Article

Glare at Outdoor Workplaces—An Underestimated Factor of Occupational Risk

Dariusz Sawicki ^{1,*} and Agnieszka Wolska ²

¹ Institute of Theory of Electrical Engineering, Measurement and Information Systems, Warsaw University of Technology, Koszykowa 75, 00-661 Warsaw, Poland

² Department of Safety Engineering and Department of Ergonomics, Central Institute for Labour Protection—National Research Institute, Czerniakowska 16, 00-701 Warsaw, Poland; agwol@ciop.pl

* Correspondence: dariusz.sawicki@pw.edu.pl

Abstract: Lighting is an integral aspect of electrical engineering and public safety, as buildings, public areas—both indoors and outdoors—or any type of workplace must be illuminated in a way to prevent accidents. The sensation of glare, in particular, plays an important role in visual comfort and consequently influences occupational risk. The aim of this article is to draw attention to the problem of glare at outdoor workplaces. We have carried out an assessment of glare at outdoor workplaces in 19 different industrial plants. At 20 task areas (21.5% of the 93 examined) the determined degree of glare exceeded the limits specified in the standard. In eight categories of industrial plants (66.7% of 12 examined) defined in the standard, there was at least one task area where the requirements of the standard in terms of glare limitation were not met. The presented analysis leaves no doubt about drawing the conclusion that glare at outdoor workplaces is mostly underestimated or simply neglected, although it could cause high risk in workplaces.

Keywords: glare; outdoor workplaces; artificial lighting; occupational accidents; risk

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1. Introduction

1.1. Motivation

Lighting is one of the most important physical factors of the living and working environment, as it has a significant impact on human safety [1]. Besides providing safety, lighting is closely linked to visual performance and health. The rapid technological development of light sources in recent years has changed the approach to lighting design. Today, it is not enough to provide a sufficiently illuminated workplace—lighting must be also energy-efficient and of low cost [2]. These factors determine also the choice of light sources and luminaire levels, not only their effect on visual comfort, especially on the sensation of glare [3]. The lighting design is a multi-criteria issue, including technical as well as psychological aspects.

The main functions of workplace lighting are to ensure visual task performance and safety and good health at work. Appropriate lighting needs to meet international or European standards requirements concerning lighting parameters to acquire visual comfort and visual performance at workplaces both indoors and outdoors [4–8]. However, attention generally is focused mainly on indoor workplaces. It seems to be forgotten that a significant amount of work is performed outdoors—at workplaces with no or insufficient daylighting [9]. Lighting at outdoor workplaces should fulfill specific requirements, which differ from both indoor lighting and road lighting. Good lighting for outdoor workplaces should take into account the significant drop of the visual acuity of human eyes at night to the range between 3% and 30% of its daylight level [9]. Furthermore, the dark environment outdoors results in significantly higher risk of glare and considerably reduced spatial orientation and visual fields. It is worth mentioning that physical and cognitive performance also drops during the night time as a result of fatigue and circadian rhythm disruption. All

these factors point to the fact that most occupational accidents that are caused by human error occur at night and they are usually more serious than those occurring during the day. According to the law, an employer is obliged to carry out risk assessment arising from all hazardous agents, including artificial lighting parameters. People tend to assume that lighting can be improved by very bright lighting, but it usually causes substantial glare, especially at outdoors. Improvement of lighting conditions by increasing the level of illuminance but using a random luminaire which may cause strong glare and luminance contrasts is a common situation, especially at temporary outdoor workplaces. Glare becomes a crucial factor influencing the quality of lighting, visual comfort, and safety at work.

1.2. Accidents at Work—The Impact of Inadequate Lighting

Good visibility is determined by the following lighting aspects: well-balanced luminance distribution, illuminance level and its uniformity adequate to the type of visual task, glare limitation to an acceptable level, color appearance and color rendering index of light sources suitable for the task to be performed, and limitation of light flicker [10]. All of the aforementioned lighting parameters can influence the poor visibility and that way, in specific circumstances, become indirect reasons for occupational accidents. According to Hinze and Teizer [11], lack of good visibility was found to be the principal factor or contributing cause of 659 fatal accidents that occurred in the construction industry in the USA based on information from the Occupational Safety and Health Administration (OSHA) database of 13,511 fatalities recorded between 1990 and 2007. Their study showed that lighting that was too bright (glare) or too dark (insufficient illuminance) was the primary contributing factors in 7.2% visibility-related fatalities. The description of accidents demonstrated that in many cases workers were blinded by glare just before their involvement in a fatality [11]. Furthermore, a correlation between lighting factors and accident frequency during the day and night was noted—many more accidents occurred during the night between 6 p.m. and 6 a.m. [11].

Inadequate lighting (including glare) as the factor contributing to occupational safety and health (OSH) risk is also included in a new analytical hierarchy process (AHP) of a multi-criteria comparison model of accident analysis and prevention proposed by Badri et al. [12]. It has been demonstrated that lighting, as one of the ambient physical factors, could influence work-related illness (risk factor 0.56) considerably, and influence a drop in productivity (risk factor 0.29) mildly [12].

Another analysis of the influence of working conditions on occupational accidents was carried out in Spain based on the survey data of an 11,054 active population random sample [13]. The probabilistic model took into consideration the frequency of exposure to various occupational hazards and determined which of the factors influenced the health and safety of workers. Among predictor variables that could result in an occupational accident was the “inadequate lighting” (in midst of ergonomic conditions). The sensitivity analysis showed that poor lighting had caused an increase in the accident rate with a probability of 11.80%, while physical symptoms aggravating with 40% probability of more than three physical symptoms [13].

Babović [14] analyzed occupational accident occurrence rate due to inadequate working conditions including poor lighting during the 10-year period in two groups of workers: occupationally exposed to hazardous factors (noise, harmful chemical substances, poor microclimate, and poor lighting)—1854 male workers and an unexposed group of 1380 male workers. The number of accidents at the workplace in the exposed group was significantly higher (seven times) than in the unexposed group. It was proved that work environment factors are of special importance and can lead to more frequent occupational accidents in exposed workers. Lighting was found to be the most common cause of accidents [14].

The health risks associated with lighting of the workplace were also analyzed in Estonian enterprises, and results showed that hazards arising from insufficient or badly organized lighting were mainly the controlling factor [10]. The risk criterion for lighting was developed by Reinhold and Tint [10], where recommended illuminance was between

300 and 500 lx. Intolerable risk was associated with the presence of disability glare, veiling reflections, or strong flicker together with an illuminance level below 50 lx or higher than 2000 lx and color rendering index below 50. Inadmissible risk was associated with the presence of discomfort glare and/or mild flicker together with illuminance level of 100 lx and color rendering index of 60.

The occupational risk related to glare was also analyzed and criteria for glare type assessment and related risk for non-stationary outdoor workplaces were proposed by Wol-ska [15]. Based on the predicted retinal illuminance as a result of background (adaptation) luminance and glare source luminance, the criteria for discomfort, disability, and blinding glare were proposed. A simple method for rough estimation of glare type for the purpose of risk assessment was based on background and glare source luminance [15].

All the examples of analyses of occupational accidents presented here show that artificial lighting at outdoor workplaces at night time applied in the wrong way increases the risk and occurrence of accidents.

1.3. Glare at Outdoor Workplaces—A Short Story

Glare rating (GR) as a measure of glare at outdoor spaces was introduced on 25 November 1985, by the CIE organization (in TC 5-04 Technical Committee). The first publication in which GR was used for analysis of illumination of tennis courts dates back to 1986 [16]. However, the first analysis concerning glare was performed earlier during the years 1982–1983. It was centered on football fields [17,18] and timber terminals [19]. The glare assessment method used in sports facilities was also adopted for outdoor workplaces. In CIE documents of 1994 [20] and 1998 [21], we can find glare analyses for both sport facilities and outdoor workplaces. The first attempts to determine the approximate GR value were described in 1995 [22]. The GR scale includes values ranging from 0 to 100—an increase in the value means an increase in the glare [20]. The GR scale is based on de Boer glare rating scale [23,24].

GR as an index for outdoor workplaces is defined in the standard EN 12464-2, *Light and lighting—Lighting of work places. Part 2. Outdoor workplaces* [5]. In the last edition of this standard, published in 2014, R_G was introduced as a new abbreviation for glare rating. However, in this article we use GR, as used in the previous version of the standard and all other CIE documents and publications.

Despite having common roots, today the lighting of sports facilities is described in a separate standard (EN 12193, *Light and lighting—Sports lighting* [25]). By studying legal acts concerning outdoor sports facilities, interesting conclusions can be drawn. There are two documents concerning football stadiums: recommendations and requirements of UEFA [26] and FIFA [27]. In both the documents, the GR and glare requirements that need to be fulfilled during the lighting design phase of the sports facility are mentioned, but the verification of GR by measurements in real conditions is not mentioned.

It is worth mentioning that GR is not the only index discussed by international standards. There are other indices also: unified glare rating (UGR) for indoor workplaces is defined in EN 12464-1, *Light and lighting—Lighting of work places. Part 1. Indoor workplaces* [4], and threshold increment (TI) for road lighting in EN 13201, *Light and lighting—Road lighting* [28]. Discomfort glare probability (DGP) is used for the assessment of daylight glare [29] and is defined in EN 17037, *Daylight in buildings* [30].

On the other hand, in addition to the above, many other documents also discuss the glare problem in outdoor areas, for example, CIE documents: concerning limitations of the effects of obtrusive light from outdoor lighting installations [31] and concerning maintenance of outdoor lighting systems [32], along with specialized documents of other organizations [33,34].

1.4. Aim of the Paper

Lighting examinations at industrial outdoor workplaces carried out for many years by the authors of this article confirmed the poor lighting of those places because of insufficient illuminance and glare existence.

The aim of this article is to draw attention to the problem of glare at outdoor workplaces. In order to illustrate the importance of this problem, we present a number of situations from real industrial conditions. The presented analysis leaves no doubt that glare at outdoor workplaces is underestimated or simply neglected by employers.

2. Materials and Methods

2.1. How to Assess Objectively the Glare at Outdoor Workplaces—The Practice

The need for assessing lighting, including glare, as occupational accident contributor at outdoor workplaces was proved in the studies concerning accidents at work [10–14]. However, there are known statements that the measurement of the GR is very difficult [35] or even that GR “cannot be measured” [36]. This results in attempts to evaluate glare in different ways—not exactly in accordance with the standard. There is a possibility of using UGR to assess glare at outdoor workplaces: in special cases by analysis of measured UGR [37] or based on the converting values between GR and UGR indices [24]. There are also known examples of assessing glare at outdoor areas indirectly (without calculating the GR value) [38,39].

In our research, we applied the previously developed method of measuring the GR index. This method has been verified, tested under real conditions, and was published in 2019 [40]. According to the best of the authors’ knowledge, this is the first and so far the only publication describing the objective assessment of glare at outdoor workplaces based on measurement of the glare index—GR.

GR was measured in several points of a measuring grid in the task area (according to [5])—at the workplace where the employee performed visual tasks. At each measurement point, GR measurements were made for eight different observation directions (by turning the photometer around the vertical axis by 45° successively). For the final analysis, GR values with the highest value (which corresponded to the highest glare) for a given task area were selected (as is done with the glare evaluation method in lighting design programs). Most often, a fish-eye lens is used in glare measurements. Although the viewing angle of the human eye is less than 180°, such a lens covers the full human field of view. However, according to the standard [5], GR index calculations are performed only in a specific angle around the line of sight. This angle lies in the range between 1.5 and 60°. In this way, according to the standard, the GR index was determined in our research. The measurement procedure described here (and used in our research) complies with the recommendations of the standard [5]. Each measurement of GR index requires the registration of the luminance distribution in the form of a luminance map. On this basis, the author’s program determines the value of GR. Details of the measurement procedure and the algorithm for determining the GR index value can be found in [40].

The registration of the luminance map is performed with the imaging luminance measuring device (ILMD). In our study, we used the LMK Mobile and Advance photometer (manufactured by Techno Team company from Ilmenau, Germany) [41]. The range of the measured luminance depends mainly on the luminance of the glare source and most often exceeds the capabilities of the matrix photometric sensor. The high dynamic range (HDR) method used in photography partially solves this problem. However, it requires three photographs (in different exposure conditions) for one measurement. The HDR image needed to determine the luminance map is composed of these three photos. The use of HDR in the measurement of luminance distribution is a difficult task. Hence, the ILMD manufacturer uses its own algorithms for determining the luminance value in the HDR image and its own format for saving data in the HDR file. This means that the HDR method can only be used as a tool in a complex glare determination system. But in this way the

solution is fully and optimally implemented by the ILMD manufacturers. Details of taking pictures for such operations and obtaining HDR images can be found in [42].

2.2. The Research Methodology

We have carried out assessment of glare at outdoor workplaces in 19 institutions and industrial plants. These studies lasted 2 years and allowed us to collect many data of comparative material. We have performed glare assessment at 89 different task areas. GR measurements were carried out in the majority of them, i.e., at all these workplaces where it was possible to make the measurements according to OSH requirements. We have taken almost 4000 photographs to provide luminance maps generation (set of HDR images in eight directions of the observer's line of sight at one measurement point; three photographs for one HDR image; for each HDR image appropriate exposure conditions and exposure time had to be determined [42]). Due to article space constraints, we cannot present all of the collected results, hence we have tried to choose the most important and interesting, and those that best represent the problem.

Taking into consideration the requirements of the standard [5] and our experience in glare assessment and risk evaluation [43], we propose a three-point scale to assess the risk arising from glare at outdoor workplaces. Our criteria for proposed risk assessment are presented in Table 1.

Table 1. Elaborated criteria (based on glare rating (GR)) for the degree of risk arising from glare at outdoor workplaces.

Degree of Risk	GR Limit
Small	$GR \leq GR_{MAX}^1$
Medium	$GR_{MAX}^1 < GR < 70$
High	$70 \leq GR$

¹ GR_{MAX} means value defined in standard [5] as a limit for proper workplace. It should be 40, 45, 50, or 55, according to Tables 5.1–5.15 of the standard [5].

The conducted glare studies at outdoor workplaces included two types of assessment: subjective and objective. The subjective assessments were made on the basis of an analysis of interview result (using a dedicated questionnaire) conducted among employees (Table 2). The surveys were supplemented with conversations with employees

Table 2. Questionnaire for interview for subjective assessment of lighting.

	Question	Answer
1.	Does the existing outdoor lighting ensure good visibility of circulation area to recognize the obstacles after dark (openings, manholes, thresholds, steps, etc.)?	Yes/No
2.	Does the existing outdoor lighting provide good visibility at the task area after dark?	Yes/No
3.	Do you see very bright light sources when you are working after dark?	Yes/No
4.	The existing lighting at outdoor workplaces—is it satisfactory and does not require changes?	Yes/No
5.	Degree of perceived glare on a five-step scale:	Select one answer
	Unbearable Work—completely impossible Sensation of glare—the luminaires cause “blinding”	—
	Disturbing Work—hard to perform; recognizing of details is difficult during some time after looking toward the luminaire Sensation of glare—significant discomfort	—
	Just admissible Work—possible, difficulties in perception for a short period of time Sensation of glare—noticeable discomfort	—
	Noticeable Work—possible for quite a long time Sensation of glare—slight discomfort	—
	Imperceptible Work—possible for a long time Sensation of glare—imperceptible, no discomfort	—

Taking into account the de Boer’s scale of glare [23] and our own studies [24], we have assigned GR values to the degree of glare sensation from the questionnaire (Table 3).

Table 3. Proposed assignment of GR values to the scale of the subjective sensation of glare.

Sensation of Glare	Assigned Value of GR
Unbearable	$90 \leq \text{GR}$
Disturbing	$70 \leq \text{GR} < 90$
Just admissible	$50 \leq \text{GR} < 70$
Noticeable	$30 \leq \text{GR} < 50$
Imperceptible	$\text{GR} < 30$

The number of completed questionnaires was limited to the actual number of employees working at the analyzed workplaces. The subjective assessment (questionnaire research) can be subject to a large error due to the employees’ inexperience in conducting the glare assessment. However, in these specific cases, the correctness of the assessment was determined by the employees’ experience in performing tasks at given workplaces over a long period of time (often many years). Employees were well aware of the extent to which the lighting bothered them and in which exact situations related to the performance of tasks. In such circumstances, questionnaire studies conducted even on a relatively small group make it possible to compare the compliance of the subjective assessment with the assessment carried out on the basis of the GR value. Additionally, they provide an opportunity to take into account the subjective impressions of employees, which may sometimes be more important than the “dry numbers” describing the GR values. Hence, in order to ensure the comfort (and safety) of work, the final glare assessment takes into account the most unfavorable assessment variant, regardless of whether it comes from the objective assessment (GR value) or the subjective assessment (questionnaire). Table 1 shows the risk assessment based solely on the measured GR value. On the other hand, the subjective assessment of glare carried out by the employee performing the activities in a given position is superior to the objective assessment, if this subjective assessment indicates a higher degree of glare.

The objective assessment was made on the basis of measurements of GR values. Unfortunately, instruments/devices for measuring GR values are not available commercially. There is also no practical measuring method—there are no known publications on this subject. The Evalglare software [44] is widely regarded as best for the assessment of glare, but it also does not give the possibility to determine the GR. This problem has also been noticed publicly [38]. In fact, for the determination of GR not only calculations (software) but also a proper method is decisive. Therefore, we have developed a method for measuring GR values at outdoor workplaces in accordance with the standard [5] and CIE documents [20,21,31]. We have also built our own software for calculating value of GR based on a luminance map from an HDR image. Our software has been verified and tested independently. Our solution has been described in [40].

Recommendations of the standard [5] cover various outdoor workplaces and divide them into 15 categories—Tables 5.1–5.15 in [5]. While performing research in real industrial conditions, we tried to include as many categories of industrial plants and workplaces as possible, as considered in the standard [5]. Unfortunately, due to circumstances beyond our control, it was not possible to include all of them in our studies. In addition at some workplaces/task areas we had no opportunity to assess glare using two methods—there were some cases where we could only measure GR and also some where only a subjective assessment was made.

In addition, it is worth noting that in all industrial plants where we did research, modern light sources recommended for energy saving were used. At the same time, this was a basic requirement, verified at each realization stage of the lighting installation.

3. Results

Because we cannot give the names of the industrial plants assessed, we have described our research without such information.

3.1. General Circulation Areas at Outdoor Workplaces

These workplaces and task areas correspond to the category described in Table 5.1 of the standard [5]. There are two requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45$ or $GR_{MAX} = 50$. This type of area can be found in all industrial plants and institutions. In Figure 1 we present a typical view from the circulation area and the corresponding luminance map. In total, we have determined glare at nine circulation areas. Generally, the measured GR values were in the range between 9 and 45 corresponding with workers' subjective assessments of glare (see Table 3). According to Table 1 the degree of risk associated with glare at those circulation areas is estimated as small. However, we also found one circulation area where measured GR was equal to 60 and exceeded glare limit of 10–15 GR units and the subjective assessment was disturbing ($70 \leq GR < 90$), which corresponded to high risk.

Figure 1. The view from the measurement point with corresponding luminance map. Measured glare rating (GR) = 32, subjective sensation of glare: noticeable, task of activity [5]: Regular vehicle traffic (max. 40 km/h), GR_{MAX} from standard [5] = 45.

3.2. Airports

These workplaces and task areas correspond to the category described in Table 5.2 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45$, 50 or 55. We have carried out measurements at two airports: one military and one civilian. In total, we have measured GR at 10 task areas of different activities which corresponded to each of the three GR_{MAX} values. The measured GR values were in the range between 21 and 51, and corresponded with workers' subjective assessment of glare. In certain cases, GR_{MAX} was slightly exceeded what corresponded to medium risk. The examples of the highest degree of glare (based on GR values and related sensation of glare) at airport task areas is presented in Figure 2.

Figure 2. The view from the measurement point with corresponding luminance map. Measured $GR = 51$, subjective sensation of glare: just admissible, task of activity [5]: aircraft maintenance stands, GR_{MAX} from standard [5] = 45.

3.3. Building Sites

These workplaces and task areas correspond to the category described in Table 5.3 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45, 50$, or 55 . The regulation in our country introduced some restrictions, which result in rarely performing construction work after dark. This is due to the following reasons. First, after dark additional safety measures are required. Second, special permissions for night work are needed to account for the quiet hours and lights-out period for local residents. Nevertheless, in exceptional cases like removal of failures or accidents, or continuous work that cannot be interrupted, e.g., when pouring large concrete surfaces such work is carried out after dark. We have assessed glare during pouring concrete at two building sites, but only subjectively. We had no permission for GR measurement because of OSH requirements. In both cases the glare was assessed as unbearable or disturbing, which corresponded to high risk: (1). building site, subjective sensation of glare: unbearable, task of activity [5]: Construction areas, drain pipes mounting, transport, auxiliary and storage tasks, GR_{MAX} from standard [5] = 50. (2). Building site subjective sensation of glare: disturbing, task of activity [5]: Construction areas, drain pipes mounting, transport, auxiliary and storage tasks, GR_{MAX} from standard [5] = 50.

3.4. Canals, Locks, and Harbors

These workplaces and task areas correspond to the category described in Table 5.4 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45, 50$, or 55 . We carried out measurements of GR in one harbor at three task areas for different activities where glare limits corresponded to each of the three GR_{MAX} values. The measured GR values were in the range between 20 and 39, and corresponded with workers' subjective assessment. GR_{MAX} was not exceeded at any task areas, which corresponded to small risk.

3.5. Fuel Filling Stations

These workplaces and task areas correspond to the category described in Table 5.6 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45, 50$, or 55 . We carried out assessment of glare at six fuel filling stations at 13 task areas of different activities which glare limits corresponded to each of the three GR_{MAX} values. In all of them a subjective assessment was made, and in three we had the opportunity to measure GR . The measured GR values were in the range between 9 and 29. Only at one task area was the degree of glare (subjective assessment)

at the border of acceptance. It was found for task activity—meter reading area, where GR_{MAX} from standard [5] = 45, which corresponded to small risk. However, glare may cause difficulties in reading indications (Figure 3).

Figure 3. The view from the measurement point with corresponding luminance map. Measured $GR = 29$, subjective sensation of glare: just admissible, task of activity [5]: Meter reading area, GR_{MAX} from standard [5] = 45.

3.6. Industrial Sites and Storage Areas

These workplaces and task areas correspond to the category described in Table 5.6 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45, 50$, or 55 . This kind of area can be found in many industrial plants. In total, we determined glare at 10 industrial sites and storage areas of four industrial plants, and the results were similar. The measured GR values were in the range between 11 and 45, and corresponded with workers' subjective assessment. GR_{MAX} was not exceeded at any task areas, which corresponded to small risk.

3.7. Parking Areas

These workplaces and task areas correspond to the category described in Table 5.9 of the standard [5]. The risk in this case as per the standard [5] is small. Therefore, only three types of workplaces are considered with the glare rating limit in the range between $GR = 50$ – 55 . We determined glare at four parking areas of two industrial plants, and the results were similar. The measured GR values were in the range between 18 and 29. GR_{MAX} was not exceeded at any task areas, which corresponded to small risk.

3.8. Oil and Other Chemical Industries

These workplaces and task areas correspond to the category described in Table 5.10 of the standard [5]. There are four types of workplace considered in the standard [5] with three requirement limits of glare $GR_{MAX} = 45, 50$ or 55 . We carried out measurements at one oil and one petrochemical industry. In total, we measured GR at 18 task areas of different activities in which glare limits corresponded to each of the three GR_{MAX} values. The measured GR values were in the range between 21 and 51, and were consistent with subjective assessment of glare in most cases. GR_{MAX} was exceeded in some task areas, which corresponded to medium risk. Additionally, it is worth noting that exceeding the degree of glare in this category occurs in a hazardous industry. The consequences of accidents in this kind of industry can be very serious. The examples of the highest degree of glare (based on GR values and related sensation of glare) at oil and chemical industry task areas is presented in Figure 4.

Figure 4. The view from the measurement point with corresponding luminance map. Measured $GR = 53$, subjective sensation of glare: just admissible, task of activity [5]: Filling and emptying of container trucks and wagons with dangerous substances, replacements of pump packing, general service work, reading of instruments, GR_{MAX} from standard [5] = 45.

3.9. Railways and Tramways

These workplaces and task areas correspond to the category described in Table 5.12 of the standard [5]. There are 22 types of task areas/activities considered in the standard [5] with four requirement limits of glare $GR_{MAX} = 40, 45, 50$ or 55 . We have opportunity to determine glare at one railway company (repair crew workspace). We measured GR at five task areas of different activities in which glare limits corresponded to each of the four GR_{MAX} values. In all cases the temporary lighting installation was used. The measured GR values were in the range between 50 and 79, and GR_{MAX} was exceeded at all task areas. The subjective assessments were disturbing ($70 \leq GR < 90$) and unbearable ($90 \leq GR$) in the worst case. Such assessments corresponded to high risk. Additionally, it is worth noting that the consequences of accidents can be very serious. The examples of the highest degree of glare (based on GR values and related sensation of glare) at railway task areas is presented in Figure 5.

Figure 5. The view from the measurement point with corresponding luminance map. Measured $GR = 79$, subjective sensation of glare: unbearable, task of activity [5]: Freight track, continuous operations, GR_{MAX} from standard [5] = 50. In this case, the location of the glare source determined the high level of glare (high GR value). The glare source is in the field of view very close to the line of sight. According to the formula of GR [40], the value of this index is inversely proportional to the square of the angle between the observer's line of sight and the direction to the glare source.

3.10. Saw Mills

These workplaces and task areas correspond to the category described in Table 5.13 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45, 50$, or 55 . We have carried out measurements of GR in one saw mill at four task areas of different activities in which glare limits corresponded to each of the three GR_{MAX} values. The measured GR values were in the range between 8 and 21, and were consistent with subjective assessment of glare. GR_{MAX} was not exceeded at any task areas, which corresponded to small risk.

3.11. Shipyards and Docks

These workplaces and task areas correspond to the category described in Table 5.14 of the standard [5]. There are three requirement limits of glare (GR_{MAX}) for this category in the standard [5]: $GR_{MAX} = 45, 50$, or 55 . We had an opportunity to determine glare at one shipyard and dock company. We measured GR at five task areas of different activities in which glare limit corresponded to $GR_{MAX} = 50$. The measured GR values were in the range between 38 and 66, and were consistent with the subjective assessment of glare in most cases. Degree of glare (GR value or subjective assessment) was exceeded at all task areas. In three cases, it corresponded to medium risk. In two cases, where the subjective assessments were disturbing ($70 \leq GR < 90$), it corresponded to high risk. The examples of the highest degree of glare (based on GR values and related sensation of glare) at shipyard and dock company task areas is presented in Figure 6.

Figure 6. The view from the measurement point with corresponding luminance map. Measured $GR = 66$, subjective sensation of glare: disturbing, task of activity [5]: Cleaning of ship hull, GR_{MAX} from standard [5] = 50. Similar to Figure 5, in this case, the location of the glare sources determined the high level of glare (high GR value).

3.12. Water and Sewage Plants

These workplaces and task areas correspond to the category described in Table 5.15 of the standard [5]. There are three types of workplaces considered in the standard [5] and one requirement limit of glare $GR_{MAX} = 45$. We had the opportunity to determine glare at one water and sewage company. We measured GR at six task areas of different activities. The measured GR values were in the range between 9 and 62, and were generally consistent with the subjective assessment of glare. GR_{MAX} was exceeded at two task areas. In one, it corresponded to medium risk. In one, where the subjective assessments were disturbing ($70 \leq GR < 90$), it corresponded to high risk. The examples of the highest degree of glare (based on GR values and related sensation of glare) at water and sewage company task areas is presented in Figure 7.

Figure 7. The view from the measurement point with corresponding luminance map. Measured GR = 62, subjective sensation of glare: disturbing, task of activity [5]: Handling of chemicals, inspection of leakage, changing of pumps, general servicing work, reading of instruments, GR_{MAX} from standard [5] = 45. Similarly to Figure 5, in this case, the location of the glare sources determined the high level of glare (high GR value).

4. Discussion

4.1. Analysis of the Collected Results

The categorization defined in the standard [5] is justified by various visual task difficulties and by various types of hazard that may occur in a given workplace. The type of work performed and the risks associated with it determine the required limitation of glare. The maximum permissible range of glare is defined by the GR limit in ranges from GR = 40 to GR = 55. It has been assumed that the limitation to GR = 55 includes workplaces where there is no particular caution required, nor it is necessary to perform a visual task with a high degree of difficulty. The limitation to GR = 40 is intended for workplaces requiring difficult visual tasks and where there is a high risk of accidents. Such a GR limit value is defined five times in the standard [5] (at four workplaces in Table 5.8—offshore gas and oil structures and at one workplace in Table 5.12—railways and tramways). In other dangerous places and places requiring difficult visual tasks, the GR limit is 45.

The aim of this research was to analyze glare at outdoor workplaces. This analysis is directly related to the hazard evaluation. Thus, the results presented in Chapter 3 were collected in Table 4 in accordance with the criteria of hazard level discussed earlier (in Table 1). In most cases of our research (approximately 75%), the objective assessment (measurement) is consistent with the subjective assessment (employee's sensation). Only in a few cases can discrepancies be noted. In these cases, a more unfavorable assessment (either subjective or objective) determined the ranking given in Table 4.

Table 4. Summary table of results arranged according to the hazard level.

Category of Lighting Requirements (According to Standard [5])	Number of Examined Task Activities (According to Standard [5])				Task Area Where a High Degree of Risk Occurred: GR _{MAX} —Limit of Glare Defined in Standard [5] Assessment of Glare Comments
	Total	With Varying Degrees of Risk			
		Small	Medium	High	
General circulation areas at outdoor workplaces (Table 5.1 in [5])	9	8	0	1	Pedestrian passages, vehicle turning GR _{MAX} from [5] = 50, Measured GR = 60, Subjective assessment = Disturbing ($70 \leq GR < 90$)
Airports (Table 5.2 in [5])	10	8	2	0	(1. Task) Aircraft maintenance stands GR _{MAX} from [5] = 45, Measured GR = 51, Subjective assessment = just admissible ($50 \leq GR < 70$) (2. Task) Fuel depot GR _{MAX} from [5] = 50, Measured GR = 41, Subjective assessment = just admissible ($50 \leq GR < 70$) The task activity corresponded to high risk (working with dangerous substances)
Building sites (Table 5.3 in [5])	2	0	0	2	Construction areas, drain pipes mounting, transport, auxiliary and storage tasks GR _{MAX} from [5] = 50, (1. Task) Subjective assessment = Disturbing ($70 \leq GR < 90$) (2. Task) Subjective assessment = Unbearable ($90 \leq GR$)
Canals, locks, and harbors (Table 5.4 in [5])	3	3	0	0	
Fuel filling stations (Table 5.6 in [5])	13	12	1	0	Meter reading area GR _{MAX} from [5] = 45, Measured GR = 29, Subjective assessment = just admissible ($50 \leq GR < 70$) The task activity corresponded to small risk, however may cause difficulties in reading indications.
Industrial sites and storage areas (Table 5.7 in [5])	14	14	0	0	

Table 4. Cont.

Category of Lighting Requirements (According to Standard [5])	Number of Examined Task Activities (According to Standard [5])				Task Area Where a High Degree of Risk Occurred: GR _{MAX} —Limit of Glare Defined in Standard [5] Assessment of Glare Comments
	Total	With Varying Degrees of Risk			
		Small	Medium	High	
Parking areas (Table 5.9 in [5])	4	4	0	0	
Oil and other chemical industries (Table 5.10 in [5])	18	16	2	0	(1. Task) Filling and emptying of container trucks and wagons with dangerous substances, replacements of pump packing, general service work, reading of instruments GR _{MAX} from [5] = 45, Measured GR = 53, Subjective assessment = just admissible (50 ≤ GR < 70) (2. Task) Filling and emptying of container trucks and wagons with dangerous substances, replacements of pump packing, general service work, reading of instruments GR _{MAX} from [5] = 45, Measured GR = 47, Subjective assessment = noticeable (30 ≤ GR < 50) Both task activities corresponded to high risk (working with dangerous substances)
Railways and tramways (Table 5.12 in [5])	5	0	0	5	(1. Task) Freight track, short duration operations GR _{MAX} from [5] = 45, Measured GR = 50, Subjective assessment = disturbing (70 ≤ GR < 90) (4. Tasks) Freight track, continuous operations GR _{MAX} from [5] = 50, Measured GR = 60–79, Subjective assessment = disturbing (70 ≤ GR < 90) and unbearable (90 ≤ GR) In all cases a temporary lighting installation has been used. In all cases the consequences of accidents can be very serious.
Saw mills (Table 5.13 in [5])	4	4	0	0	
Shipyards and docks I (Table 5.14 in [5])	5	0	3	2	(2. Tasks with highest level) Cleaning of ship hull GR _{MAX} from [5] = 50, Measured GR = 52–66, Subjective assessment = disturbing (70 ≤ GR < 90)
Water and sewage plants (Table 5.15 in [5])	6	4	1	1	(1. Task with highest level) Handling of chemicals, inspection of leakage, changing of pumps, general servicing work, reading of instruments GR _{MAX} from [5] = 45, Measured GR = 62, Subjective assessment = disturbing (70 ≤ GR < 90)
Sum of tasks:	93	73	9	11	

When analyzing the results presented in Chapter 3 and Table 4, the following conclusions can be drawn.

- At 20 task areas (out of 93 examined, meaning 21.5%) the determined degree of glare (measured GR values or subjective assessment) exceeded the limits specified in the standard—i.e., the requirements of the standard in terms of glare limitation were not met.
- At eight categories of industrial plants defined in the standard [5] (out of 12 examined, meaning 66.7%) there was at least one task area where the requirements of the standard in terms of glare limitation were not met.
- At 11 task areas (out of 93 examined, meaning 11.8%) we found a high degree of risk. Unfortunately, this was in industries from the category of hazardous industries where the consequences of accidents can be very serious.
- No glare was found at outdoor workplaces where high masts were used and bright sources illuminated the surface from a great height. This applies to storage areas, parking areas, and some areas of airports, water and sewage installations. It is worth paying attention to the fact that the reflections of light from large surfaces with specular reflectance properties (e.g., water surfaces) can create hazards if the lamps are not installed high enough.
- The problem existed at workplaces where it was difficult to light up the task areas. Occurrence of glare in these cases is related to the specificity of the workplace and activities performed there. This is mainly the case with docks and large chemical and petrochemical installations. The glare risks are very serious in these cases. Working in such places is always dangerous, and worsening conditions by glare can result in very serious accidents or even death.
- The most serious problem was noticed at workplaces where temporary lighting installations were built to carry out tasks at a given moment. This case is practically observed mostly for maintenance and repair tasks in railway and tramway enterprises. Similarly, this condition is seen on construction/building sites where lighting is changed and glare limitation is seldom taken into consideration.

The above conclusions apply to specific industrial plants with a specific technical condition of the lighting installation, in a specific country with a specific technical culture. We believe that the problem of glare exists, but the above conclusions cannot be generalized.

In industrial conditions, luminaries are changed often: substitutes for light sources or temporary and provisional solutions are used. In such situations, it is difficult to control the lighting parameters. The glare, which then arises, becomes a threat to work safety. Moreover, relying only on the simulation rating gives illusory results—even if they are perfectly consistent with the standard and requirements. In industrial conditions, designing lighting for outdoor workplaces is a difficult task.

In general, it is worth paying attention to the fact that the only effective way to assess the glare (and its dangers) is to measure GR in proper way at outdoor workplaces. Only the measurement allows taking into account all aspects of the actual lighting layout (even with correctly implemented projects). Only the measurement allows correctly assessing emergency and temporary solutions as well as changes in lighting configuration or replacing one source of light by the others (especially by LEDs). Only the measurement allows taking into consideration the damage to and aging of elements in lighting installations. Unfortunately, such a measurement procedure is not performed and is additionally considered to be very difficult. Although measurement is difficult and requires a good knowledge of the issue, it is not impossible—we have carried out measurements that allowed us to reliably evaluate glare in real industrial conditions.

4.2. How to Improve the Situation

The problem of a high level of glare (high GR value) in most cases resulted from improper location and selection of photometric properties of the luminaire (luminous intensity curves). Instead of illuminating primarily the workplace (task area), this creates a source

of glare in other areas. This situation can be improved by changing the geometry of the arrangement and selecting a luminaire with a different (proper) photometric characteristic. In addition, the proper arrangement and selection of luminaires allows for efficient use of energy. The new lighting design should ensure adequate glare limitation in places where the normative values were exceeded. The lighting installation realized in this way should be verified by measurement.

5. Conclusions

Glare assessment was undertaken at outdoor workplaces in several different industrial plants and companies. This assessment showed that in most industrial plants there are many workplaces where glare is simply too high. This is demonstrated both by the subjective glare perception of the employees analyzed on the basis of interviews as well as objective measurements of the GR value. At 21.5% of examined task areas, the determined degree of glare (measured GR values or subjective assessment) exceeded the limits specified in the standard [5]; at 11.8% of task areas we found a high degree of risk. At 66.7% of categories of industrial plants defined in the standard [5] there was at least one task area where the requirements of the standard in terms of glare limitation were not met. It is not surprising that in almost all cases of exceeding GR values, the objective assessment was found to be consistent with the employees' perception. This means that the GR value informs us well about the level of glare in real conditions. Unfortunately, the measurement of GR is not carried out in most cases. Lighting installations at outdoor workplaces are realized in accordance with the standard recommendations, but the verification procedure of the real state is undertaken only by simulation.

In all discussed industrial plants, it was checked whether recommended light sources were used. In almost all industrial plants, efforts have been made to ensure energy efficiency, for example by using energy-saving light sources. Nowhere has the glare been evaluated in real working conditions (outside the design phase of the installation). Glare at outdoor workplaces is underappreciated. It is necessary to extend its use in the evaluation of occupational safety and health. The data concerning occupational accidents and visibility-related fatalities at outdoor workplaces [10,11] confirm the need to conduct GR measurement. We try to answer the question: why is glare at outdoor workplaces not treated equally to that in indoor workplaces? On the one hand, this is because of the lack of enforcement of requirements. On the other hand, there is a problem in the determination of GR. The measurement of GR is considered a very difficult task by many lighting specialists. We have found that there are very limited information and relevant publications on this topic. According to the best of the authors' knowledge, article [40] is so far the only publication where the measurement of GR index is proposed and discussed in a practical context. It is worth noting that scientists who deal with the study of glare pay more attention to the problem of glare at outdoor workplaces. The increase of publications in this field may contribute to an improvement of the situation.

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