing and metal working businesses was instead examined by Gardner et al. (1999) and Munshi et al. (2005), while specific data on accidents in automated production systems are also given by Mattila et al. (1995).

Bellamy et al. (2007) report that out of 9500 analyzed investigation reports from the Dutch Labor Inspectorate in the 1998–2004 period, contact with moving parts of machine accounted for 20.96% of total accidents per year, meaning about 400 accidents per year including 5 deaths.

In two Swedish automotive industries between 12% and 17% of all occupational injuries were caused by an automatically controlled machine, while according to another survey 3% of operators annually incur injuries from such accidents (Backstrom and Doos, 1995, 1997a).

Bull et al. (2001) surveyed injury rates per year per 100,000 employees in Norway during the 1991–1996 period. They found rates of 1.0 and 3.7 respectively of accidents occurring during adjusting, cleaning, lubricating tools or machines, or during ordinary operation of tools and machines. In general, with a rate of 6.7, tools and machines were the objects involved in occupational injuries.

Pratt et al. (1997) examined fatal accidents in the US construction industry. They found that between 1980 and 1992, 1901 civilian workers died in machinery-related incidents, with an average annual fatality rate of 2.13 deaths per 100,000 workers. Major contributors were “struck, pinned, crushed, or run over” by mobile machine (29.9% of cases), by boom, bucket or arm (7.5%), “overturn” (17%), “compressed between equipment or between equipment and object” (6.8%).

Goodwin Gerberich et al. (1998) compiled statistics of machinery-related injuries of farm workers reporting that among the total of 764 farming-related injury events examined 151 (20%) were related to large machinery, use, 72 (9.4%) to hand/power tools and 68 (8.9%) to tractors. The majority of injury events occurred while persons were lifting, pushing, or pulling (21%), adjusting a machine (20%), or repairing a machine (17%) and 19.8% were related to large machinery. The overall injury rate from machinery was 2214 per 100,000 workers per year, while the injury rate was 1127 from large machinery, 541 from power tools and 517 from tractors. Machine-related injuries in farming were also analyzed by Layde et al. (1995), by Lim et al. (2004) who, in particular, focused on accidents involving children up to 17 years old, by McCurdy and Carroll (2000) who reviewed studies on occupational injury among agricultural populations, and by Mohan et al. (2004) who analyzed the Indian situation. Narasimhan et al. (2010) instead correlated machine-related injury data of Saskatchewan farmers to presence of safety devices and low level of routine maintenance. Baker
et al. (2008) examined causes of injuries from agricultural machinery in Australia. The mining industry was surveyed by Ruff et al. (2011), who found that of the 562 severe accidents that occurred during 2000–2007 in the US, machine-related accidents accounted for 41% of all accidents. Machinery most often involved in these accidents included conveyors, rock bolting machines, milling machines and haulage equipment such as trucks and loaders. The most common activities associated with these accidents were operation of the machine and maintenance and repair.

Maintenance and repair have an especially high risk of injury death with an overall fatality rate of 7.6 per 100,000 workers per year in the USA as compared to 2.9 for production workers and 4.0 for all workers. Contact with equipment caused 27% of deaths among maintenance workers (Bulzacchelli et al., 2008). National Institute for Occupational Safety and Health (NIOSH, 1999) surveyed 152 fatal accidents which occurred in the USA in the period 1982–1997 during the installation, maintenance, service or repair of machinery, and found that 82% of fatalities occurred due to a failure to completely de-energize, isolate, block and/or dissipate the energy source, 11% due to failure to lockout and tagout energy control devices, and 7% owing to a failure to verify that the energy source was de-energized before beginning work. Health and Safety Executive (HSE, 2006) while surveying accidents in the printing industry observed that 75% of accidents involving contact with moving parts happened during maintenance or interventions on machines.

Many of the above accidents are imputable to inadequate safeguarding of machines. In fact, in a survey of 76 accidents in automated installations, Backstrom and Doos (2000) report that in 45% of cases passive safeguards were installed on the equipment but proved ineffective, in 41% of cases the only safeguard was an instruction that a stop device had to be employed on entering a danger zone, and in 12% of cases no safeguards or precautionary actions had been taken. Vautrin and Dei-Svaldi (1989) report that in 44% of installations covered by accidents investigations they surveyed no safeguards were provided or signals and instructions were the sole source of protection. Edwards (1993) and Jarvinen and Karwowski (1993) observed that 26% and 16% respectively of investigated accident cases could be categorized as “no-guard” situations.

3. Safety by design

Without any doubt the main responsibility of making a machine safe lies in the design process. Hazards should be eliminated and risk reduced right from the conceptual design phase of the equipment, as additional safeguards may only mitigate any residual risk.

General principles for safe design of machinery are stated in technical standards such as ANSI B11.0, ISO 12100, ANSI RIA 15.06, CSA Z432, CSA Z434, EN 292. Moreover, many specific standards have been issued to detail the design requirements, typical applications, and mode of utilization of various types of safeguards. Similarly, technical standards have been released to give guidelines to safeguard specific types of industrial machinery. Listing of safeguards-specific or machine-specific standards is provided elsewhere (Chinniah et al., 2007; Sick Inc., 2012; Neudorfer (2011) and guidelines from manufacturers of safety systems (Sick Inc., 2012; Neudorfer, 2012; Allen Bradley, 2011) provide detailed technical guidance to design safe machines by suitably integrating technical standards with sample computations, application examples and discussion of specific technical solutions.

Generally speaking the process to design safe machines includes the following steps:

(a) Identify all hazards including those resulting from materials, technical features and mode of utilization.

(b) Evaluate probability of occurrence of accidents, including exposure assessment.

(c) Assess risk and safety level during the various activities in the operational phase (e.g., installation, operation, cleaning, maintenance and disposal).

(d) Perform a formal design review with focus on safety aspects.

(e) Decide whether the safety of the product is adequate otherwise adopt mitigation measures.

(f) Verify that the desired safety level is achieved through testing, analysis of the results, and modifications to the design in an iterative manner.

Unacceptable risk may be reduced by the designer based on a four-step safety improvement strategy (according to ISO 14121-2) in this order of priority:

(i) Elimination of hazards by design (i.e. changing materials and energy sources, eliminating hazardous tasks etc.).

(ii) Risk reduction by design. This can be obtained by reducing energy (e.g. lower speed, lower force), using more reliable components, modifying the features of components etc.

(iii) Safeguarding by using proper barriers and implementing protective measures through engineering controls and specific safety functions.

(iv) Adopt administrative measures to inform and warn about residual risks.

The above steps are to be applied in an iterative manner during all the phases of equipment life cycle at the business, product and component level as detailed by Rausand and Bouwer Utne (2009).


Fadier and Ciccotelli (1999) made an early survey about method and models available to integrate safety in design, while Fadier and De la Garza (2006) discuss from a conceptual point of view recommendations for making work equipment design safer. They claim that a designer first proposes a design based on other requirements than safety, and then the design is evaluated against safety criteria. This means that safety aspects are not considered before the system or product is technically designed, and that safety devices are “add-ons” to the original design. Finally, in the design process, the operational context of the product is considered and defined by the designer, resulting in a non-optimal safety design as he may not be fully aware of the actual operating environment. Hasgrave and Holmes (1994) advise about the importance of incorporating even ergonomic factors in the design process. Gauthier and Charron (2002) state that while it appears that design engineers do not lack awareness or motivation to integrate safety into their design, many of them do not know how to make this integration efficiently. Therefore, they propose a systematic method to intimately integrate risk analysis and control into the design process of industrial machinery which is demonstrated by re-designing a wood chipper.

Methods for systematic introduction of safety concepts in design were developed by Harms-Ringdahl (1987) who proposed a seven-step analysis procedure to ensure product safety during design and applied it to a paper mill, by Schoone-Harmsen (1990) who adopted instead a four-step procedure, by INRS (1994) following the introduction of Standard EN 292-1, by Stoop (1993) who introduced a set of iterative decision points during design where safety aspects are weighted against all other design considerations, and by Reunanen (1993; Worsell and Wilday (2000) proposed a risk assessment method applicable to design safe machinery. Anderson (2005) proposes a risk analysis methodology that includes hazards identified from the machine design.
and those that occur from the mitigating methods. A general methodology for ensuring safety of complex machinery systems is discussed in Tiusanen et al. (2007), Bernard and Hasan (2002) and Hasan et al. (2003) presented a working situation modeling approach and tool allowing to integrate safety into design as early as possible. A method called Safety Function Analysis (SFA) has been developed by Harms-Ringdahl (2003) to evaluate safety characteristics at industrial installations and suggest improvements, and successively extended for use in accidents investigation (Harms-Ringdahl, 2009). Blaise et al. (2003) present a formal methodology for modeling knowledge included in safety standards, allowing the designer to use standards much easier than in their current textual expression when designing machinery and automated production systems. Coulibaly et al. (2008) provide a CAD-based approach which, relying on a 3D model of the machine and a semantic matrix gathering information of the components criticality, predicts safety and assesses risk at an early design stage allowing to explore alternative design configurations.

A practical example of application of safety by design approaches is given in (Fadier and De la Garza, 2007) focusing on printing machines, while an industrial example of design integrating machinery safety and functional safety requirements is presented by Kohanawa and Hasegawa (2008). Mohan et al. (2004) discuss design changes to improve machine safety in the case of fodder-cutter machines, while Gauthier and Charron (2002) consider a wood chipper. Bisset (1999) describes the formal Machinery Safety Design and Review Process, used by Gillette Company to identify, eliminate, or minimize the risks, and to implement the appropriate engineering controls when designing production machinery and illustrates the case of the production of blades and razors products. Drogoul et al. (2007) compare safety by design practices in different industries, but mainly focus on software development and large scale systems or entire processes.

Overall, the interested reader can find state of the art reviews on design and safety culture integration as well as about broader issue of consumer and industrial products safety in Hale et al. (2006) and Rausand and Bouwer Utne (2009). The latter detail all safety related activities through the entire life cycle of the product or equipment.

However, while from a conceptual point of view the process leading to proper risk reduction and safeguarding of machines is suitably defined, one observes that in practice machine safety is often inadequate. As an example, Cordero et al. (2009) highlight the current status of compliance to the Machinery Directive 98/37/EC in Spain. According to a sample of 264 essays carried out in the 2002 to 2006 period, only 9% of essays fulfilled the Directive. However, it has to be pointed out that essays referred only to equipment considered suspect, after a visual inspection, of presenting a breach in safety terms. The reasons for non conformities are multiple: for instance 73.5% of tested machinery had shortcomings related to marking, while about 50% had incomplete accompanying documentation or lacking declaration of conformity. 31.4% had no indication about airborne noise emission, 12.5% of inspected machines failed to comply with safety requirements of controls, while in 11% of cases the protection against mechanical hazards failed, while another 11% had shortcomings in the protection devices. Similarly, Samant et al. (2006) examined 824 machines in small metal shops in Minnesota, USA, and found that no single machine complied with all critical safety requirements. Overall, guards were found on 62% of machines and emergency stops on 34% only. They concluded that machine guarding and related safety programs in small metal fabrication businesses were inadequate.

This confirms that selection of safeguards is not only a concern in the design phase, but also an operational problem for shop managers and users of installed machines.

However, it should be pointed out that in this paper no attempt is made to develop a new method for designing safe machines, but rather a methodology is presented to compare the suitability and desirability of candidate alternative safeguards, based on a multiple criteria ranking and the explicitation of a consistent set of rating criteria, which can be used either by designer during the design phase as well as by users.

4. Classification of mechanical hazards

A hazard is a “potential source of harm” (ISO 14121-1) and may lead to hazardous events that can cause immediate or delayed harm to people, the environment, and/or financial and material assets affecting both the users and the manufacturer. Hazard may derive from how a machine is designed and even from how it is used. For users the consequences can range from a mere nuisance to a serious damage, in the form of injuries, fatalities, and/or economic loss. In some cases a safe product may also lead to significant consequences because of the way it is used. In that respect the possibilities are a willful misuse of the product, much harder to prevent, and misuse due to misunderstanding the product application owing to misreading the user instructions, or user-generated assumptions about the product’s intended use (Reinert et al., 2007), which could be prevented through suitable instructions manuals and warning statements in the manual or on the product, provided that the user reads them.

For producers, harm caused by unsafe products may lead to consequences like payment for settlement of injury or death claims, property damage claims not covered by insurance, warranty claims, liability and callback costs, loss of prestige and public confidence, market share loss, and so on (Rausand and Bouwer Utne, 2009). Product hazards may be attributed to component failure, material failure, environmental stress, and operator errors (Hamer, 1993). These categories of causes are related to dangerous properties of a product. Such properties may be inherent in the product, or stem from a design error and inadequate specification when developing the product, a production defect, or some other kind of deficiency. The hazards may be eliminated or controlled and the development of consequences may be stopped or mitigated by various barriers and safety functions.

Generally speaking a mechanical hazard may occur when a part of the human body enters in contact with a moving or stationary part of the machine or when part of the machine, of the workpiece or some working fluids are ejected from the machine. A wide variety of mechanical motions and actions may present hazards to the operator. These include rotating, reciprocating and transversing motions which give rise to hazards of entanglement, cutting, punching, shearing, bending, striking, crushing. A number of mechanical components of tools and mechanisms can be thus classified as hazardous, such as rotating members, reciprocating arms, moving belts, meshing gears, cutting teeth, flywheels, pulleys, connecting rods, couplings, cams, spindles, chains, cranks, and any parts that impact or shear. As such the three basic areas needing safeguarding are the point of operation (that point where work is performed on the material), the components of the power transmission apparatus, and any other parts of the machine that move while the machine is working including feed mechanisms and auxiliary parts of the machine. Usually mechanical hazards do not include contact with toxic material, electrical contact, contact with hot or cold surfaces, noise and vibration, radiation exposure, falling objects, but often these hazard are also associated to machinery.

Bulzacchelli et al. (2008) examined fatal injuries while performing maintenance and servicing of machinery in the US manufacturing industries from 1984 to 1997. They found that the most common mechanisms of injury were being caught in or between parts of equipment (52.1% of fatal lockout/tagout injuries), electrocution (26.4%) and being struck by or against objects (10.7%), and
concluded that enhanced training and designs that facilitate lockout and minimize worker contact with machine parts may prevent many lockout/tagout-related injuries. Even Lind (2008) analyzed maintenance injuries and concluded that fatal injuries occur mainly owing to dangerous work methods, while non-fatal injuries happen while working when the machine is running.

Categorization of mechanical hazards from machinery is not standardized thus giving rise to confusion. Baker et al. (2008), classified causes of injury in the following categories with reference to industrial machinery: injured by moving parts on operating machinery; struck by machine/equipment; shear/pinch points; fall from stationary machinery; equipment falling on farmer; fall from mobile machinery.

Chinniah et al. (2007) classifies the following 16 different kinds of mechanical hazards: sharp edges; cutting or severing parts; entanglement with rotating parts and with rotating parts with projections or gaps; crushing with in-running nip points; with rotating and tangentially moving parts; with parts rotating in opposite directions; with a rotating and a fixed part; with reciprocating parts; or with a part of the body caught within moving parts; instability of masses; friction and abrasion; release of accumulated energy within the machine; impact without penetration; puncturing with penetration; drawing-in; shearing.

Pratt et al. (1997) adopt the World Health Organization practice which uses the following classification of machine-related hazards: burned by: caught in moving parts of; collapse of; crushed by; cut or pierced by; drowning or submersion caused by: explosion; fall from or into moving part of; fire starting in or on; mechanical suffocation caused by: object falling from, on, in motion by; overturning of; pinned under: run over by, struck by, thrown from, caught between other object and.

However, research showed that even access paths to mobile machinery are significant hazards to be accounted for (Leskinen et al., 2002), while posture problems are a well-known ergonomic hazard which can affect long term health of workers and should be analyzed in conjunction with safety and design issues (Li et al., 1995).

5. Approaches to machinery risk assessment

Risk can be defined as “the considered expected loss or damage associated with the occurrence of a possible undesired event” (Nieuwhof, 1985). Therefore, hazards refer to the source of loss or damage while risk is the probability of occurrence of the loss or damage (Arunraj and Maiti, 2007). The probability of occurrence of adverse effects is affected by exposure to the hazard (in turn influenced by time spent in hazard zone, and need for, nature of and frequency of access to hazard zone, as well as number of exposed people), the occurrence of a hazardous event, and the possibility of avoiding or mitigating the harm (ISO 14121-1). European Commission (2008) distinguishes between eight levels of probability: from “virtually impossible” (≤1E-06) to “expected” (>0.5), and four levels of consequences or severity (1–4); one causing minor injuries and four more than 10% disabilities or fatalities.

The product risk can be evaluated qualitatively or quantitatively (Macdonald, 2004). Several standards and guidelines are available as a basis for risk analysis and assessment. Among these are ANSI B11.TR3, ISO 14121 and IEC 60300-3-9. Even publications by manufacturer of safety devices detail from a practical perspective the steps of a correct risk assessment (Sick Inc., 2012; Neudorfer, 2012; Allen Bradley, 2011) as does the trade literature (Main, 2005; Paques et al., 2005; Piampiano and Rizzo, 2006; Routdebush, 2005; Tolbert, 2005).

From a more academic perspective, Clemens (1982) provides an early review of available hazard identification and assessment methods. Hazard analysis techniques are also surveyed by Ericson (2005). Tixier et al. (2002) list 62 risk analysis methodologies including deterministic, probabilistic and combined techniques. Although they refer mainly to process plants, most of the described methods are general purpose and can be applied to the case of machinery as well. Gauthier and Charron (2001) review safety analysis methods specific to machinery and applicable to design problems. Etherton et al. (2001) discuss overall issues connected to machinery risk estimation also pointing out economical consequences of accidents. They then review quantitative risk assessment methods for machinery considered much more effective than prescriptive machine safety standards (Etherton, 2007).


Sierla et al. (2012) developed a risk analysis methodology that can be applied at the early concept design stage, whose purpose is to identify functional failures propagation paths in software-based automation subsystems, electric subsystems and mechanical subsystems. This allows to perform risk assessment even in complex mechatronic systems.

In an attempt to provide a systematic procedure to analyze accidents scenarios Backstrom and Doos (1997b) developed a conceptual methodology that helps in describing the technical genesis of machine failures leading to accidents. They recognized a chain of the following factors able to describe the process from the emergence of a technical fault to how it is handled: Origin, History, Type, Location, Manifestation of fault, Machine failure, Human intervention. However, their method is limited to automated machines as it only considers that part of the course of the accident which is related to a machine failure, and neglects human error. Bellamy et al. (2007, 2008) developed a software tool called Storybuilder which allows to construct models for quantifying occupational risk from accident histories by building event structures and accident pathways. Aneziiris et al. (2008) developed a model for calculating occupational risk in the Netherlands based on 9000 accident reports, on a bowtie schematization of the accident process and a classification of 36 accident scenarios. This model provides employers with a tool to compute risk rates and assess measures aimed at reducing the risk of employees suffering injury or death as a consequence of job-related incidents. They covered 63 types of occupational accident hazards. For instance, the following risk rates were computed for contact with moving parts of a machine event, namely, operating a machine (recoverable injury 3.80E–08 h⁻¹, permanent injury 2.07E–07 h⁻¹, fatality 5.17E–10 h⁻¹), maintaining (recoverable injury 3.67E–08 h⁻¹, permanent injury 1.27E–07 h⁻¹, fatality 5.26E–09 h⁻¹), clearing (recoverable injury 2.81E–07 h⁻¹, permanent injury 1.10E–06 h⁻¹, fatality 5.51E–08 h⁻¹), cleaning (recoverable injury 1.33E–07 h⁻¹, permanent injury 5.40E–07 h⁻¹, fatality 6.73E–09 h⁻¹), while rates for “trapped between” event were: recoverable injury 7.65E–08 h⁻¹, permanent injury 1.60E–07 h⁻¹, fatality 1.20E–08 h⁻¹. Further details can be found in Papazoglou and Ale (2007), Ale et al. (2008), and Papazoglou et al. (2009).

Nevertheless, the context of manufacturing plants and job shops often makes sophisticated probabilistic analysis and detailed risk modeling not applicable, so that simplified methods based on check lists (OSHA, 2007a; Kjellen et al., 1990) and risk matrix are most often used (European Commission, 2008).
Finally, it is well known that equipment, however well designed, will not remain safe or reliable if it is not properly maintained. Therefore, risk based decision making in machinery maintenance plays an important role in keeping the workplace safe. Arunraj and Maiti (2007) review risk-based maintenance techniques which can help in achieving the possible safety with minimum cost and planning effective machine maintenance policies. Moreover, as already mentioned, many accidents occur not during processing but during machine maintenance, so that selection of safeguards and work instructions should explicitly account for maintenance activities (Etherton, 1988).

6. Classification of safety devices

A number of APDs are available on the market to improve safety of machinery. The types of safeguards and their configurations are fully described in the literature (Allen Bradley, 2011; OSHA, 1992; Macdonald, 2004; National Safety Council, 2002; Ridley, 2006; Spellman, 1999).

Martin and Walters (2001) and OSHA (2007b) provide a survey of safeguards for small businesses for shop machinery. Available safeguards are also described by Etherton (1987) taking into account human factors concerns in their design. Apart from technical measures Kjellen et al. (1990) include in their safeguards classification workers training and attitude changes, organizational measures, maintenance, and safety systems such as signaling, stop functions, alarms and so on. Lockout/tagout devices to control hazardous energy are described by OSHA (2002).

Safeguards are often classified according to the kind of safety function they implement. Backstrom and Doos (2000), relying on ISO 11161 standard, classify safeguards according to their functions in the following categories: material barriers, inter-locks, enabling devices, hold-to-run controls, two-hand controls, presence sensing devices, hand-removal devices, limiting devices, and stop devices. Sick Inc. (2012), instead, categorizes the following safety functions, namely permanently preventing access; temporarily preventing access; retaining parts/substances/radiation; initiating a stop; avoiding unexpected start-up; preventing start; combining the initiation of a stop and preventing start; differentiating between man and material; monitoring machine parameters; disabling safety functions manually and for a limited time; shutting down in an emergency; combining or changing safety functions according to operating mode of the machine.

Haddon (1974) distinguishes between active safeguards (those requiring action from a person to function) and passive safeguards (which work automatically), while a third basis for classification, often used in the context of industrial robots, relies on categorizing the degree of proximity of the safeguard to machine movements, i.e., perimeter penetration detection around workstation, intruder detection on floor surface within workstation and intruder detection of close proximity of manipulators (Haddon, 1974; Bellino, 1988; Etherton, 1988; Sneckenberger et al., 1987). Here we prefer the following classification based on the typology of the devices.

6.1. Fixed enclosing guards (FEGs)

These guards are permanently fixed to the machinery and must require tools for removal. Fixed guards are suitable in cases when the hazard is on a part of the machinery which does not require access. Fixed guards may have openings to check the process or insert and withdraw material, but the size of the openings must prevent the operator from reaching the hazard.

If made of robust construction can also contain projectiles. FEGs provide maximum protection with minimum maintenance requirement and have low cost and long life. Can be constructed even in-plant and in shapes to suit specific applications. As a drawback, FEGs may interfere with visibility and machine adjustment, while repair often requires their removal, but unauthorized removal could remain undetected.

6.2. Movable enclosing guards (MEGs)

These guards are not held in a fixed position but can be opened (unsafe position) or closed (safe position). An interlock (usually a switch) is to be associated to the guard so that machine can be operated only when the guard is in closed position. When the machine is running a sudden guard opening should be impeded (by using guard locking interlock switches) or the machine should be brought to immediate stop by the interlock. Movable guards are suited to cases where access to the hazardous area is required between working cycles but is infrequent. Sometimes a closure of the guard automatically triggers a work cycle of the machine and its opening stops the cycle. This solution is adopted when high frequency work cycles are sought and eliminate the dead time of separate guard handling and machine switch-on and shut-off. MEGs can provide maximum protection and allow access to machine for removing jams without time consuming removal of fixed guards, but may be easy to disengage, require careful adjustment and maintenance and are much more costly than fixed guards.

6.3. Adjustable guards (AGs)

Such guards are mobile but do not have definite resting positions so that it is not possible to interlock guard position and machine operation. These guards are used when parts of different size are to be worked and continuous access to the hazardous area is required during operation. Some guards can be self-adjusting. In this case the openings of these barriers are determined by the movement of the stock. As the operator moves the stock into the danger area, the guard is pushed away, providing an opening which is only large enough to admit the stock. After the stock is removed, the guard returns to the rest position. Protection may not be complete as hands may enter danger area, and may require frequent maintenance and/or adjustment. Moreover the guard may be made ineffective by the operator and may interfere with visibility.

6.4. Pullback devices (PDs)

Old-fashioned devices consisting in a series of cables attached to the operator's hands and/or arms. This type of device is primarily used on machines with stroking action. A mechanical linkage automatically assures withdrawal of the hands from the point of operation as soon as the machine starts its working cycle. When the cycle is finished the operator is allowed access to the point of operation again. Articulated mechanisms can also extend from the machine to pull back the entire body. Pullbacks limit movement of operator and may obstruct work space around operator.

6.5. Access detection devices (ADDS)

These devices are intended to sense access to hazardous area and are also known as Presence Sensing Devices (PSDs). A worker entering a given space can be detected by means of a suitable detector. Detection may take place with the aid of a light beam, Doppler effect radar, TV camera, electromagnetic field or thermal field etc. (Vartiala, 1982).

When the access is sensed the status of the safety system is checked and an output device is eventually triggered to switch off hazardous machine operations, to trip off the power, or to con-
trol an actuator to bring in position a movable guard. Otherwise the ADD prevents switching on when a person or a body part is in the hazard area.

Examples of ADDs are the following.

**Safety light curtains:** in this case photelectric presence sensors provide perimeter access control through a set of light beams arranged in a manner to create a virtual wall that must be penetrated by the worker to reach the hazardous area.

**Single beam safety light barriers:** this is the same as the above where the multiple light beams making a virtual wall are superseded by a single light beam.

**Radiofrequency (capacitance) presence-sensing devices:** in this case the proximity sensor is a volumetric sensor using reflected radio waves or the change of capacitance when an intruder penetrates the dielectric space between the armatures of a capacitor.

**Pressure sensitive safety mats:** are laid on the floor around the machine and provide guarding of its perimeter by sensing the weight of an intruder in the controlled area. The working principle is based on the elastic deformation of a hollow body that ensures an internal signal generator (electromechanical or optical) performs the safety function.

**Pressure sensitive edges:** usually take the form of flexible air filled strips that can be mounted to the edge of a moving part, such as a machine table or powered door that poses a risk of a crushing or shearing. When the hazardous part enters in contact with a body part the flexible element deforms and triggers (usually resorting to a pneumatic device) the safety action. The working principle is similar to that of pressure sensitive mats, but in this case the sensitive device is installed on the line-shaped hazardous part instead of being fixed to the floor.

**Surface or volume scanners:** here movable laser beams are used to scan a surface or a volume around the hazardous area resorting to rotating mirror and sense the light reflected or scattered by the intruder. Ultrasound devices are also used to sense the echo generated by the intruder.

**Safety trip controls:** this class includes a large variety of devices such as pressure-sensitive body bar, swinging arms or triprods which, when depressed, will deactivate the machine. The main difference with pressure sensitive edges devices is that a solid-body motion is used instead of an elastic deformation of the sensing device and that an electromechanical switch is mostly employed instead of pressure waves, optoelectronic effects and resistance changes to trigger the signal.

ADDs provide quick and easy access to the hazard area and are often selected when operators must frequently access it. In fact, ADDs allow for greater productivity and are a more ergonomically sound solution when compared to mechanical guards. Most of them allow freer movement for operators, simplicity of use, can be used by multiple operators and provide passby protection. Some do not require adjustment, and provide low cost protection of large sized areas. Nevertheless, these types of devices do not provide protection against mechanical failures, projectiles, mists, fluids. Moreover, the stopping time of hazard must be shorter that the time needed for the body part accessing the area to actually reach the hazard. In fact, the machine should be capable of being stopped before the worker can reach the danger area.

### 6.6. Manually operated controls (MOCs)

These are machine operation controls which can perform a safety function. Among them the following are relevant examples.

**Emergency stop buttons:** they are considered complementary, although customary, safeguarding devices because they do not prevent access to a hazard nor do they detect access to a hazard. They only limit the amount of damage. Their function is to stop the machine as soon as possible, without inducing additional hazards when actuated in case of an emergency.

**Cable pull switches:** these are cables laid along the hazard area to be pulled in case of an emergency to stop the machine. Are convenient in case of long equipments such as conveyors or assembly lines.

**Two-hands controls:** these are devices where two controls must be operated concurrently to start the machine. This ensures that both hands of the operator are occupied in a safe position outside the hazard area. The controls must be operated continuously during the hazardous conditions. Machine operation must cease when either of the controls is released. If one control is released, the other control must also be released before the machine can be re-started. Obviously a two-hand control does not provide any kind of physical protection to the operator or passerbys and can be rendered unsafe by holding with arm or blocking, thereby permitting one-hand operation. However, they are low cost, easy to install and operate and not space consuming.

**Hold-to-run controls:** they are similar to two-hands controls exception made that a single hand-held command is used which must be hold throughout the machine operation. Machine starts working when the command is operated and stops when the command is release. They only protect the single hand holding the command.

**Enabling devices:** enabling devices are controls that allow an operator to enter a hazard area with the hazard running only while the operator is holding the device in the actuated position.

From the above description the advantages and drawbacks of each type of safeguard can be easily pointed out. For reader’s convenience Table 1 summarizes the pros and cons of each kind of solution. The Table has been also compiled on the basis of literature sources (Backstrom and Doos, 2000; Sick Inc., 2012; Neudorfer, 2012).

### 7. Decision making criteria for safety devices selection

The proper choice of safeguards is one of the available options to mitigate risk of machinery (Rausand and Bouwer Utne, 2009). Guidelines exist to select safeguards for a machine. For instance, ISO 14120 provides a chart for the selection of guards according to the number and location of hazards, while ISO 12100 provides guidelines to help make the choice of safeguards against hazards generated by moving parts. Generic requirements that safeguards have to satisfy are also listed in current regulations such as the Machinery Directive 2006/42/EC.

General guidelines for machine safeguarding are provided by Governmental bodies (Marshall and Bingham, 1977; Manitoba Labour Workplace Safety, 1989; Government of Western Australia, 2012; Giraud, 2012; WCBC, 2006). Quite useful to practitioners and designers are publications of manufacturers of safeguards which describe available types of safety devices and show practical application examples and preferred design, often accompanied by numerical sizing examples, while providing guidance about selection and usage of safety devices (Sick Inc., 2012; Neudorfer, 2012; Allen Bradley, 2011). The above publication are often more informative and exhaustive than traditional textbooks and institutional publications.

In the specific case of automated systems Jiang et al. (1991) discussed how traditional safeguarding techniques could be used transferred to robotic systems, while George and Mital (1989) present a few case studies showing the application of safety devices in automation. Safety application in industrial robotics are also discussed for instance by Gaskill and West (1996), Nicolaïsen (1987), Sheehy and Chapman (1988), Jones (1986), Millard (1991),
and Toola (1993) who describe frequent problems, specific kind of accidents and suggested solutions.

However, the process of choosing a safeguard is by no means automatic, and to install one or more appropriate safeguards is by no means conclusive to achieve safety.

Relying on evidence from the accident records they investigated Vaibin and Dei-Svaldi (1989), Edwards (1993), Jarvinen and Karwowski (1993), Samant et al. (2006), Backstrom and Doos (2000) confirm that often safeguards proved ineffective, when not entirely missing. This means that the point is not just installing a safeguard, but verifying that the safeguard can be effective against the intended hazard in any operational condition and that it is always available and operational.

In fact, Backstrom and Doos (2000) pinpoint four common problems with safeguarding emerging from accidents investigations: no or a low level of safeguarding, safeguards not being used or being defeated or removed, safeguards not stopping all machine movements in the risk zone, and safeguards providing access to hazardous zones or not being capable of providing protection under the circumstances that prevail. This is confirmed by other authors (Edwards, 1993; Jarvinen and Karwowski, 1993; Vautrin and Dei-Svaldi, 1989). It is shown that all types of safeguards have their problems and, in particular, that they do not always function adequately in conjunction with the handling of production disturbances. The above authors warn that a production installation should not automatically be regarded as safe simply because it possesses an impressive range of safeguards and urge to go beyond regulations and standards when addressing safeguarding problems by demonstrating how accidents occur despite the presence of safeguards, and how safeguards may be deficient in an operational setting.

Gauthier and Charron (2002) state that although there can be many risk control measures, they are generally not all satisfactory, and that the selection of the final solution or set of solutions to control a particular risk must be made with consideration of significant criteria. They cite the following subdivided in three areas, namely Safety-related (i.e. effectiveness of the control measure; reliability and stability of the control measure; new risks generated with the introduction of the measure; other risks whose ‘criticality’ is increased by the measure; delay for implementation of the measure; controllability of measures), Functionality-related (i.e. the adaptability of a control measure not to disturb the work task; organizational and/or technical feasibility) and, finally, Cost-related (i.e. the cost of the risk control measure; the influence of the measure on the cost of operation of the machinery). They also assumed that the safety effectiveness of a risk control measure can be expressed by the evaluation of the reduction in risk level that is obtained following its implementation.

Booth (1979) raises criticism about the effectiveness of machine guards and discuss the criteria which determine whether a guard is likely or unlikely to fulfill its function effectively. Vaillancourt and Snook (1995) warn that machine guarding sizing and placement criteria developed during the 1940s representing the relationship between gap size and safe distance may no longer be consistent with subsequent large scale anthropometric surveys, so that original recommendations appearing in widely utilized guidelines and technical standards may not be completely reliable.

From the above discussion it follows that specific criteria have to be determined to allow a meaningful comparison of safeguarding options available to designers and users.

Accidents investigations and surveys of safeguards utilization practices in industry provide useful guidelines to determine the requirements an effective safeguard should satisfy.

Backstrom and Doos (2000) report that a frequent failure of safeguards is the “non-use” owing to removal, circumvention, defeat, decoupling, failure to activate, or inexperience. Therefore, it is important that the safeguard is reliable but even difficult to remove or neutralize. They also report that safeguards are often

| Table 1 | Comparison of safeguards features. |
|---|---|---|
| **Safeguard** | **Advantages** | **Drawbacks** |
| Fixed enclosing guards | Fixed to the machine and hard to remove. May contain projectiles ejected by the machine. Low cost, reliable and maintenance free. Long life. Shape easily adapted to machine features. Protect multiple operators | Gaps and safety distance may be inappropriate. Scarcity flexibility to changing operations. May interfere with machine operation and adjustment. May limit operator’s visibility of work piece and its productivity. May shatter if not robust enough. Unauthorized removal may be undetected. May be expensive if extended over long distances or areas. | |
| Movable enclosing guards with interlocks | High protection while allowing hazardous workspace accessibility between working cycles. Protect multiple operators. May allow easy integration with computerized control systems | Interlocks need careful mounting, adjustment and maintenance. Interlocks may not affect all machine movements in the danger zone. Easy to disengage or defeat the interlock. Possible wrong dimensioning. Add the cost of interlock. | |
| Adjustable guards | Allow work pieces of different sizes and continuous access to hazardous area during operation if needed. Self-adjusting. Guards designed for right-handed people may be unsuitable to left-handed people | Incomplete protection. Frequent maintenance and/or adjustment. May interfere with visibility. Easily made ineffective | |
| Pullback devices | Effective protection of operator’s body | Require adjustment and maintenance. Do not work if hands are in abnormal position. Limit operator’s movements. Obstruct work space around operator. Only protect operator. May not protect from projectiles | |
| Access detection device | Quick and easy access to the hazard area. Improved ergonomy respect other guards. Do not limit freedom of movement. Protect multiple operators. Easy to use. Low cost protection of large areas or volumes. Easy to install and use. May not require adjustment. Do not interfere with loading–unloading operations. Maintenance free. May allow easy integration with computerized control systems | Do not protect against projectiles. Ineffective if machine cannot be stopped promptly before operator reaches danger. May allow working on the dangerous side of a detection device. Machine movements and environmental factors may cause false alarms. Protection of short distances is relatively expensive | |
| Manually operated controls | Compact, easy to operate, low cost and maintenance free. Do not obstruct work space visibility. Do not interfere with loading–unloading operations and productivity | Do not prevent nor detect access to a hazard. Do not provide a physical barrier and do not protect against projectiles. Protect mostly the operator holding the device. May be inadvertently operated thus non-voluntarily starting the machine. Stop device may be difficult to reach in a dangerous situation. Hold-to-run controls and two-hand controls may be disconnected or manipulated permitting one-hand control or hands-free operation. May only limit the amount of damage. May not allow machine to be stopped safely/ in time. Numerous monotonous hand movements for cyclical operation. May be unreliable. Ergonomic arrangement not easy | |

Comparison of safeguards features.
non utilized because of excess work to do to put the safeguard in place or due to production disturbances caused by the safeguard when in place. Therefore, safeguards should be easy to operate and should not impair the work cycle. Inexperience is also a common reason for not using a safeguard. Therefore the safeguard should be easy to operate even to novices with no or minimal training. If possible the operation of a safeguard should be intuitive and self-explaining. Finally, they report cases where the safeguard did not stop all machine movements. This is often a consequence of wrong logic of the safety control system or unintended operation of the actuating devices. In other cases the safeguard had a limited range and provided incapable of providing full protection. Therefore, when choosing a safeguard it is important to verify that the safeguard is effective, i.e. it gives full protection against all hazards, to all persons involved in machine operation or persons standing nearby, and in all positions that could be reasonably reached by the operators in any operating condition.

Salminen and Saari (1995) advise about the importance of preserving workers productivity while pursuing machine safety. This means that a safeguard should not interfere with the production cycles and should be easy and quick to operate. In fact, according to Neudorfer (2012) there is risk of misuse and removal of safeguards when guard devices must be removed or opened too frequently or too awkwardly, because the machine or process is susceptible to faults; when the guard device vibrates and rattles; when the guard device cannot be operated easily; when the guard devices can be bypassed with little practical and intellectual effort; when the required view of the operating sequences is not possible; when the tripping of interlock causes follow-on failures; when the work necessary in the special operating mode with guard devices open can not be carried out; when the guard devices with guard-locking can only be opened after a lengthy waiting period; when guards are a hindrance to the user, or when are arranged in the working and traffic areas such that they are triggered too often guards are a hindrance to the user, or when are arranged in the working and traffic areas such that they are triggered too often or machines. Therefore, the selection of safeguards should take into means that a safeguard should not interfere with the production cycles and should be easy and quick to operate. In fact, according to Neudorfer (2012) there is risk of misuse and removal of safeguards when guard devices must be removed or opened too frequently or too awkwardly, because the machine or process is susceptible to faults; when the guard device vibrates and rattles; when the guard device cannot be operated easily; when the guard devices can be bypassed with little practical and intellectual effort; when the required view of the operating sequences is not possible; when the tripping of interlock causes follow-on failures; when the work necessary in the special operating mode with guard devices open can not be carried out; when the guard devices with guard-locking can only be opened after a lengthy waiting period; when guards are a hindrance to the user, or when are arranged in the working and traffic areas such that they are triggered too often or machines. Therefore, the selection of safeguards should take into means that a safeguard should not interfere with the production cycles and should be easy and quick to operate. In fact, according to Neudorfer (2012) there is risk of misuse and removal of safeguards when guard devices must be removed or opened too frequently or too awkwardly, because the machine or process is susceptible to faults; when the guard device vibrates and rattles; when the guard device cannot be operated easily; when the guard devices can be bypassed with little practical and intellectual effort; when the required view of the operating sequences is not possible; when the tripping of interlock causes follow-on failures; when the work necessary in the special operating mode with guard devices open can not be carried out; when the guard devices with guard-locking can only be opened after a lengthy waiting period; when guards are a hindrance to the user, or when are arranged in the working and traffic areas such that they are triggered too often unintentionally, thereby leading to process disturbances.

However, the problem remains of assessing the overconfidence of operators which leads to not utilize existing safety devices. In fact, people often install safety devices and plan to use them, but fail to do so (Yechiam et al., 2006).

Finally, Etcherton (1988), Goodwin Gerberich et al. (1998), Ruff et al. (2011), Bulzacchelli et al. (2008), Bull et al. (2001), HSE (2006) and Aneziros et al. (2008) warn about the high incidence of accidents occurring during adjusting, cleaning, lubricating tools or machines. Therefore, the selection of safeguards should take into consideration safety requirements during this kind of occupations.

From this empirical evidence, and from the analysis of advantages and drawbacks of available safeguard types (see Table 1), one concludes that a safeguard to be adequate should satisfy the following basic requirements.

(a) Provide an effective protection against all possible hazards and operational conditions.
(b) Can be used without impairing work or lowering productivity, otherwise the worker is tempted to remove it and, to avoid this occurrence, should be hard to neutralize.
(c) Should not cause any additional hazard.
(d) Should be affordable over its life cycle.

Therefore, we identified the following 15 factors as useful to judge the suitability of a safety device according to the above requirements.

7.1. Effectiveness (E)

This is an overall measure of the device’s fitness for the scope, that is the capability of effectively preventing contact with dangerous moving or stationary members of all body parts which could be harmed by the machine, including people different from the machine operator in all foreseeable operational conditions. It is a judgement about the degree of protection offered and the consistency of the device with the kind of mechanical hazard occurring, i.e. whether the safety device is right for the job. In case the safety device is interlocked with machines drives or shutdown devices, a judgement must also be given about compatibility of safety device alarm signal and machine response delay, i.e. whether the safety device can command the machine to stop all dangerous movements in the risk zone in a suitably short time to prevent hazardous contact.

Obviously the choice of safety device is influenced by the part of the body to be protected, but a device which protects only a specific part of the body may not effectively protect other parts which could be accidentally harmed as well. For instance, a two-hands control may protect effectively the hands of the operator but does not ensure that he can not insert a leg or the head in a dangerous place or that a second operator could touch the machine’s working parts. Moreover, it does not protect the operator itself from parts that could be projected from the work piece during processing. Conversely, a guard fully enclosing the machines protects any body part of the operator as well any other party and also prevents damage from parts projection. Thus it could be considered more effective. However, if the fixed guard has some slots through which a hand or a finger could be inserted and touch hazardous machine components, then the safety device effectiveness should be intended as compromised.

As a conclusive remark we assume that the alternative safeguards to be ranked have been already verified to provide an adequate effectiveness in risk control and that this is expressed by the Effectiveness parameter (E). In fact, this method is not aimed at choosing the safeguard appropriate to a given hazard, but rather to choose the most suitable one among those adequate to the machine and the hazard.

7.2. Protection from falling objects (PFO)

Objects falling into moving parts of cycling machines can be ejected as projectiles. An effective safeguard should avoid any falling object to reach a moving part of the machine and being projected outside the machine.

7.3. Cost (C)

This includes the purchase and installation cost of the safety device and the operational cost (maintenance, periodical inspections, spare parts etc.) expressed in both monetary terms and down time.

7.4. Reliability (R)

This is a measure of the attitude of the device not to fail. It is a proxy for the mean time between failure or the probability of failure on demand. It can also be a proxy for the sensitivity of the safety device to rugged operating conditions on the work place and to rough handling. For instance a sensitive electronic device can be damaged by machine vibration and fail thus being unreliable.

7.5. Maintainability (M)

This factor is inversely proportional to the amount of effort required to maintain the device in good service (includes periodical inspection and preventive maintenance) as well as the capability of quickly being repaired when failed.
7.6. Fault tolerance (FT)

This is the capability of graceful degradation as opposed to sudden failure, i.e. the capability of maintaining a residual safeguarding action even if not fully operational or failed, or the capability of slowly degrading the safeguarding action so that the hazard is at least mitigated while the restoration action can be applied. The capability to maintain the safety function even in case of faults of the safety device is usually associated to the architecture of the safety device and its control system. In this respect EN 954-1 technical standard (to be superseded by ISO 13849-1) identifies five categories, namely category B: A fault can lead to the loss of the safety function; category 1: A fault can lead to the loss of the safety function but probability is lower than for B; category 2: A fault is detected by a check but may lose the safety function between the checks; category 3: When the single fault occurs the safety function is always performed. Some, but not all faults will be detected; category 4: When the single fault occurs the safety function is always performed. The faults will be detected in time to prevent the loss of the safety function.

7.7. Detectability (DET)

The possibility of promptly detecting or signaling an incipient failure of the failed state of the safety device. This may also include the possibility of checking that the safety device is operational and in proper working position by a visual inspection. This may even be associated to the extent of diagnostic coverage, i.e. the ability of the system in a safety related control function to detect faults by itself.

7.8. Interference avoidance (IA)

This measures the overall degree of interference with work tasks or machine loading–unloading, adjustment and control activities. This also includes a judgment about any factors that can induce the worker to disconnect or remove the safety device which is perceived as hampering proper work execution. This also includes space requirements for cumbersome safety devices and interference with job shop layout or materials handling equipment. An assessment is also required about whether the safety device can be triggered unintentionally.

7.9. Tampering avoidance (TA)

This is the possibility of avoiding safety function bypass. In fact, in case a safety device obstacles the work task it is possible that the worker tries to remove, sabotage, deceive, defeat, disassemble, bypass or make ineffective the APD. This exposes the worker to mechanical hazards as it is the same of not installing at all an APD and should be avoided at any cost. The safety device should also be evaluated in respect to the possibility of being made ineffective or bypassed by operators in case of foreseeable misuse. This also includes susceptibility to common cause failures.

7.10. New hazards avoidance (HA)

This is the capability that APDs have of not creating new hazards. For instance, a fixed guard may have sharp or jagged edges and shear points, or a mobile guard can crush the operators fingers when moved into working position.

7.11. Flexibility (FL)

This is the potential of a given safety device of protecting from multiple hazards or to adapt to changing working conditions without requiring changes to the machine, the safety device or the working procedures.

7.12. Ease of use (EU)

This is the capability of being used by the worker in the proper manner with minimal training, in a self-explaining way without introducing further mental stress or possibility of error. This also include user-friendliness in general and proper ergonomic design so that it can be operated without fatigue for a long period of time.

7.13. Useful life (UL)

This describes the expected durability of the safety device in the considered working environment given its ruggedness, and is a proxy for the expected number of replacements.

7.14. Ease of installation (EI)

This describes how quickly and cheaply a safety device can be installed even resorting to unexperienced personnel.

7.15. Safe lubrication (SL)

Capability to allow workers perform lubrication safely without the need for removing the safeguard.

In the following a justification is provided about why the selected parameters are appropriate to assess the suitability of a safeguard according to the above specified basic requirements.

(a) Provide an effective protection against all possible hazards and operational conditions.

This happens when the safeguard is both operationally available to perform its intended function. (i.e. it is present and fully functional) and is able to counter the specific hazards that can arise in any reasonable operating condition. Parameter E rates the technical effectiveness of the safeguard, while parameter FL measures the ability of the safeguard to be effective in changing operational conditions and multiple hazards. To be available the safeguard must have long time between failures (parameter R) and low time to repair (parameter M). Moreover it should be robust against unexpected and sudden failures (parameter FT) and any failure should be quickly detected to allow rapid restoration of full operability (parameter DET). Finally, the safeguard should be in place and be hardly defeatable (parameter TA).

(b) Can be used without impairing work or lowering productivity otherwise the worker is tempted to remove it and, to avoid this occurrence, should be hard to neutralize.

To satisfy this requirement the safeguard should be easy to operate without increasing cycle time and determining fatigue (parameter EU) and should not interfere with working task (parameter IA) but should be also hard to circumvent and remove (parameter TA).

(c) Should not cause any additional hazard.

This is expressed by parameter HA and SL.

(d) Should be affordable over its life cycle.

Therefore, it should have low purchase cost (parameters C, UL and R), low installation cost (parameter EI), low maintenance cost (parameter R).
Finally, parameter PFO, together with parameters E, and HA, expresses explicit requirements imposed by existing regulations such as Machinery Directive in EU and has been included for completeness.

Most of the above parameters lend themselves to some sort of objective quantification which helps a pair-wise wise comparison of alternative safeguards against each decision parameter. In greater detail, SL and PFO may allow a binary assessment as Yes/No. FT allows a qualitative rating according to the five categories of EN954 standard. Cost C may be quantified on the basis of purchase cost or the equivalent annual cost including the cost of inspection, maintenance and spares. Reliability R can be rated according to any of the quantitative performance measures used in reliability theory, such as mean time between failure (MTBF) which is a figure often made available by the vendor or easily computable (Sick Inc., 2012). M can be assessed according to any of the quantitative performance measures used in maintainability theory, such as mean time to repair (MTTR) or spares cost. UL is a value usually supplied by vendor which can also be estimated based on economic and reliability based analyses and historical data. In case the device is not repairable the useful life corresponds to the mean time to failure. EL can be rated on the basis of time to install which determines the downtime cost of installing the device and the labor cost of technicians performing the installation.

Effectiveness of a safeguard is hard to express through a single numerical parameter but can be assessed resorting to check lists (Sick Inc., 2012). All remaining decision parameters, namely, DET, backs and preferred field of applications, also showing many examples of correct implementation of safeguards to specific machines and hazards, but fail to describe a general purpose methodology to help designers and users to choose, among the available options, the preferred solution better suited to their applications.

Therefore, in this work we develop a methodology to establish a consistent prioritization of the previously defined judgment criteria, based on the analyst’s preferences, and to perform a multi-criteria comparison of safeguarding options in order to obtain an objective ranking of alternatives that allows an assisted decision making.

Analytic Hierarchy Process (AHP) is a method to select one alternative from a given set of alternatives, where there are multiple decision criteria involved, and to rank available alternatives in a desirability order based on a rational framework of quantitative comparisons (Saaty, 1990). AHP has been applied in many distinct sectors (Kumar and Vaidya, 2006). More specifically, AHP techniques have also been successfully applied in the sectors of safety management and risk assessment (Cagno et al., 2003; Chan et al., 2004; Ha and Seong, 2004; Fera and Macchiarioli, 2010; Law et al., 2006). AHP was also applied as a tool to select safety improvement strategies in spatial applications (Frank, 1995). However, to the best of our knowledge, AHP has not yet been applied to the practical case of protection systems selection for industrial machinery.

In this paper the AHP methodology is used to rank alternative safety devices to be installed on machinery to protect workers from hazards.

Here the AHP method is applied in its basic form (Saaty, 1990) which is briefly resumed in the following steps.

### Step (1)
Define judgement criteria $C_i$ to be used to evaluate and rank alternatives.

Here we adopt the factors already listed in Section 7.

### Step (2)
Define a set of alternatives to be ranked. Here the alternative safety devices are of the categories listed in Section 6. However, in actual applications that set can be enlarged or reduced as desired, and instead of comparing devices belonging to different categories, as done in the example below, the choice can be performed even between different commercial off-the-shelf devices of the same categories supplied by competing vendors.

### Step (3)
Define a pair-wise comparison of relative importance between the $n$ rating criteria. This results in an $n$-by-$n$ matrix $A(a_{ij})$ with $(i = 1, 2, \ldots, n)$

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{1}$$

where $a_{ij} > 0$, $a_{ij} = 1/a_{ji}$, and $a_{ij}$ is the user-defined rating of relative importance of criterion $i$ respect criterion $j$. In case criteria $i$ and $j$ are of equal relative importance then $a_{ij} = a_{ji} = 1$.

Values of relative rankings $a_{ij}$ can be assumed as follows.

- Criteria $i$ and $j$ are equally important: $1$.
- Criterion $i$ is slightly more important than criterion $j$: $3$.
- Criterion $i$ is significantly more important than criterion $j$: $5$.
- Criterion $i$ is strongly more important than criterion $j$: $7$.
- Criterion $i$ is extremely more important than criterion $j$: $9$.

Obviously, it is possible to utilize intermediate numerical values to give more graduality to the expressed judgments.

### Step (4)
Compute the resulting numerical weight to be assigned to the rating criteria $C_1, C_2, \ldots, C_n$ on the basis of the pair-wise comparison matrix $A$. This results in a weight vector

$$W = [w_1 \, w_2 \, \ldots \, w_n]^T \tag{2}$$

which is the normalized principal eigenvector of matrix $A$. For simplicity the elements of the weight vector are computed as the average value of the rows in the normalized pair-wise comparison matrix $A$, i.e. by dividing the elements of each column in $A$ by the sum of that column to normalize the column values. Then the elements in each resulting row are added and the sum is divided by the number of elements in the row

$$W_i = \frac{1}{n} \sum_{j} \left( \frac{a_{ij}}{\sum a_{ij}} \right) \tag{3}$$

### Step (5)
The consistency of pair-wise comparison matrix $A$ is checked by computing the Consistency Index $CI$

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1} \tag{4}$$

where $\lambda_{\text{max}}$ is the maximum eigenvalue

$$\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} (Aw_i)_i$$

Then the obtained CI value is compared to a Random coincidence Index $RI$ through the Consistency Ratio $CR = CI/RI$. RI is the average value of CI one would obtain were the entries in $A$ chosen at random, subject that all diagonal entries must equal 1. For instance, in case $n = 2$ then $RI = 0$, for $n = 6$ then $RI = 1.25$, for $n = 10$ then $RI = 1.49$, for $n = 15$ then $RI = 1.58$. In case $CR < 0.1$ the degree of consistency is satisfactory.

### Step (6)
A matrix of pair-wise comparison between alternative safeguards is then built for each rating criterion, following the pro-

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cedure of Step (3). This allows to express a judgement about how well any alternative compares to the others respect the considered criterion.

Step (7). A normalized relative rating \( b_i \) is computed for each ith candidate alternative respect any judgement criterion \( C_j \), in comparison with the other alternatives. The normalized relative rankings are obtained by applying the same procedure of steps (3) and (4) to the pair-wise alternatives comparison matrices built at step (6).

Step (8). A ranking score \( R_i \) is given to the ith candidate alternative simply as

\[
R_i = \sum_j b_{ij} W_j.
\]

According to this approach, the analyst should express two different sets of judgments. First he must express the relative preference between the rating criteria in order to obtain matrix \( A \).

This can be made only once and is a means to express the subjective priorities of the analyst. It should be pointed out that the advantage of AHP in this phase is to ensure that the analyst's judgments are self-consistent. However, the pair-wise comparison matrix \( A \) is by no means a tool to express objective and absolute priorities. In fact, another decision maker, with different goals and priorities would come up with an entirely different matrix. Nevertheless, a consensus about the priority scale involved by matrix \( A \) could be searched between the stakeholders. Second, he must express judgments about the competing alternative safeguards, with respect to the predefined set of rating criteria, through pair-wise comparisons. In this latter phase it is true that the analyst could give subjective judgments, but most of the adopted rating criteria are at least partially suitable to an objective quantification, which limits the subjectivity of the analyst.

Here a general purpose rating criteria pair-wise comparison matrix \( A \) is built and the resulting weight vector \( W \) is computed as shown in Table 2.

The matrix was obtained based on the authors’ expert opinion and educated guess, also relying on consultations with industrial practitioners and users in order to come up with an agreed priority scale. However, informal discussion instead of a structured questionnaire was used to collect experts' opinion.

In the following a succinct discussion is included to exemplify the reasoning process leading to the numerical judgments of Table 2 and provide their justification.

Safeguard effectiveness (E) was considered the main prerequisite so that it was assigned the highest priority respect other decision parameters (score 6), exception made for cost and reliability. Therefore, nearly the same priority was assigned respect parameters C and R (score 2) because it was considered useless to have an effective safeguard when the device was not affordable to be adopted or in case the device was not operational owing to low reliability and availability. For the same reason C and R were ranked only slightly less important than parameter E (score ½), but more important than all other parameters, even if slightly less than the score assigned to E (score 5 instead of 6). Given that a machine has to remain productive regardless of the adopted safeguard, parameter IA has been judged as second rank in the priority list. It was assigned a high score respect other decision parameters (mostly a score 4 has been assigned) exception made for the top parameters E, C, R. The same applies to ease of use (parameter EU) which has been considered only slightly less important than IA. On the same level have been also placed parameters HA and SL with nearly the same scores. This to confirm that safeguards should not induce additional hazards and should allow safe machine maintenance. However, a top priority has not been assigned to the two parameters above because all safeguards on the market are likely to satisfy those requirements which are stated as EHSR according to current regulations. Detectability of failures (DET) and fault tolerance (FT) are important factors indeed but not critical, so that intermediate priority was assigned (scores both lower or greater than 1 respect other decision parameters). The same applies to TA which, nevertheless, has been judged a little more important than DET and FT by assigning a superior score in two cases.

PFO is among the EHSR according to current regulations, so that it has priority over most of other parameters (score greater than 1). Nevertheless, it has not a top priority (i.e. score 2 is assigned instead of a higher value) and is less important then the other top priority factors (i.e. E, C, R and IA).

Maintainability was judged a useful but not primary factor, so that it had assigned lower priority respect all other parameters exception made for FL, UL, and EL. In fact, maintainability affects life cycle costs for any value of useful life and is economically more relevant than one-shot installation costs.

UL and EL were considered to be secondary factors, so that a lower priority was assigned respect all other parameters. Nevertheless, UL was judged as slightly more important than EL because of the greater economic impact of a longer useful life respect an easy installation which only represent a one-shot cost. The same applies to flexibility (FL) which is surely a desirable feature but not a determining factor.

As can be noticed from vector

\( W \)

of Table 2, the resulting prioritized list of rating factors is the following (the factors are listed in descending order of priority with weight in parentheses):

\[
\begin{align*}
E & (0.21); C (0.15); R (0.14); TA (0.11); PFO (0.06); SL (0.05); HA (0.04); EU (0.04); FT (0.03); DET (0.03); M (0.03); FL (0.03); UL (0.02), El (0.02).
\end{align*}
\]

This means that the most important rating factors are Effectiveness, Cost, Reliability, and Interference avoidance, followed by two

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additional groups of factors at about the same priority, namely Protection from falling objects, Safe lubrication, New hazards avoidance, Ease of use, Tampering avoidance, and finally, Fault tolerance, Detectability, Maintainability, Flexibility, Useful life, Ease of installation. Judgments implied by this matrix are consistent as the consistency ratio has a value CR = 0.041. From a practical perspective this would represent a decision maker who wants a highly cost-effective safeguard without sacrificing workers productivity and with an eye to safe maintenance. The proposed matrix is a general purpose tool so that, according to the authors, it can be reasonably used as a starting point for selecting any kind of safety device.

Nevertheless, any user can modify this matrix to suit specific requirements, so that alternative formulations of matrix A could have been possible. For instance, Table 3 shows another possibility of rating criteria pair-wise comparison matrix with a value CR = 0.098. Justification of the scores given in Table 3 can be provided following the reasoning outlined in case of Table 2.

In this case the list of priorities is [HA (0.19); TA (0.15); FT (0.10); E (0.09); IA (0.09); EU (0.08); SL (0.07); C (0.06); R (0.04); DET (0.04); PFO (0.02); M (0.02); FL (0.02); UL (0.01); EI (0.01)]. Here, greater emphasis is given to the safeguard robustness while preserving protection and productivity, while cost and ease of maintenance have a lower priority. This is a more balanced view as the weights are more evenly distributed.

Therefore, the set of priorities is a matter of preferences of the decision maker and the method ensures that this set is declared instead of implicit and is self-consistent.

9. Numerical example

For sake of generality, we consider here a fictitious application example referring to a general purpose machine. In this numerical example it is assumed that only four distinct classes of safety devices are to be compared, namely, a FEG (Fixed Enclosing Guard), a MEG (Mobile Enclosing Guard), an ADD (safety light curtain ADD) and a MOC (a two-hands MOC). Based on the intrinsic characteristics of these protection devices the following pair-wise comparison matrices shown in Table 4 were built based on authors’ opinions and verified to be consistent.

To exemplify the utilization of the method a brief description of the logic used to assign subjective pair-wise comparison scores to the considered alternatives is given below. It should be pointed out that when comparing actual devices instead of categories of devices, more quantitative and objective judgments could be assigned.

With reference to parameter E, a FEG and a MEG were considered superior to ADD and MOC because the former provided a physical barrier. However, the FEG was preferred to a MEG because the MEG is only effective if it is correctly in place. ADD and MOC were considered to be similar. Passing to PFO, the pairs of FEG and MEG and ADD and MOC were judged equivalent, being FEG/MEG largely superior to ADD/MOC thanks to the presence of a physical barrier. With respect to Cost, the alternatives were considered to be similar, exception made for the MEG which was judged inferior owing to the added complexity of the interlocking system. In fact, a MEG is intrinsically cheap as it does not include moving parts, while an ADD is cheap because it is often a solid state electronic device, while a MOC while being an electromechanical device is quite compact and mechanically simple. With reference to Reliability a FEG is clearly superior as it has no moving parts and is not susceptible to logic errors. The MEG has been judged as reliable as a MOC, which also has moving parts, and less reliable than an ADD which is mostly an electronic device or an electromechanical device with few moving or mechanically stressed parts. For the same reason an ADD has been rated superior to a MOC. Passing to maintainability, the absence of moving parts and the constructive simplicity clearly favors the FEG and disfavors the MEG, while ADD and MOC can be considered as equivalent. With reference to Fault Tolerance the MEG is superior because it is virtually fault-free unless it is shuttered. MEG is inferior to FEG but is superior to ADD and MOC because even if logically failed it may retain the physical barrier, while MOC and ADD are roughly equivalent in that any failure may totally impair their safeguarding functionality.

When considering Detectability similar arguments hold. FEG is superior because its failure is mostly visible, MEG is inferior to FEG because its failure may be partially visible, but is superior to ADD and MOC whose failure may be not visible, while MOC and ADD are roughly equivalent with a slight superiority of MOC. As far as the interference potential is considered, ADD and MOC are clearly superior respect MEG and FEG owing to the absence of a physical barrier. In case of MEG, owing to the movable barrier, it is preferable to a FEG. However, an ADD is better than a MOC because it leaves the operator’s hands free. Passing to the risk of unauthorized removal or tampering of the safeguard the FEG is preferred as it is virtually not removable. ADD may be harder to tamper respect other alternatives. Lowest score is assigned to MEG and MOC which are more likely to be misused. With respect to hazard creation ADD and MOC are superior respect FEG/MEG because of the absence of sharp edges, crushing points etc., while a FEG is better than a MEG because the fixed guard has not crushing risk.

Passing to Flexibility of use, the couples FEG/MEG and ADD/MOC were considered as roughly equivalent, with the former less flexible than the latter. In fact non-material barriers allow surely a greater flexibility in working cycles and processed materials changes.

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10. Advantages and limitation

There is empirical evidence that several problems may affect the choice of a safety device, namely

(a) The decision maker may not include all relevant factors in its evaluation.

(b) The decision maker may not establish consistent priorities among evaluation factors.

(c) The decision maker may not express judgments about each alternative in a consistent manner.

(d) The judgment may be excessively affected by arbitrary subjective opinions not grounded on factual data or objective parameters.

The proposed approach may help in overcoming some of the above problems.

The method, in fact, offers a set of exhaustive evaluation parameters and makes the decision maker more aware about the priority scale he is tacitly adopting to weigh the evaluation parameters. Moreover, it ensures that this scale is self-consistent. It also includes evaluation factors which mostly allow a quantitative assessment, and ensures that evaluation judgments about alternatives, although subjective, are also consistent.

However, this by no means means that the automated decision process, as the decision maker is still asked to express an opinion and is left with full responsibility of establishing a subjective priority among decision factors, as long as this priority scale is self-consistent.

The method, nevertheless, ensures that the decision parameters, the priorities and the judgments are explicit and consistent.

Finally, the method is really easy to implement in widespread office automation software, such as spreadsheets, and allows a quick rating of alternatives.

As a final remark it can be noticed that this method is especially useful when different embodiments of the same category of safety devices are to be compared, instead of different kinds of safety devices, and when no clearly dominant alternative exists. Otherwise the choice may become trivial.

Nevertheless, the method also has some limitations. First, it does not help in defining, according to existing hazards and specific machines features, the set of candidate alternatives to be compared. This is a choice left to the analyst.
11. Conclusions

In this paper the problem of machine safety and safeguarding has been examined in detail. Then the problem of selecting the proper safeguard has been examined. A comprehensive set of problem-specific rating criteria has been defined to compare safeguarding options and AHP has been utilized as a means of providing a consistent ranking of candidate alternatives. This demonstrated how AHP methodology can assist in the selection of safety devices for industrial machinery. Moreover, as a general contribution to the practical applicability of the proposed approach a general purpose pair-wise comparison matrix of rating factors was determined. This allows the user to immediately apply the method, as only the statement of relative rating judgments about case-dependent candidate solutions is left to the analyst. The application example showed that an effective quantitative ranking of candidates can be rapidly obtained using the proposed method.

The advantage of the proposed method is not that of avoiding arbitrary or subjective decisions, but rather that of providing an assisted and systematic decision process using consistent rating criteria and consistent evaluations of the alternatives, based on an explicit statement of the decision maker’s subjective preferences. This helps in avoiding much of the guesswork and inconsistency in qualitative and naive multiple-criteria decision making.

References

A-generated list of references related to the topic of safety in machinery and design is included here.

Second, the method does not eliminate the need to express subjective judgments. In particular, the adequacy of a safeguard in effectively protecting the worker is left to the analyst’s opinion, and also the expression of the pair-wise preference between any two alternatives is left to a personal judgment.


