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Functional safety of hybrid laser safety systems – how can a combination between passive and active components prevent accidents?

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Abstract

Modern laser systems are widely used in industry due to their excellent flexibility and high beam intensities. This leads to an increased hazard potential, because conventional laser safety barriers only offer a short protection time when illuminated with high laser powers. For that reason active systems are used more and more to prevent accidents with laser machines. These systems must fulfil the requirements of functional safety, e.g. according to IEC 61508, which causes high costs. The safety provided by common passive barriers is usually unconsidered in this context. In the presented approach, active and passive systems are evaluated from a holistic perspective. To assess the functional safety of hybrid safety systems, the failure probability of passive barriers is analysed and added to the failure probability of the active system.

Keywords: laser safety; health and safety; safety at work; failure probability; functional safety

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1. Introduction

1.1. Status quo of industrial laser safety

According to Mayer (2009), the worldwide laser market in 2008 was dominated by the application of high power cutting and welding with a share in excess of 50 %. The world market for laser material processing systems has increased approximately by a factor of 8 between 1993 and 2014, whereas the figures for machine tools roughly

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doubled within the same period (Mayer 2015). These values show the relevance and widespread use of high power laser machines.

To protect the environment from laser radiation, the process area is usually shielded by a housing. The housing typically consists of passive barriers made of metal or concrete, which provide protection by absorbing the beam energy. Goebel (2015) stated that passive laser guards are easy to build and economically advantageous in small systems; when used in large processing machines, a high effort of work, money and material is required to design and build the barriers, especially due to the lack of suitable materials for high laser powers. The mentioned disadvantages become evident, when the low protection times of passive laser safety barriers under irradiation with high-power laser beams are considered (cf. Lugauer et al. 2014, Zaeh et al. 2009).

Active laser safety facilities can be used in addition to passive sytems. In most cases they are wall-based and identify a fault by various physical detection mechanisms like optical recognition (Goebel 2011) or detecting a laser-induced increase in temperature by strain measurement (Wilhelmi and Feistel 2011). Active safety units are expensive due to high requirements of the EC Machinery Directive (Directive 2006/42/EC 2006) and the harmonised standard EN ISO 13849-1 (2008) on the functional safety of such devices. Moreover, only few commercial providers exist. Two items are currently available on the market: The LaserSpy-Sensor of REIS Lasertec (REIS unknown) and the Laser Jailer of Lasermet Ltd. (Lasermet 2015). The financial expenses for both systems scale strongly with the size of the protective housing.

Passive barriers are always needed for several reasons, even when using active systems: First of all active devices require a latency period to recognise a failure and to stop the emission. For this amount of time, the passive component has to protect the environment from dangerous radiation. In Addition, dangerous scattered radiation has to be expected even during normal operation at high power processes. To prevent a permanent emergency shutdown during regular processing, the intensity of this scattered radiation has to be below the triggering threshold of the sensors or alternatively the sensor must be shielded from this radiation. Furthermore, hazardous emissions like welding fumes or toxic degradation products are often generated during material processing, which can be extracted more effectively from an enclosed area. Moreover, a mechanical barrier is required to prevent injuries to the operator caused by a collision with moving parts of the kinematics, like industrial robots or gantries.

Due to the low protection time of passive components, modern high-power laser systems are often secured by an expensive active laser safety system of high functional safety. Despite that, passive components are still needed to provide adequate protection, but remain unconsidered when estimating a functional safety level.

1.2. Evaluation of the safety of laser safety systems – state of the art

In Annex I of the EC Machinery Directive (Directive 2006/42/EC, 2006) named ‘Essential health and safety requirements relating to the design and construction of machinery’ it is noted in paragraph 1.5 ‘Risk due to other hazards’, subparagraph 1.5.12 ‘Laser radiation’ that ‘laser equipment on machinery must be protected in such a way that effective radiation, radiation produced by reflection or diffusion and secondary radiation do not damage health’. To meet these requirements, harmonised standards are commonly used, because they induce the presumption of conformity as described in §110 of the Guide to application of the Machinery Directive (European Commission 2010).

The relevant harmonised standard for laser material processing machines is ISO 11553-1 (2005), which affirms in paragraph 5.3 that ‘Laser guards shall comply with requirements specified in IEC 60825-4’. Within the last-mentioned standard, a distinction is made between passive and active laser guards. While proprietary passive laser guards are classified in three stages according to their maintenance interval, ‘active laserguards have to meet the requirement that the protection time exceeds the laser termination time up to the foreseeable exposure limits’ (IEC 60825-4 2011).

Both types of safety facilities (active and passive) correspond to the definition of Art. 2 c EC Machinery Directive when they are placed separately on the market, because they fulfil a safety function, their failure and/or malfunction endangers the safety of persons and they are not necessary for the machine to function (Directive 2006/42/EC 2006). This classifies them as safety components according to the EC Machinery Directive. Active barriers are covered additionally by Annex IV of the directive, more precisely by item 21 ‘Logic units to ensure safety functions’ according to §388 of the Guide to application of the Machinery Directive (European Commission 2010). This means, an active laser safety barrier may ‘also be subject to the procedure of assessment of conformity with internal checks when it is manufactured in accordance with harmonized standards that cover all of the applicable ESHRs’ (Essential Health and Safety Requirements) (European Commission 2010). To apply the standard conformity assessment procedure, among other things the harmonised standard EN ISO 13849-1 (2008) has to be fulfilled.

The result of the above can be summarised: Passive barriers as well as active laser safety systems are safety components and must conform to the established rules. Whereas the first-mentioned facilities are primarily characterised by their maintenance interval, respectively their protection time, and their protective exposure limit. The evaluation of the latter is focussed on functional safety.

1.3. Risk assessment and safety in mechanical engineering with a focus on laser material processing units

According to annex I of the Directive 2006/42/EC (2006), ‘the manufacturer of machinery or his authorized representative must ensure that a risk assessment is carried out in order to determine the health and safety requirements which apply to machinery’. In §158 of the Guide to application of the Machinery Directive (European Commission 2010) it is stated that the general principles for risk assessment of machinery are explained in EN ISO 14121-1 (2007). This standard, however, was replaced by EN ISO 12100 (2010) in 2011. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a simplified iterative process of risk reduction according to this standard.

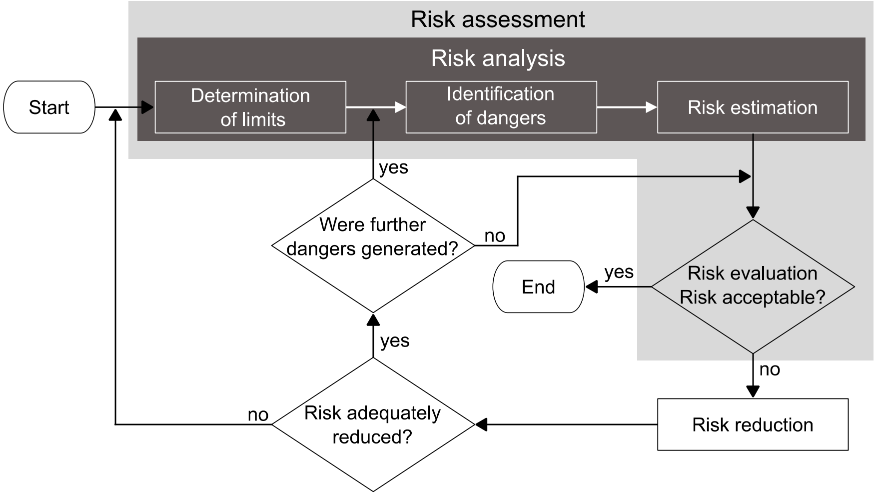

Fig. 1. Simplified iterative process of risk reduction according to EN ISO 12100 (2010).

The sequence starts with a risk analysis. For this purpose, the limits of the considered machine have to be determined with regard to spatial and temporal aspects as well as to the different types of applications. Subsequently, hazards, which can occur within the defined framework, must be identified. Then the risks posed by these hazards have to be estimated. The risk is assessed by the severity of the harm and by the probability of occurrence. The last-mentioned component depends on the number of people at risk and the frequency of a hazardous occurrence, the probability of a true incident and the opportunity to avert any damage. After that, the risk evaluation must be performed and has to be repeated for every identified danger. Depending on the result of this step, the risk reduction process is carried out. A variety of methods and tools is available for risk assessment. The most noteworthy methods are: The risk assessment with a risk graph according to EN ISO 13849-1 (2008), the risk assessment with a risk matrix after EN 62061 (2005), the risk management for lifts, escalators and moving walks described in EN ISO 14789 (2013), the Failure Mode and Effects Analysis (FMEA) according to EN 60812 (2006), the Fault Tree Analysis as mentioned for example in Verma (2015), the RAPEX-risk assessment procedure for market surveillance authorities as written down in the Commission Decision of 16 December 2009 (Commission Decision 2010/15/EU) and described in European Union (2010) and the nomogram according to Raafat (1995).

Fig. 2 shows the risk graph according to EN ISO 13849-1 (2008) as an example for a tool to determine the necessary safety level in the framework of risk assessment. A tolerable probability range of dangerous failures per hour is determined, based on three queries concerning severity of injury, frequency and/or exposure time to hazard and possibility of avoiding the hazard or limiting the harm.

The danger of exposure to direct or indirect laser radiation is a hazard, which must be registered during the risk analysis of every laser processing machine. This exposure can typically cause eye damages up to blindness if lasers for material processing are being used. Therefore the severity of injury for this danger has to be classified as serious according to the risk graph (S2). The frequency of exposure depends on the particular machining task, but in general it can be assumed that the emission is turned on during a considerable part of the shift, due to economic reasons (F2). Since laser light propagates much faster than humans can react and beam deflection is quick, the possibility of avoiding the hazard is virtually impossible (P2). Thus, this danger must be adressed by a safety system, which provides a probability of a dangerous failure per hour of less than 10^{-7} (PFH_{max}) corresponding to the required performance level e. Deviating from this, a lower performance level, e. g. level d may be adequate, depending on the particular machine.

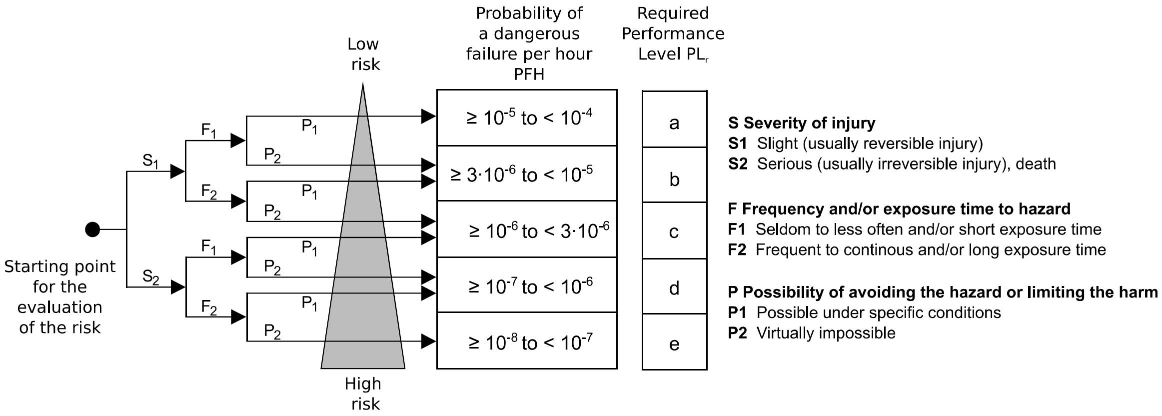

Fig. 2. Risk graph and performance levels with corresponding probabilities of a dangerous failure per hour according to EN ISO 13849-1 (2008).

2. Shortcoming analysis and aim of the work

Laser safety is an issue of increasing importance, but also drives a significant portion of the costs of laser machines. This applies especially for active safety systems, which are often used for high power systems and come with a high demand on functional safety. It is noteworthy, that safety barriers are strictly classified into passive and active systems, but a holistic approach for their assessment is missing. Three independent malfunctions need to occur for a dangerous failure of the safety system: A misuse or malfunction of the laser system occurs (1), which is not recognised by the active safety facility (2), and the passive barrier collapses simultaneousely (3). For this reason, an approach will be presented, which allows the evaluation and dimensioning of laser safety systems consisting of passive and active components (hybrid systems) with regard to adequate safety as well as a reduction of costs and time.

3. Approach

Nomenclature

b	independent variable of the standard normal distribution cumulative distribution function
R	achieved risk reduction
r	response time of the sensor-actuator-chain in h
SD	standard deviation of the sample
SM	sample mean
$P_{act}(k)$	occurrence probability of the event k for the active component
$P_{pas}(k)$	occurrence probability of the event k for the passive component
PFH_{max}	maximum permissible probability of a dangerous failure per hour
PFH_{sac}	probability of an dangerous failure per hour of the sensor-actuator-chain
t	maintenance interval in s
X	random variable for the protection time of the passive component
Z	random variable, linearly transformed to standard normal distribution
z	independent variable of the standard normal distribution probability density function
Φ	function value of the cumulative distribution function
μ	mean of the normal distribution
σ	standard deviation
σ^2	variance of the normal distribution

The goal for the approach is to allow a holistic view. For that reason the maximum failure property per hour (PFH_{max}) according to EN 13849-1 (2008) was used as a reference for the safety that must be provided by the hybrid system. Subsequently it must be determined, in which way the specification can be fulfilled. Therefore, the probability of failure for the entire system has to be calculated. For this purpose, a fault tree analysis as described in Verma et al. (2015) was carried out for a hybrid system, assuming that every single component is able to prevent the damage on its own. The result is shown in Fig. 3.

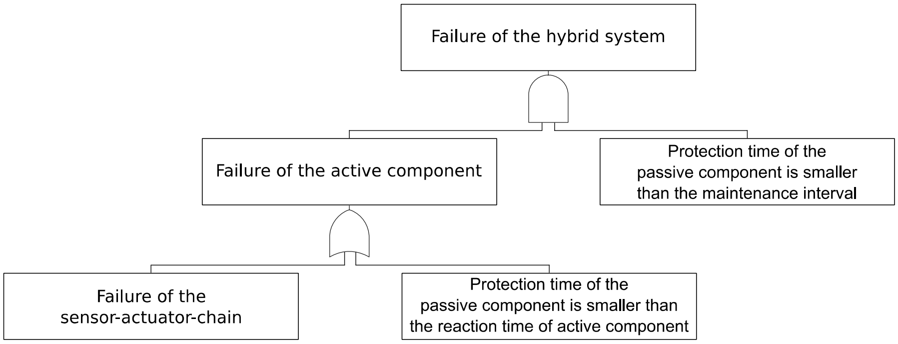

Fig. 3. Fault tree analysis of a hybrid laser safety system.

A failure of the whole system only occurs if the protection time of the passive component is smaller than the specified maintenance interval and if a failure of the active component occurs simultaneously. The latter failure can arise if the sensor-actuator-chain fails or if the protection time of the passive component is smaller than the reaction time of the active part. The latter mentioned period is to be understood as the time from the exceeding of a threshold value by the incident laser radiation till the emission is terminated by the active system. If t is the specified maintenance interval, P_{act}(failure within t) is the probability of failure of the active component within the maintenance interval t and P_{pas}(failure within t) the probability of failure of the passive component within the maintenance interval t, a risk comparison can be described mathematically according to the upper part of the fault tree as:

$$P_{act}(failure\ within\ t)\cdot P_{pas}(failure\ within\ t)\leq t\cdot PFH_{\max} \tag{1}$$

Using the probability of complementary events, the branch for the failure of the active component can be expressed by equation 2:

$$P_{act}(failure\ within\ t)=1-\left(1-t\cdot PFH_{sac}\right)\cdot P_{pas}(no\ \ failure\ within\ r) \tag{2}$$

where PFH_{sac} is the probability of a dangerous failure per hour of the sensor-actuator-chain and P_{pas}(no failure within t) the probability that the protection time of the passive component is larger than the reaction time of the active component.

Since the protection time of the passive component is a random variable (cf. section 4.2), here named X, the probability of failure of the barrier can be written as $P(X \leq t)$. This describes the probability that X – and therefore the protection time – is smaller than the maintenance interval t, independently of the probability distribution of the protection time. The description of the probability of a failure within the response time r can be determined in the same way. By insertion of $1-P_{pas}(X \leq r)$ for P_{pas}(no failure within t) and subsequent transformation, equation (2) can be written as:

$$P_{act}(failure\ within\ t)=P_{pas}\left(X\leq r\right)+t\cdot PFH_{sac}-t\cdot PFH_{sac}\cdot P_{pas}(X\leq r) \tag{3}$$

By simplification of equation (3) and insertion in equation (1), the probability of failure of a hybrid laser safety system can be compared to the normative requirements by:

$$P_{pas}\left(X\leq t\right)\cdot\left[P_{pas}\left(X\leq r\right)+t\cdot PFH_{sac}\cdot\left(1-P_{pas}\left(X\leq r\right)\right)\right]\leq t\cdot PFH_{\max} \tag{4}$$

4. Determination of the particular probabilities of failure

4.1. Probability of a critical failure of the sensor-actuator-chain

To determine the probability of a critical failure per hour (PFH_{sac}) of the sensor-actuator-chain, the performance level (PL) of the whole chain must be calculated by a summation of the probabilities of a dangerous failure per hour (PFHd) of the particular subsystems. The latter can be determined according to EN ISO 13849-1 (2008) using the relationship between mean time to failure (MTTFd), diagnostic coverage (DC), and category. If a commercial component is used, the manufacturer commonly provides the values for PL and PFHd respectively. The maximum achievable PL is calculated with this value. If qualitative requirements are fulfilled by any subsystem only for a certain PL, the achieved PL has to be reduced appropriately. (Ost 2011)

4.2. Probability of a critical failure of the passive barrier

In contrast to the probability of a critical failure of the senso-actuator-chain, the probability of failure of the passive component cannot be assumed to be linear in dependence of time. Rather, the failure probability of a barrier increases at the beginning of the maintenance interval and decreases later (cf. Lugauer et al. 2015). Hence, the experimentally obtained probability density function (PDF) is used to calculate the cumulative distribution function (CDF) by integration. Then, the probability of a failure within the considered period is estimated (Johnson and Wichern 2007, Verma et al. 2015).

For clarity, the above-mentioned method was carried out using an example with protection times, which can be assumed as approximately normally distributed. The underlying values were taken from Lugauer et al. 2015. The normal distribution is characterised by two values: The mean μ as location parameter and the variance σ^2 as dispersion parameter. If $\mu = 0$ and $\sigma^2 = 1$, the distribution is called a standard normal distribution. Its PDF and CDF are shown in Fig. 4.

Since there is no closed form solution for the CDF integral of the normal distribution, the linear transformation shown in equation (5) is applied. This allows to transform any normal distribution into the standard normal distribution, for which tables of values of the CDF are available. Z is therefore the linearly transformed random variable X. (Verma et al. 2015)

$$Z = \frac{X-\mu}{\sigma} \tag{5}$$

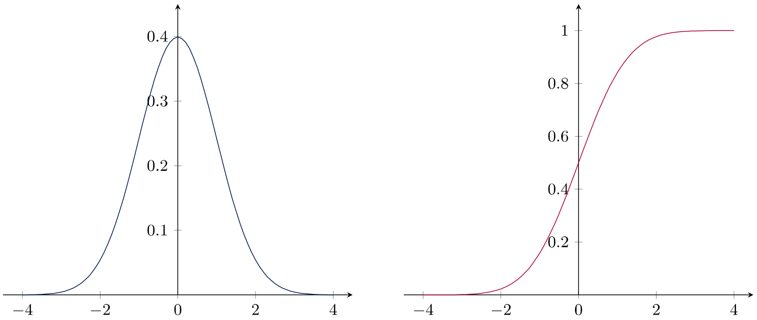

Fig. 4. Probability density function (left) and cumulative distribution function (right) of the standard normal distribution.

The CDF of the standard normal distribution can be mathematically described as:

$$\Phi(b) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{b} \exp\left(-\frac{z^2}{2}\right) dz \tag{6}$$

After the transformation, the probability to get a value X which is smaller than or equal to the maintenance interval t (or analog the response time r) can be determined by (Johnson and Wichern 2007, Verma et al. 2015):

$$P(X \le t) = \Phi\left(\frac{t-\mu}{\sigma}\right) \tag{7}$$

So assuming a normal distribution, the probability of failure within the maintenance interval of 10 s (audit class T1 according to IEC 60825-4 (2011)) of the protection time distribution shown in Fig. 5 can be calculated by (Johnson and Wichern 2007, Verma et al. 2015):

$$\mu \approx SM = \frac{\sum_{i=1}^{150} n_i}{150} = 11.83\ s \tag{8}$$

$$\sigma \approx SD = \sqrt{\frac{1}{150-1}\sum_{i=1}^{150}(x_i-\mu)^2} = 0.36\ s \tag{9}$$

$$P(X \leq 10\,s) = \Phi\left(\frac{10\,s - 11.83\,s}{0.36\,s}\right) = \Phi(-5.08) = 1.89 \cdot 10^{-7} \tag{10}$$

A risk comparison with the determined value of maximum failure property (cf. section 1.3) reveals that an adequate failure property could not be achieved in this example:

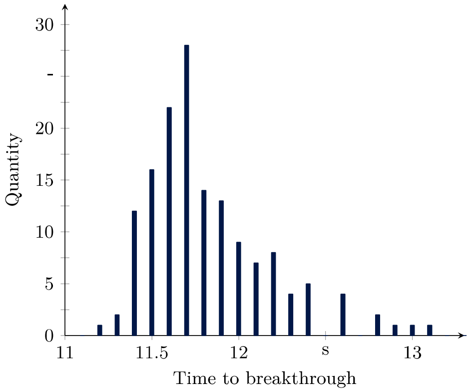

Fig. 5. Statistic distribution of the time until breakthrough of 150 zinc-magnesium-coated steel samples (1.0241) of 1.5 mm thickness, irradiated with an ytterbium-fibre-laser with an output power of 8 kW and a beam diameter of 80 mm (Lugauer et al. 2015).

$$P(X \leq 10\,s) \overset{!}{<} t \cdot PFH_{\max} \Rightarrow 1.89 \cdot 10^{-7} \overset{!}{<} 2.78 \cdot 10^{-9} \tag{11}$$

5. The method in practical use

Three essential simplifications can be distinguished (Fig. 6): The use of a purely passive barrier, the application of a system in which the passive component only bridges the reaction time of the active system, and a facility in which the passive component as well as the active component provide a substantial contribution to achieve the objective of protection. In the first instance, the active component is not present, so its probability of failure is 1. Insertion in equation (4) results in:

$$P_{pas}(X \leq t) \leq t \cdot PFH_{\max} \tag{12}$$

In the second case, the probability of failure of the passive component within the maintenance interval can be assumed to be 1 due to the short protection time. This means that $P_{pas}(X \leq t) = 1$. Assuming a short response time of the sensor-actuator-chain and a sufficient protection time, the probability of failure of the passive component below the response time can be set to 0, so $P_{pas}(X \leq r) = 0$. Thus equation (4) can be simplified to:

$$PFH_{sac} \leq PFH_{\max} \tag{13}$$

The result is a conventional risk reduction according to EN ISO 13849-1 (2008). Thus, the method can be assumed to be valid. To judge whether the protection time of the passive component is sufficient, the initial estimation of the protection time calculated according to IEC 60825-4 (2011) might be used.

In the third case, it can be assumed that the failure property within the response time of the sensor-actuator-chain is 0 due to the necessary significant protection time of the passive barrier. Equation (4) can be modified to:

$$P_{pas}(X \leq t) \cdot t \cdot PFH_{sac} \leq t \cdot PFH_{\max} \tag{14}$$

In all other cases, the whole risk comparison shown in equation 4 is to be used.

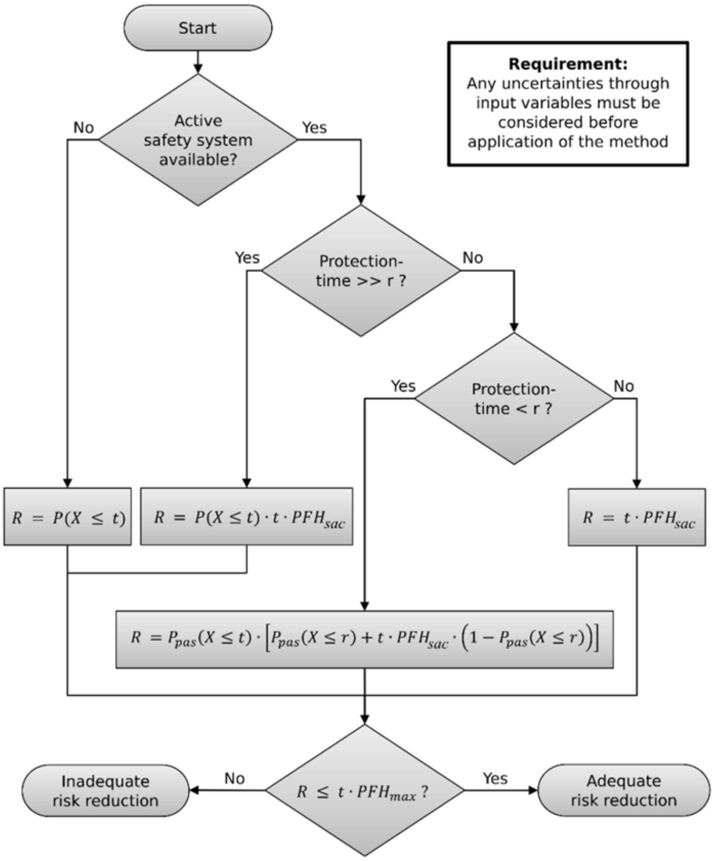

Fig. 6. Flowchart for the application of the holistic method for assessment and dimensioning of laser safety systems. The different ways of calculating R are resulting from simplifications, which can be made for the various cases. Nomenclature see section 3.

6. Conclusion and prospects

A method to assess the safety of laser safety systems from a holistic point of view was shown. It covers all currently used systems and is therefore universally applicable. A crucial point of the approach was to evaluate the safety provided by passive components in a comparison to the safety of the active system. Based on proven and standardised practices, a new method was developed, which allows to estimate the probability of failure of passive barriers analogously to the determination of functional safety provided by active systems.

The result of this work is a tool, which allows the dimensioning and assessment of safety parts, which provide the same safety as a single active system would do, regardless of the type of components. By these means, not only a new opportunity for evaluation of passive laser safety barriers in addition to the normative calculation of

IEC 60825-4 (2011) could be demonstrated, but also a possibility to reduce the costs of laser safety systems considering the protection functions of all parts involved in accordance to legislation was shown.

So the main advantages of the new method in contrast to the existing procedures are the consideration of the actual statistical protection time distributions and a possible reduction of the required performance level of an active laser safety system when using a suitable laser safety barrier.

To ensure an effective use of the method, it is essential to gain more data of the statistical distributions of protection times of laser safety barriers and more insights concerning the influencing parameters. Therefore, the future activities should aim at the analysis of protection times of commonly used materials.

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