

A Methodology for Estimate Safety Barriers Effectiveness on Construction Industry Incorporating Uncertainties by the Use of Fuzzy Sets

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Abstract

In occupational safety, prevention and protection usually involve the use of some sort of barriers.

To estimate accurately safety barriers effectiveness it is of paramount importance to assure its performance and consequently keep the risks on adequate levels. But, what is safety barrier effectiveness? How to estimate it without statistical reliable data?

Estimate the effectiveness of safety barriers is a complex process that entails the consideration some quantitative parameters as well as perceptions which are fuzzy by nature and its assessment process involves complexity and uncertainty. A fuzzy approach is a better mathematical framework to estimate safety climate because uncertainty represented on fuzzy systems is a non-statistical uncertainty, which express vagueness, imprecision and/or ambiguity through fuzzy membership functions, and has a different nature from statistical uncertainty that is based on the laws of probability and is resolved through observations.

Departing from a literature review on safety climate, a set of factors affecting safety climate on construction sites were identified. A pole of six Portuguese construction safety experts contributed to adapt these factors to the Portuguese construction sites reality. The model was tested, conducting real case studies, by "peer" reviews by a pool of 11 safety experts from Brezil (2), Greece (3), Portugal (2), Turkey (3) and Bulgaria (1).

Estimate safety barriers effectiveness is of particular value to avoid the occurrence of work accidents that are costly in terms of the potential for loss of equipment, material, man-hours and human lives. The assessment tool developed and presented in this work seems suitable and easy to use by safety practitioners in construction sites.

Hence, in this work our objectives are: (1) to present a survey about concepts and performance of SB, (2) to overview how SB are used in construction industry and, (3) to provide a practical tool for assessing safety barriers effectiveness, using a fuzzy sets theory approach.

Keywords: Manoeuvres; Hazards; Vagueness and Ambiguity; Symbolic Barriers; Morphology; Safety Helmet; Safety Resilience; SB Effectiveness

Introduction

High standards of occupational safety could be defined as the absence of accidents (and incidents), and therefore it means working with low risk. There are many contributing elements to ensure an adequate safety level at a workplace in the construction industry, such as technical and organizational safety features in an immediate level, and social factors and informal behaviour on a more remote level.

Prevention in occupational safety is based on mitigation (reducing the likelihood of occurrence of the undesirable event) and contingency (measures taken to decrease the impact of an event).

The means of prevention developed in occupational safety are numerous and include in particular:

- a) Elimination of risk by design;
- b) Limiting dangerous parameters from machines and processes;
- c) Installation of isolating devices and equipment;
- d) Blocking or prohibiting dangerous manoeuvres;
- e) Analysis of safety failures;
- f) Reducing the likelihood of breakdown or errors;
- g) Individual protection;
- h) Development and use of work procedures and;
- i) Learning from dangerous incidents. In the construction industry, prevention and protection usually involve the use of some sort of barriers. Noted that barriers constitute only one of numerous possible prevention means but, on construction, they are extensively used, so to assure its effectiveness is of paramount importance.

Prevention consists in blocking or hampering initiating factors from triggering or contributing to an accident. Prevention and protection are always accomplished by using the four possible barrier systems, namely: physical, functional, symbolic and incorporeal, either individually or, in a more reliable way, in combination. Protection implies blocking or hindering accident's consequences and involves the use of either physical or functional barrier systems [1]. Prevention is preferable to mitigation, in other words, risks should be reduced by reducing frequency of occurrence than by mitigation actions [2].

Although some kind of Safety Barriers (SB) have been used since the origins of our species to protect humans and property from enemies and natural hazards (e.g. energy sources floods, fires) there is no commonly/general accepted definition for them [3]. Different authors use different terms with similar meanings, such as: barrier, safety barrier, defense,

safety defense, protection barrier, protection layer, safety critical element, safety function and safety system [3-10]. Without a clear definition and delimitation of the concept, a safety barrier could be any physical entity, any technical aspect (e.g. hardware component) or even any procedural or organizational element of the work environment, which aims to avoid, prevent, control, or mitigate undesired events such as work accidents and incidents. Moreover, European regulations and International standards enhance the importance of considering safety barriers to reduce the risk of accidents [11-15]. Reason [16] states that most of the accidents are due to a combination of an unexpected event with a dysfunctional or missing barrier, rather than to a single initiating action.

To ensure acceptable levels of occupational safety by preventing work accidents or minimizing their consequences, it is first of all necessary to identify all involved risks and its characteristics. Any SB design should only be attempted after completing the occupational risk assessment process thus ensuring its adequacy by function specificity. Guldenmund, et al. [17] states that each SB has to be designed (or ordered) according to particular specifications and must be built or delivered including installation and adjusted for use. Even for checking the performance of existing SB we need to know, in detail, the characteristics of the risks that intend to be reduced.

Another point to consider is that when we work with vague and/or imprecise knowledge or concepts, like effectiveness, adequacy, efficiency or performance, this cannot be accurately estimated by numeric values, so, a more realistic approach may be the use of linguistic assessment by means of assessing the problem fuzzy variables by linguistic semantic terms. Linguistic variable values are words or sentences in natural language and not numbers. As words are less precise than numbers, linguistic variables provide a mean to characterize phenomena that are too complex or too ill-defined to be described in quantitative traditional way. In our case, risk assessment on construction industry is made, in an informal way, in natural language, using semantic terms like: too risky, risky, too dangerous, safe, very safe, or more specifically, in SB assessment by terms like: very adequate, inadequate, efficient, effective, nor effective.

Hence, identifying the main parameters involved in SB and estimate their effectiveness with some accuracy is of paramount importance to assure its performance and consequently keep the occupational safety risks on acceptable levels. But, what means SB effectiveness? How to measure (estimate) it without statistical data?

The main aim of this work is to contribute to answer these important questions. Specifically, the objectives of this paper are: (1) to present a short survey about concepts and performance of SB, (2) to overview how SB are used in construction industry and, (3) to provide a practical framework for assessing safety barriers effectiveness, using a fuzzy sets theory approach. It should be pointed that this work is based on several sources of knowledge: scientific literature; safety expert's opinions on construction industry.

Safety Barriers Concept and Types

To understand SB performance it is necessary, first of all, to understand what it is and how it works.

Overview of SB

In general, a barrier is any obstacle that obstructs the access, the progress or the spread of something. A common definition of SB is an obstacle (physical barrier), which function is to protect vulnerable targets (e.g. humans, environment, objects...) from hazards (e.g. dangerous energy) [18-20]. Later, this concept was extended to a "defense in depth" [21]; meaning a set of barriers (barrier system), located along the chain between hazards and possible accidents (or unwanted events), where each one (barrier element) is not sufficient to protect the target from the hazard, but working as a whole they can.

The term "defense barrier" was defined by Reason [22] as "the various means by which the goals of ensuring the safety of people and assets can be achieved". The same author divided defenses in "hard defenses", such as physical barriers and alarms, and "soft defenses" such as regulation, procedures, and training and refers to defense-in-depth as "successive layers of protection". Comparing with other similar terms, such as: safety barrier, protection barrier or protection layer, defense concept has a wider range.

Accident investigations highlight the influence that management has on the SB effective operation. For example, MTO-analysis (Human, Technology, and Organization) applied in accident investigations, defined SB as "any operational, organisational, or technical solution or system that minimizes the probability of events to occur, and limit the consequences of such events" [23]. Svenson [5] pointed that is useful and very necessary to use a more precise terminology particularly to make a distinction between barrier systems and barrier functions. Barrier function, describes the modes by which it is possible generically to prevent or to protect against the hazards.

Barrier system, describes the means by which the barrier functions are fulfilled. Hollnagel [10] divide barrier systems, in four groups, by describing how which barrier functions are applied (what barriers are), namely:

- Physical or material – aim to prevent accidents or mitigate its consequences by blocking mass and/or energy flow. Examples of physical barrier systems are buildings, walls, fences, railings, bars, cages, gates, containers, fire curtains, etc. An important characteristic of a physical barrier is that it does not have to be perceived or interpreted by someone (or something) in order to work and can therefore be used against energy and material, as well as opposed to people.
- Functional-aim to create at least one pre-condition that have to be met before an action can be performed, for instance by establishing an interlock, either logical or temporal. May or may not require human action, some requires a user to change from one state to another; others are autonomous and can change depending on external conditions. A functional barrier system could not be visible or discernible by a human user, although its presence usually is indicated in some way.
- Symbolic – requires an act of interpretation by someone, indirectly through their 'meaning'. Are omnipresent everywhere by a variety of visual and auditory signs and signals, warnings (by text or symbol), alarms, etc.
- Incorporeal – aim to incorporate knowledge from users to achieve their purpose. These SB have not physical presence in the working site. In safety occupational context, incorporeal barrier systems are related to organizational aspects, such as, rules and procedures for actions (that are imposed by the organization), knowing and complying with regulations and standards, etc.

Other SB division was presented by other authors of whom we highlight:

1. Duijm et al. [1], presents a division based on the action verbs to avoid, to prevent, to control, and to protect: (1) avoid intends to suppress all the potential causes of an event by changing the design of the equipment or the type of product used, (2) prevent intends to reduce the probability of an event by suppressing part of its potential causes or by reducing their intensity, (3) control intends to limit the deviation from a normal situation to an abnormal (and unacceptable) one and, (4) to protect intends to cover.
2. Schupp (in Sklet) [3] divided SB in two types related to "hazard targets", namely: (1) primary

barriers which are associated with primary hazards (hazards that could be directly harmful to humans) and, (2) secondary barriers which are associated with functional hazards (hazards that could indirectly become hazardous to humans).

3. Hale, Kjellén [24,25] divided SB in two types related to dependence on actions in order to achieve its function, namely: (1) passive barriers (do not requires any action to achieve its function in reducing risk) and, (2) active barriers (requires an action to achieve its function).
4. Guldenmund et al. [17] whom divided barrier systems, in two groups, hardware and behavioural elements, related with the risk assessment and management process:
 - A- Hardware related:
 1. hazard (scenario) identification, barrier selection and specification;
 2. monitoring, feedback, learning and change management;
 3. design specification, purchase, construction, installation, interface design/layout and spares;
 4. inspection, testing, performance monitoring, maintenance and repair;
 - B- Behaviour related:
 5. procedures, plans, rules and goals;
 6. availability, manpower planning;
 7. competence, suitability;
 8. commitment, conflict resolution;
 9. coordination, communication.

Hence, in this work we follow the division proposed by Hollnagel (2008) [10] although it is not as simple and intuitive than the SB division proposed by Schupp (2004) or Duijm, et al. (2003), [1] because it seems more flexible, understandable and quite appropriate for

the construction industry (because it is closer of what should be the good practice).

Safety Barriers on Construction Industry

Construction sites usually have formal and informal SB elements in parallel, often overlapping. Sometimes it works as safety redundancy, which makes the safety system less vulnerable to changes and supports safety preservation (safety resilience). Ringdahl (2009) [26] describes this as a safety web rather than a distinct set of barriers. This feature can improve safety resilience but, on the other hand, this interaction between SB could decrease its effectiveness and/or create new risks, hence, it complicates the analysis and evaluation of the SB system implemented. Further, the analyst should understand well the SB elements and systems implemented, and its interactions, to understand its adequacy and availability. To achieve this understanding he will observe directly the site, and perform interviews with workers, foreman and engineers (to understand informal SB) and consultation of site documents (working procedures, reports of work accident investigation and others) in order to understand the reliability, robustness and resilience of the SB system.

As mentioned before, the first step for assessing SB in the construction industry is to determine which the most common accident modes are and which are the SB implemented to avoid it or to minimize their consequences.

In (Tables 1-8) we summarize the most used SB for the eight most common accident modes found in construction sites, using the Hollnagel [10] division into four classes. This list is based on a preliminary list of accident modes for occupational accident scenarios, adapted for the construction industry [27-30].

Barrier type	Examples (not exhaustive) on construction
Physical	Fixed standard railings. Safety nets. Safety belts system.
Functional	Construction Hazards Prevention through Design (CHPtD). Stability devices on Mobile Elevating Working Platforms (MEWP'S).
Symbolic	Demarcation of fragile surfaces (e.g. asbestos cement sheet, plastic sheet, corroded metal sheet, glass, wood, wool slabs, roof lights, bridged materials in silos, crusted surfaces of sludge lagoons).Forbidden of work in suspended scaffolds with winds exceeding 40 km/h.Training, instructions, procedures, safety meetings.
Incorporeal	Law: EU Directive 92/57/CEE , 24-06-1992.

Table 1: Safety Barriers for Falls.

Barrier type	Examples (not exhaustive) on construction
Physical	Keep safety distances to the electric lines (2 m until 1 kV, 4 m between 1 kV and 60 kV, 5 m to over 60 kV). Hand electric powered tools with double insulation. Enclosure doors locked.
Functional	CHPtD. Stroke limiters in aerial lift equipments working near energized lines. Residual-current devices. Residual current circuit breakers.
Symbolic	Signaling enclosure doors and other spots with electrical risk. Lock-out procedures. Training, instructions, procedures, safety meetings.
Incorporeal	Law EU Directive 92/57/CEE , 24-06-1992 and Directive 98/34/EC , 20-07-1998

Table 2: Safety Barriers for Contact with electricity.

Barrier type	Examples (not exhaustive) on construction
Physical	Keep safety distances to the electric lines (2 m until 1 kV, 4 m between 1 kV and 60 kV, 5 m to over 60 kV). Hand electric powered tools with double insulation. Enclosure doors locked.
Functional	CHPtD. Stroke limiters in aerial lift equipments working near energized lines. Residual-current devices. Residual current circuit breakers.
Symbolic	Signaling enclosure doors and other spots with electrical risk. Lock-out procedures. Training, instructions, procedures, safety meetings.
Incorporeal	Law EU Directive 92/57/CEE , 24-06-1992 and Directive 98/34/EC , 20-07-1998

Table 3: Safety Barriers for Struck by Moving Vehicle.

Barrier type	Examples (not exhaustive) on construction
Physical	Accessible areas within the swing radius of the rotating superstructure of the crane properly barricaded or protected. Scaffoldings provided with toe-boards. Materials stored in tiers either stacked, racked, blocked, interlocked, or otherwise properly secured to prevent sliding, falling, or collapse. Helmets. Falling Object Protective Structures on vehicles.
Functional	Mobile Elevating Working Platforms (MEWP'S) provided with stability devices
Symbolic	Demarcation areas around portable ladders. Forbidden of work in MEWP'S with winds exceeding 40 km/h. Training, instructions, procedures, safety meetings.
Incorporeal	Law: EU Directive 92/57/CEE , 24-06-1992 and EU Directive 89/655/CEE , 30/11/1989, revue by EU Directive 95/63/CE , 05/12/1995 and EU Directive 2001/45/CE , 27/06/2001. Formal works inspections.

Table 4: Safety Barriers for Injured by Falling Objects.

Barrier type	Examples (not exhaustive) on construction
Physical	Shoring systems. Anchorage of existing structures (walls, trees, poles).

Functional	CHPtD.
Symbolic	Excavation area demarcated and signalized. Training, instructions, procedures, safety meetings.
Incorporeal	Law: EU Directive 92/57/CEE , 24-06-1992

Table 5: Safety Barriers for Cave-ins.

Barrier type	Examples (not exhaustive) on construction
Physical	Abrasive wheel grinders provided with safety guards. Vehicles loaded safely.
Functional	Mobile Elevating Working Platforms (MEWP'S) provided with stability devices. Rolling Over Protective Structures on vehicles.
Symbolic	Excavation area demarcated and signalized. Training, instructions, procedures, safety meetings.
Incorporeal	Forbidden of throw tools or other objects

Table 6: Safety Barriers for Hit by rolling/sliding object.

Barrier type	Examples (not exhaustive) on construction
Physical	Machinery guards in risky spots (e.g. belts, gears, shaft, pulleys, sprockets, spindles, drums, fly wheels, and chains). Guards in removable mechanical transmission devices.
Functional	Power-operated interlocking movable guards.
Symbolic	Signaling of risky spots. Lock-out procedure. Training, instructions, safety meetings.
Incorporeal	Law: EU Directive 2006/42/CE , 10-01-2006.

Table 7: Safety Barriers for Contact with Machinery Moving Parts.

Barrier type	Examples (not exhaustive) on construction
Physical	Flammable, combustible and explosives materials stored in appropriated containers and in appropriated conditions.
Functional	Energy limiters and relief devices
Symbolic	Signalling of risky spots. Training, instructions, procedures, safety meetings.
Incorporeal	Law: EU Directive 92/57/CEE , 24-06-1992.

Table 8: Safety Barriers for Fire or explosion.

Assessment of Safety Barriers Performance: A Fuzzy Tool

In this section we describe the proposed tool for SB effectiveness estimation. We start by presenting the basic concepts of fuzzy sets; second, we describe the proposed relative importance for the different SB types; third, we present the proposed "SB-Effectiveness-scale"; and, finally, we describe how to use the proposed scale and relative importance to estimate SB effectiveness.

Basics on Fuzzy Sets

In occupational safety, vagueness and ambiguity exist due to the limitations of our language and other factors such as ill-defined concepts, human variability and subjective information. Moreover, the nature of the work in construction sites is usually plagued with imprecisions, for example, On-site inspections generally use linguistic expressions rather than metrics to assess safety risks [31-33]. Additionally, legal records, statistical data and site documentation produced by companies are generally insufficient for analyzing the

risks accurately. These facts increase the imprecision/uncertainty of the obtained results of occupational risk analysis, safety inspections or SB evaluations, and highlight the crucial need for flexible tools to handle uncertainty.

Fuzzy Set Theory was formulated in 1965 by Zadeh [34] and provides a mathematical framework for the systematic treatment of vagueness and imprecision. More specifically, FST may be viewed as an attempt at formalizing two remarkable human capabilities [34,35], namely: 1) to converse, reason and make rational decisions in uncertain environments; and 2) to perform a wide variety of physical and mental tasks without quantitative measurements.

A fuzzy set is said to include a boundary with a gradual contour, by contrast with classical sets, which present a discrete border, i.e. any object either belongs or not to a set. Formally, let U be the universe of discourse and u a generic element of U , a fuzzy subset A , defined in U , is one set of the dual pairs:

$$A = \{(u, \mu_A(u)) \mid u \in U\} \quad (1)$$

Where $\mu_A(u)$ is designated as membership function or membership grade of u in A . The membership function associates to each element u , of U , a real number $\mu_A(u)$, in the interval $[0,1]$, where 0 means that it does not belong to the set and 1 means it "strongly" belongs, while intermediate values mean different degrees of "membership".

An important concept in FST is the linguistic variable [36-38]. A linguistic variable is a variable that admits a set of labels (terms) of a natural language, each represented by a fuzzy set. An example is "temperature" that can be represented by the labels (cold, average-temperature, warm) and each label will then be represented as a fuzzy set. Another example is our proposed transformation of Hollnagel [10] linguistic scale, as shown in Table 9, where we created a linguistic variable "Importance/weight", which is represented by the discrete fuzzy set [high/1, medium-high/0.8, medium/0.6, low-medium/ 0.4, low/0.2] (details will be discussed in the next section).

It should also be pointed that FST deals with possible events and not with probable events. Possibility is the degree with which a variable may take a value and describes whether an outcome may happen while probability describes whether it will happen [39]. Hence, probability theory does not get displaced by FST, the two approaches are complementary. Probability theory is good for crisp but dispersed information, whereas FST is good for fuzzy but coherent information [39]. Moreover, probability theory requires that the complete set of possible outcomes must sum up to one,

while FST allows freedom regarding the outcomes and their sum is not constrained by summing up to 1.

In summary the flexibility and adaptability of FST to handle ill-defined information constitute the motivation for our choice of mathematical framework for the proposed tool for estimating SB effectiveness.

Determination of SB Types Relative Importance

As shown in section 2 (Tables 1-8) all SB types are always related to a hazard and/or an accident sequence, in a preventive and/or protective way. Given their diversity and their specific characteristics, their assessment cannot be performed based solely on specific and strictly objective criteria but should also include some qualitative assessments, i.e. SB assessment should also rely on safety expert knowledge and experience as well as on the knowledge of the risks' characteristics. However, the utilization of subjective judgement data based on expert's opinions increases uncertainty. It is difficult to estimate probabilities related to perceptions because perception uncertainty are fuzzy by nature and probabilistic framework was developed to deal with random uncertainty [40]. So, fuzzy approach seems to be more useful to make estimates related to perceptions [41].

The main criteria that should be considered for SB assessment are: fitness to the purpose, fitness for usage, reliability, proper implementation, ease of comprehension (for symbolic barriers), knowledge of their applicability (for incorporeal barriers), robustness, functionality, response time, etc [3,9].

From our practical experience we elect, as the most important criteria for SB effectiveness estimation, the following:

- Adequacy – evaluate the SB ability to achieve its purpose within the design specifications, and if it meets the set of required requirements (following legal requirements and/or applied standards);
- Reliability – evaluate if the SB can fulfill its purpose when it is needed;
- Robustness – evaluate how well the SB can withstand the variability of the environment and the ability to withstand extreme events (e.g. fire);
- Specificity - evaluate if the effects of activating the barrier will not lead to other accidents or destroys other protections.

It should be noted that for some types of barriers, not all the above criteria are relevant or necessary in order to describe the barrier performance.

An interesting definition of SB effectiveness is the ability (of a SB) to perform a safety function during a period, in a non-degraded mode and in pre-specified conditions [42]. Our definition of effectiveness applied to SB has a broader scope and includes the adequacy, reliability, robustness and specificity in order to produce the intended (or expected) result. Hence, our definition is: “effectiveness” evaluates the ability of a SB to achieve its purpose, when it is needed and how well it can withstand the variability of the environment and not lead to other accidents.

To evaluate a SB, we follow the criteria and evaluation levels defined by [10], about how barriers systems can achieve their purpose (Table 9). The set of 8 attributes according to Hollnagel [10] are: (1) Efficiency, which means “how well the SB meets its

intended purpose”, (2) Resources (cost), which means “what is needed to design, develop, implement and maintain a SB”, (3) Robustness (reliability), which means “how well a SB can withstand the variability of the (work) environment”, (4) Implementation delay, which means “the time interval from conception to implementation of a SB”, (5) Applicable to safety critical tasks, which means “is a proper solution to risks on critical tasks”, (6) Availability, which means “whether a SB can fulfill its purpose when needed”, (7) Evaluation, which means “how easy it is to determine whether a SB works as expected, both during design and actual use” and, (8) Independence on humans (during operation), which means “the extent to which a barrier does not depends on human actions to achieve its purpose”.

Criteria	Safety Barriers Types			
	Physical Ling term/membership	Functional Ling term/membership	Symbolic Ling term/membership	Incorporeal Ling term/membership
Efficiency	High/1	High/1	Medium/0.6	Low/0,2
Resource needs	Medium-high/0.8	Low-medium/0.4	Low-medium/0.4	Low/0,2
Robustness	Medium-high/0.8	Medium-high/0.8	Low-medium/0.4	Low/0,2
Implementation delay	Long/0,2	Medium-long/0.4	Medium/0.6	Short/1
Applicable to safety critical tasks	Low/0,2	Medium 0.6	Low/0,2	Low/0,2
Availability	High/1	Low-high/0.8	High/1	Uncertain/0
Evaluation	Easy/1	Difficult/0,2	Difficult/0,2	Difficult/0,2
Independence on humans	High/1	High/1	Low/0,2	Low/0,2
SB-IMPORTANCE	0.75	0.65	0.45	0.27

Table 9: SB types ‘evaluation, According to Hollnagel (2008) and its Fuzzification.

Hollnagel [10] used a linguistic scale with eleven different semantic terms to evaluate the SB types regarding the set of 8 attributes, just described, as shown in Table 9. However, we can observe that some of the terms are similar in terms of attributes classification. For example (1) “high” in criteria Efficiency is similar to both “short” in Implementation-delay and “easy” in Evaluation (because they represent the same concept in terms of importance or weight of SBs; (2) “medium-high” and “low-high” have similar meaning when related with Robustness and Availability, respectively; (3) “medium” has no similar terms; (4)

“low-medium” and “medium-long” again express the same concept in terms of importance for Resource-needs and Implementation-delay, respectively; (5) “low”, “long” and “difficult” have the same meaning for Efficiency, Implementation-delay and Evaluation, respectively.

In our proposal we assume the described similarity between the semantic terms for evaluating the 8 criteria of Hollnagel [10], regarding the different types of SB, to extend this study with a fuzzy approach. To start, we determine a common relative importance by fuzzifying

the above evaluation using just 5 discriminative terms (relative to the above similarity described). This fuzzification process implies the creation of a fuzzy membership function (Zimmerman, 2003), which in our case is a discrete fuzzy membership function. The defined discrete fuzzy set is:

IMPORTANCE-SCALE= [high/1, medium-high/0.8, medium/0.6, low-medium/0.4, low/0.2, uncertain/0].

The numerical values used in the membership function, took in consideration an equal division of the 0-1 scale for the 5 discriminative linguistic terms of Hollnagel [10]. It should be noted that in fuzzy logic we could assume that “uncertain” is outside the fuzzy function (value 0) because we do not have any knowledge about its degree of belonging (i.e. it does not belong with any degree to the defined fuzzy set), while with probabilities this value would (in our view incorrectly) be 0.5.

After, defining the fuzzy set importance -scale we can determine the final importance/weight for each SB type using a simple averaging operator (by column) as depicted in Table 9. The calculation of the SB-Importance, or weight of each SB type is the first step to estimate SB’s effectiveness; the remaining steps to determine the SB effectiveness are described in section 3.3.

It should be noted that Hollnagel [10] evaluation included both Personal Protective Equipments (PPE) and collective protection devices in the physical type. However, these two types of equipment’s have significant differences regarding efficiency, availability and independence on humans – hence they should not have been included in the same group. The SB effectiveness-scale that we propose in the next section takes into account this aspect.

Determination of SB Effectiveness-Scale

After determining the relative importance of each SB type we will now define a linguistic variable to act as the scale for classifying the SB effectiveness. We start by

creating a linguistic variable with six terms that are represented by triangular membership functions in the interval [0, 1], as shown in Figure 1. The six terms will allow a more user-friendly elicitation of information from the involved stakeholders (e.g. workers, safety experts, managers, among others) because the checklists with the criteria and alternatives (SB types) will be answered semantically as: (a) “excellent” (corresponds to triangle range [0.8, 1.0] in Figure 1); (b) “very good” (Figure 1 range [0.6, 1.0]); (c) “good”, (Figure 1 range [0.4, 0.8]); (d) “partial” (Figure 1 range [0.2, 0.6]); (e) “insufficient” (Figure 1 range [0.0, 0.4]); (f) and “bad” (Figure 1 range [0.0, 0.2]).

To simplify the rating and calculation process we now discretize this linguistic variable, by using a simple discretization method proposed by Chen and Hwang as presented in Marques [43,44]. Furthermore, information loss resulting from this discretization will not significantly affect the evaluation result as shown by Chen and Hwang [43]. The discretization process for the linguistic variable (Figure 1) is explained below.

The discretization process starts by considering two fuzzy linear functions, a maximizing one $m_{\max}(x)$ (see red line on figure) and a minimizing one $m_{\min}(x)$ (see red dotted line on figure). Second, we determine the values of the intersection of the left side of each linguistic term with the minimizer and the right side of each linguistic variable term with the maximizer, such as:

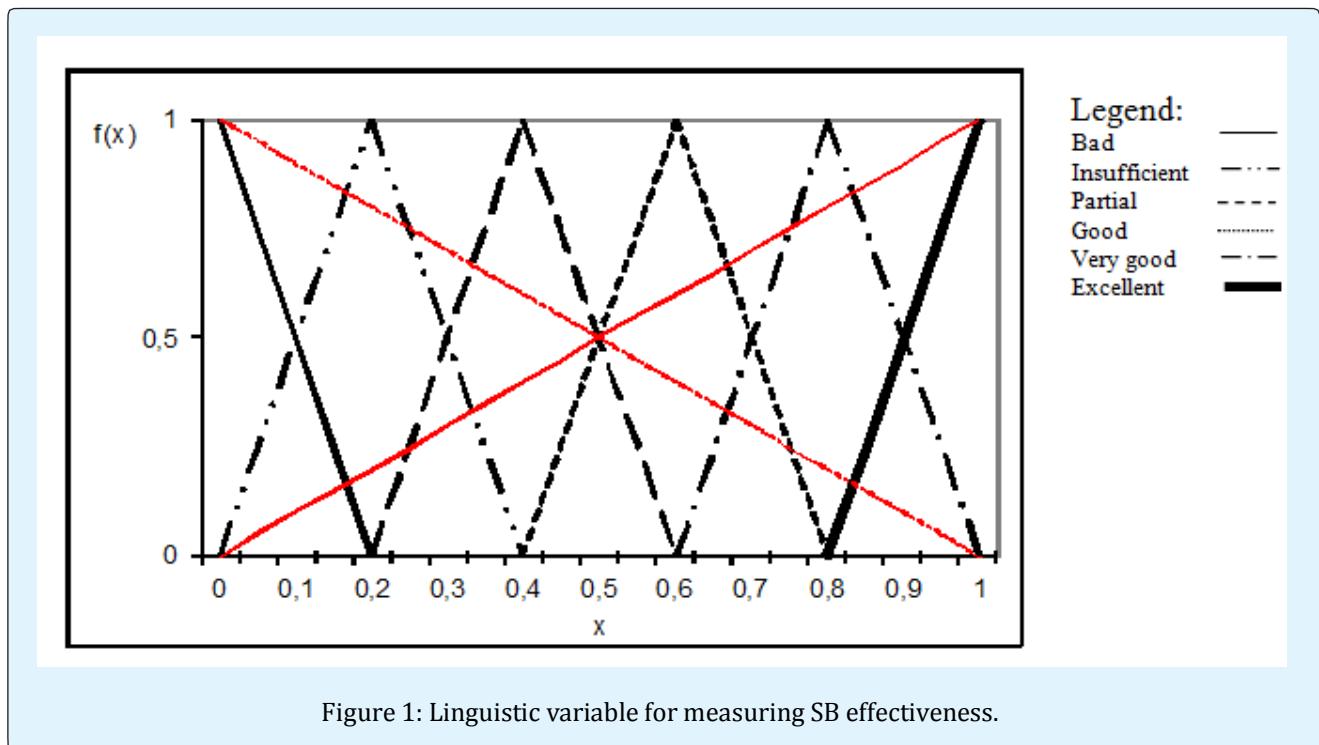
$$\mu_E(A) = \sup_x [\mu_A(x) \wedge \mu_{\min}(x)] \quad (2) \text{ and}$$

$$\mu_D(A) = \sup_x [\mu_A(x) \wedge \mu_{\max}(x)]$$

And, finally, the membership grade for each linguistic term (T) is obtained through the expression:

$$\mu_T(A) = [\mu_D(A) + 1 - \mu_E(A)] / 2 \quad (3)$$

After these calculations we can now propose a discrete “SB-effectiveness-scale” to be used in our tool, as shown in Table 10.



Semantic term	Meaning	Membership grade (μ)
Excellent	The BS is adequate to the risk, is well built and works effectively, in a very reliable way (takes into account workers expected bad practices) and is robust.	0.94
Very good	The BS is adequate to the risk, is well built and works effectively, in a very reliable way (takes into account workers expected bad practices) and is robust, but is intrusive or requires important resources to implement and/or maintain.	0.78
Good	The BS is adequate to the risk, is well built and works effectively, in a very reliable way (takes into account workers expected bad practices) but its robustness are not assured in some extreme events (e.g., fire).	0.56
Partial	The BS is not effective enough or there are doubts about its reliability (e.g. depends on humans in order to achieve its purpose).	0.41
Insufficient	The BS did not perform always as expected or permits short comings that could make it	0.21

	unreliable.	
Bad	The BS is ineffective (do not achieve its purpose) or could have a counter-effect (increased risk in some way or creates new risks).	0.06

Table 10: "SB-Effectiveness-scale".

Observing Table 10 we see on the left the semantic terms to be used during the elicitation process by the analysts. On the center we see a description with the meaning of each term in the SB context (this explanation serves as guide for the analysts and can also be explained to the workers involved). Finally the right column includes the numerical scale that will be used in the calculation process to estimate the SB effectiveness.

As noted in section 3.2, there is a difference in effectiveness between PPEs and collective protection equipment and our proposed measure reflects this fact. Since PPEs depends on humans to achieve its purpose (and only offers limited protection to a part of the body of one worker), its maximum effectiveness will be classified as "partial" (never reach the "excellent", "very good" or "good" levels). By the same reason (dependence on humans), work instructions and procedures, training, signalization, alarms, or more generally, for all symbolic barriers type the maximum effectiveness should be "partial". Between "excellent" and "very good" there is no difference with regard (directly) to safety, the difference lies on resources efficiency and intrusiveness to the production process. An efficient and not intrusive SB have better acceptance at all organization levels.

In the next section we explain the process to obtain the estimation for SB system effectiveness, using the two determined measures: the relative importance of each SB (Table 9) and the SB-effectiveness-scale (Table 10).

Estimation of SB effectiveness

For obtaining an evaluation for any SB system the safety experts should follow the sequence of the possible chain of events, either by starting with the accident modes and going backwards or starting in the hazard and look forward to the probable work accident.

In general, for each accident mode, the analysis should be guided with questions such as:

- What technical mean could prevent work accident mode X and in what circumstances? And how?
- What human action could prevent work accident mode X and in what circumstances? And how?

- What organisational routine could prevent work accident mode X and in what circumstances? And how?
- Are there any legal or other requirements applicable to it?

To answer these questions, the analyst should check key points, namely: (1) SB design – including interfaces and work modifications required, (2) checking/supervision of construction and installation, (3) human factors of SB operation and maintenance – availability, commitment and competence of personnel, (4) inspections and maintenance programs, (5) supervision of maintenance tasks, (6) SBs management – including communication and coordination, conflict resolution and the existence of spares (when required) and, (7) risks review (including the SBs). Whose data can be obtained by direct observation and analysis of documents such as: a) SB project, b) accidents and incidents research reports, c) inspections and maintenance programs and reports, etc.

In this article we do not present more details about defining a checklist with questions to obtain the classifications for effectiveness of SB because our focus is on defining a tool for estimating SB effectiveness. Our proposed tool can be used with any type of checklist.

To obtain the estimate of the SB system effectiveness, we need to aggregate the analysts classifications for each SB type using the previous scale. However, the choice of aggregation operator is a difficult task since it is a context-based question.

Aggregation operations on fuzzy sets are operations by which several fuzzy sets are combined in some way to produce a single representative either fuzzy or crisp set [45]. There is no simple rule to choose the adequate operator among the existing variety, but Zimmerman [46] pointed eight important criteria that can be helpful to select the appropriate operator, namely: axiomatic strength, empirical fit, adaptability, numerical efficiency, compensation, range of compensation, aggregating behavior and required scale level of membership functions. Beliakov and Warren [47] added another criteria: semantical clarity.

In occupational safety risk assessment little is known about how the factors should be fuzzified and aggregated. Safety experts provide their perceptions about the behavior of the model and the corresponding empirical data by considering practical cases. Due to the absence of set-theoretical criteria, the aggregation operator was chosen using what seem to be the most adequate qualities for risk assessment: (1) empirical fitness; (2) adaptability; and (3) semantic clarity.

The reasoning used for SB regarding these qualities is:

- Empirical fitness - The value 1 (one) corresponds to a very high risky situations (or to a factors that may cause these situations) and the value 0 (zero) corresponds to an absence of risk (or to a factors that may cause these situations);
- Adaptability - The aggregation of the membership degrees of the various factors should generate a synergistic effect (positive or negative, according

the case). In our case we need a union operator (positive synergetic effect) to ensure that the more barriers the less risk we have;

- Semantic clarity - The result should allow to discriminate the factors that have contributed most negatively in terms of SB risk protection.

Using the above quality criteria and corresponding reasoning for SBs, we know that we need an operator from the class of "Union" (OR) because we want a synergistic positive effect. The positive synergy allows us to express the added value of having more than 1 SB type in construction sites, i.e. if we have 2 SB their "sum" should be bigger than the simple arithmetic sum. From the most known union operators we tested the following: Max, Yager, Dubois&Prade, Hamacher and Fuzzy-Or [46] (Table 11). In fact, multiple SB works like a set of layers whose result is always better than the worst barrier.

So, observing Table 11 it is clear that:

Cases	SB Effectiveness				Aggregation operators				
	Physical	Functional	Symbolic	Incorporeal	Yager	Dubois Prade	Hamacher	Fuzzy-Or	Max
1	Excellent /0.94	Excellent /0.94	Excellent /0.94	Excellent /0.94	1.00	1.00	1.00	0.94	0.94
2	Very good /0.78	Very good /0.78	Very good /0.78	Very good /0.78	1.00	0.98	1.00	0.78	0.78
3	Bad/0.06	Bad/0.06	Bad/0.06	Bad/0.06	0.24	0.06	0.22	0.06	0.06
4	Good/0.56	Good/0.56	Good/0.56	Good/0.56	1.00	0.70	0.96	0.56	0.56
5	Partial/0.41	Partial/0.41	Partial/0.41	Partial/0.41	1.00	0.41	0.88	0.41	0.41
6	Partial/0.41	Partial/0.41	Bad/0.06	Bad/0.06	0.94	0.41	0.69	0.41	0.41
7	Good/0.56	Good/0.56	Bad/0.06	Bad/0.06	1.00	0.61	0.83	0.56	0.56
8	Excellent /0.94	Excellent /0.94	Bad/0.06	Bad/0.06	1.00	0.99	1.00	0.94	0.94
9	Excellent /0.94	Bad/0.06	Bad/0.06	Bad/0.06	1.00	0.94	0.95	0.94	1.00

Table 11: Aggregation results.

1. The Yager operator does not fit because it is not sufficiently discriminative (e.g. only cases 3 and 6 have aggregated effectiveness levels different from 1!);
2. The Max and the Fuzzy-or operators do not display any synergetic effect, i.e. it always chooses the highest classification achieved for all 4 cases disregarding any compensation for having more than one with good classification;
3. If all the SB are "excellent" , the result should be higher than the average of a MAX . Yager, Dubois&Prade and Hamacher operators fit this empirical knowledge (case 1= 1);
4. If all barriers are "bad", the result should be "insufficient" but should encompass the added

value (synergetic effect) because a set of four bad SB have a better performance than one single bad SB. In this case only the Hamacher operator fit this empirical knowledge (case 3= 0.22);

5. If the four barriers are “good”, the result should be “excellent” (though somewhat less excellent than four “excellent”). Again only the Hamacher operator fit the empirical knowledge (case 4=0.96);
6. If we have two barriers “partial” and two barriers “bad”, the result should be “good” due to the synergistic effect of this combination of SB working together, resulting in a “good” performance. In this case only the Hamacher operator fit (case 6 = 0.69), since Yager results in “excellent” (0.94) and the others result in “partial” (0.41);
7. If we have two barriers “excellent” and two barriers “bad”, the result should continue to be “excellent” but with a slight added reward (synergistic effect of two “excellent” SB) . Yager and Hamacher operator fit this requirement (case 8 =1);
8. If we have one barrier “excellent” and three barriers “bad”, the result should still be “excellent” but with a lesser degree because the safety level - related to the risk- decreases, i.e. in this case the result should be somewhat less excellent than the previous one (point 7). Dubois & Prade, Hamacher and Fuzzy-OR operators fit this empirical knowledge and present an adequate discriminative effect (0.94 and 0.95 in case 9).

From the observations made on points 1-8 above, it is clear that Hammacher union operator is the one that best answers the quality criteria for SB effectiveness estimation and, consequently, the one selected for our tool.

Formally, the Hammacher-OR operator is:

$$\mu_{A\gamma B}(\mu_{A(x)}, \mu_{B(x)}) = \frac{(1-\gamma)\mu_A \cdot \mu_B + \mu_A + \mu_B}{1 + \gamma \cdot \mu_A \cdot \mu_B}$$

$$x \in X, \gamma \in [-1, +\infty]$$
(4)

However, since we also need to incorporate the relative importance for each SB type, as described in section 3.2., we selected the version with relative importance weighting, such as:

$$\mu_{A\gamma B}(\mu_{A(x)}, \mu_{B(x)}) = \frac{(1-\gamma)w_A\mu_A \cdot w_B\mu_B + w_A\mu_A + w_B\mu_B}{1 + \gamma \cdot w_A\mu_A \cdot w_B\mu_B}$$

$$x \in X, \gamma \in [-1, +\infty]$$
(5)

4.8. Illustrative Examples of SB Effectiveness Tool Usage

In this section we will use a safety net example. Safety Nets are barrier systems because their effectiveness depends on the physical device and the riggers training, inspection and maintenance procedures. So, physical effectiveness is “excellent” if the net complies with EN 1263-1 standard and is mounted to cover all possible points of fall. If there are cheaper preventive techniques available (and to ensure the same level of effectiveness), effectiveness should be considered “very good”. If the site is located in a climate adverse place, e.g. snow and strong winds, its effectiveness should be “good” (because reliability may be compromised). If the net does not cover one spot (e.g. in a corner or a pillar...) or is fitted far away from the work position, effectiveness should be “partial”. If the safety net does not comply with any recognized and accepted standard (even if its robustness seems to be adequate) effectiveness should be “insufficient”. If the safety net possesses some defects (color changes, broken wires or ropes...) effectiveness should be “bad” (because robustness may be compromised).

If the safety net rigging is carried out by riggers who are fully qualified and are inspected and systematically maintained, symbolic effectiveness should be “partial”. If the safety net is not inspected or systematically maintained, within appropriate intervals symbolic effectiveness should be “insufficient”. If the safety net rigging are carried out by riggers who are not qualified symbolic effectiveness should be “bad”.

Now considering an illustrative example with two SB types, a physical one and a symbolic one, and by direct observation the analyst classified the 2 SB, as depicted in table 12. Then using the respective relative importance/weights (from Table 9 and reproduced in Table 12) and the selected weighted Hammacher operator (equation 5) with a parameter, $\gamma = 0.98$ the result for the SB effectiveness estimation is

$$SB\ Effectiveness = \frac{(1 - 0.98) * 0.75 * 0.94 * 0.45 * 0.41 + 0.75 * 0.94 + 0.45 * 0.41}{1 + 0.98 * 0.75 * 0.94 * 0.45 * 0.41}$$

$$SB\ Effectiveness = 0.79.$$

Since this SB system is the “sum” (aggregation) of two safety barriers that contribute to mitigate the same risk, one excellent and important and one partial and less important, the effectiveness result is “very good” = 0.79. This result matched the conservative empiric expert knowledge of the analyst.

SB Type	Analyst Assessment (Semantic term) and respective grade	Analyst choice justification
Physical (weight=0.75)	Excellent/0.94	The net complies with EN 1263-1 standard and is mounted to cover all possible points of fall and there aren't cheaper preventive techniques available that ensure the same level of effectiveness
Symbolic (weight=0.45)	Partial/0.41	The safety net rigging is carried out by riggers who are fully qualified and are inspected and systematically maintained

Table 12: Illustrative example of SB effectiveness for Safety Nets.

Now, let us considering another example, the use of safety helmets to protect against falling objects, which is also a barrier system. If the physical device complies with EN397:1995 standard (or other similar), is in good condition, is suitable for the workplace and can be adapted to the users morphology, so physical effectiveness should be "partial". If the helmet has small defects such as: color changes, small changes in structure (small holes for ventilation, for example), paintings (names or something else), stickers (some manufacturers advise against), etc or is not suitable for the workplace or can't be adapted to the users morphology effectiveness should be "insufficient". If the helmet does not comply with EN397:1995 standard (or other similar) or has defects such as fissures effectiveness should be "bad". If workers had training and know how properly use, inspect, maintain and clean

and there is a procedure for the proper PPEs management symbolic effectiveness should be "partial". If workers didn't inspect, maintain or clean the helmets regularly (but use them and had training) or the company don't manage PPEs properly (although a procedure) symbolic effectiveness should be "insufficient". If workers didn't had training or there are no procedure for PPEs management symbolic effectiveness should be "bad". **Table 13** depicts the classifications for this example, considering two similar "partial" classification of SB elements (0.41) but since they have different importance weights, when applying the expression 5 we obtain SB Effectiveness= 0.47, i.e. it is classified as a little better than a "partially safe" SB system. This result also matches the conservative empiric expert knowledge.

SB Type	Analyst decisions	
	Analyst Assessment (Semantic term) and respective grade	Analyst choice justification
Physical (weight 0.75)	Partial/0.41	The helmet complies with the EN397:1995 standard, is in good condition, is suitable for the workplace and can be adapted to the user morphology.
Symbolic (weight =0.45)	Partial/0.41	The user (worker) had training and know how properly use, inspect, maintain and clean and there is a procedure for the proper PPEs management.

Table 13: Illustrative example of SB effectiveness for Safety Helmets.

Another example of SB widely used at construction is the fall arrest system. Although it is a PPE that protects the entire body their effectiveness is not the same as an collective protective equipment. The use of this equipment carries the risk of orthostatic syndrome [48-49]. If all physical device (harness, ropes, lanyards,

shock absorbing...) complies with EN361 standard (or other similar), are in good condition, are suitable for the workplace, can be adapted to the users morphology and there are sufficient and robust anchor points to which workers could fasten their personal fall arrest equipment, so physical effectiveness should be "partial".

If the harness (or accessories) has small defects such as: color changes, small changes in structure geometry etc or is not suitable for the workplace effectiveness should be “insufficient”. If the harness (or accessories) does not comply with EN361 standard (or other similar) or has defects or there aren’t sufficient or robust anchor points to which workers could fasten their personal fall arrest equipment, effectiveness should be “bad”. If workers had training and know how properly use, inspect, maintain and clean and there is a procedure for the proper PPIs management and work at height, including emergency rescue, symbolic effectiveness should be “partial”.

If workers didn’t inspect, maintain or clean the equipment daily (but use them and had training) or the company don’t manage PPEs properly (although a procedure) symbolic effectiveness should be “insufficient”. If workers didn’t have training or there are no procedure for PPEs management or emergency rescue is nor assured, should symbolic effectiveness be “bad”.

Incorporeal barriers, such as legal requirements (or others), should be “excellent” if the company identify, access and apply legal or other requirements, keep this information up-to-date and communicates, timely, relevant information about these requirements to persons working under its control and other interested parties, in an efficient way. If the company doesn’t have an efficient procedure, incorporeal BS should be considered “very good” (because, could reach the same result with less resources). If the company identify, access and apply legal or other requirements, keep this information up-to-date but not communicate, timely, relevant information, effectiveness should be “good”. If the company identify, access and apply legal or other requirements, keep this information up-to-date but not communicates relevant information, effectiveness should be “partial”. If the company don’t identify, access

and apply legal or other requirements, keep this information up-to-date and communicates, timely, relevant information, timely and in a reliable way, effectiveness should be “insufficient”. If the company don’t identify or access or apply legal or other requirements or don’t keep this information up-to-date or not communicates, timely, relevant information effectiveness should be “bad”.

This model was tested by application on real sites and results “peer” review by a pool of 11 safety experts from Brezil (2), Greece (3), Portugal (2), Turkey (3) and Bulgaria (1). This way seems appropriate to evaluate the rationality of the framework structure and the adequacy to which the safety climate is scored. According to Habermas the rationality of science stems not from any objective, external measures, but from agreed formalisms involving transactions between knowledgeable human beings and agreement between them about what can be considered to be “rational”, given the base of available knowledge and experience.

In each of the referred countries, the model was first presented to the safety experts; the features and the rational underlying its development were explained. Second, the model was applied to real construction sites and the safety experts were requested to verify if the results correspond to their empirical knowledge, by a 5-point semantic Liker scale questionnaire (Strongly Approved, Approved, Undecided, Disapproved and Strongly Disapproved). Questionnaires were taken individually. In general experts agreed with the model results (63,6% Approve and 36,4% Undecided) and all have made comments, which are summarized in the table 4.

Despite the differences by their local environment and culture, there were no substantial differences in the pattern of responses of the construction safety experts from the different countries (and continents).

Country	Company data	Construction type	Construction brief description	Experts evaluation
Brazil	Private company with over 250 employees with a safety engineer on site.	Housing building	Building with eleven floors with concrete structure and masonry walls. When the evaluation was conducted, masonry work (on the upper floors) and specialized work (sewers, water and electricity	It is easy to apply but it is not intuitive. It needs some time to be well understood. UNDECIDED.

			supply) were ongoing. About fifty workers were on site.	
Brazil	Private company with less than 250 employees, with a part-time safety engineer (at the headquarters, had never visited the site).	School building	Ground floor building with concrete structure and masonry walls. When the evaluation was conducted, the masonry work was starting and the structure work was being concluded. Twenty-three workers were on site.	Allows estimating the SB effectiveness in a reliable way. APPROVED.
Greece	Private company with more than 250 employees, with a safety technician on site. When the evaluation was conducted were six sub contractors on site.	Housing building	Set of three buildings with four floors with concrete structure and masonry walls. When the evaluation was conducted, masonry work and conclude structure work (on one of the buildings) and specialty work (sewers, water and electricity supply) and finish works (painting, paving, carpentry) on the other two were ongoing. About seventy workers were on site.	The categorisation should be re-examined in terms of the legal requirements category. I do not think that this is clearly defined. It may be closely associated with other categories also. APPROVED..
Greece	Private company with more than 250 employees, with a safety engineer at headquarters that goes to the site when requested. When the evaluation was conducted was one sub	Housing building	Rebuild of a building with five floors with concrete structure and masonry walls. When the evaluation was conducted, finish works (painting, paving, carpentry), works on the roof (traditional roof with slope and tile coverage) and painting of the facades were ongoing. Seventeen workers were on site.	The categories in which safety barriers are distinguished should be re-examined with a clear distinction between them. Further research should be made in the bibliography to check the categorisation of safety barriers. Besides, legal requirements are present in all categories of safety barriers. It needs a more clear

	contractor on site.			distinction of the categories of safety barriers. UNDECIDED.
Greece	Private company with less than 250 employees, with a part-time safety technician (at the headquarters, had never visited the site).	Housing building	Building with two floors with concrete structure and masonry walls and garden. When the evaluation was conducted, works on the roof (traditional roof with slope and tile coverage), painting works (inside and outside) and modulation of the ground in the garden were ongoing. Twelve workers were on site.	Cat. confusing and incomplete. I would consider safety barriers as layers of immediate (physical, mechanical etc.), basic (procedures, training, signs) and underlying (mgt commitment, organizational arrangements) measures, and I would not incorporate h&s legislation in these since this can be taken into account in all types of measures as minimum requirements. UNDECIDED.
Turkey	Private company with more than 250 employees, with a safety technician at headquarters that goes to the site when requested (in this construction step). When the evaluation was conducted was one sub	Housing building	Building with nine floors with concrete structure and masonry walls. When the evaluation was conducted, only excavation works were ongoing. Eleven workers were on site.	The categories of safety barriers should be clear so as not to be repeated (for example, legal requirements coincide with physical safety barriers in many cases). UNDECIDED.

	contractor on site.			
Turkey	Private company with less than 250 employees, with a safety technician on site. When the evaluation was conducted were two sub contractors on site.	Services building	Building with ten floors with concrete structure and masonry walls. When the evaluation was conducted, masonry work (on the ground floors and basement), specialty work (communications and electricity supply) and finish works (painting, paving, carpentry) were ongoing. About one hundred workers were on site.	This categorization could be confusing in construction industry and if safety technicians don't understand well the methodology; this could affect the quality of the results. APPROVED.
Turkey	Private company with more than 250 employees, with a safety technician on site (watched several spots along the construction).	Highway	Construction of a highway with four lanes, in a plain ground. When the evaluation was conducted, works of grading and compaction of the ground were ongoing. Seven workers were on the visited spot.	The categories in which safety barriers are divided are not incorrect but are not intuitive. It is needed a more clear distinction of the safety barriers categories. APPROVED.
Portugal	Private company with more than 250 employees, with a safety technician at headquarters that goes to the site when requested. The site had a safety coordinator. When the evaluation was	Hotel building	Rebuild of a building with five floors with resistant stone walls and wooden floors and construction of a new building with four floors with concrete structure and masonry walls. When the evaluation was conducted, works of installation of plasterboard partitions and specialty work (sewers, water and electricity supply) and finish works (painting, paving, carpentry), in the old building and	Allows estimating the SB effectiveness in a reliable way but only by experienced safety technicians on construction industry. APPROVED.

	conducted were five sub contractors on site.		masonry works on the new building were ongoing. About fifty workers were on site.	
Portugal	Private company with more than 250 employees, with a safety technician on site (watched several spots along the construction).	Apartment remodeling	Remodeling the interior of a luxurious apartment, located in central Lisbon. When the evaluation was carried out, 2 plasterers and 4 painters was working, headed by a foreman.	The safety barriers division categories are not easy to understand. APPROVED.
Bulgaria	Private company with less than 250 employees, with a safety technician at headquarters that goes to the site when requested.	Housing building	Building with five floors with concrete structure and masonry walls, built on the riverbank (on cliff). When the evaluation was conducted, finish works (painting, paving, carpentry) were ongoing and the roof (traditional roof with slope and tile coverage) was being concluded. About thirty workers were on site.	The safety barriers division should be clearer. It is not easy to understand. Seems that more applied investigation is needed. APPROVED.

Table 14: Summary of the expert's opinions.

The main causes of criticism are about the SB division. Some of the experts consider the categorization confusing and incomplete and stated that should be re-examined to make a clear distinction between types and they consider that legal requirements are present in all categories of safety barriers. They suggested to consider safety barriers as layers of: immediate (physical, mechanical etc.), basic (procedures, training, signs) and underlying measures (management commitment, organizational arrangements), and should not incorporate H&S legislation since this can be taken into account in all types of measures as minimum requirements. This criticism seems to be rooted in the difficult intuitiveness of the proposed division. When well understand this division in the most appropriate to use on construction industry.

The main advantages pointed by the safety experts were the linguistic scale measurement and the calculation process because it is intuitive, user-friendly and quick to apply.

Conclusion

In this work we presented a versatile tool for estimating the SB effectiveness in construction sites. The proposed tool is based on fuzzy ratings to assess the features than can affect the SB effectiveness by addressing the following attributes (1) Efficiency, (2) Resources needed (3) Robustness (reliability), (4) Availability, and, (5) Independence on humans (during operation).

The fuzzy approach seems quite suitable to deal with the vagueness and imprecision that is ever present in an SB effectiveness estimation and allows to mimic human decision making.

The advantages of the proposed tool are:

- Supports proactive estimates by identifying effective, adequate, efficient, reliable and robust features.
- Uses the useful four types of SB proposed by Hollnagel and enumerate the criteria to be used for the assessment of their effectiveness.
- Both technical and organizational SB, formal and informal, can be analysed in a uniformly way.
- The tool is easy to understand for safety practitioners and construction technical personnel because it uses semantic evaluations such as “very good”, etc. This understanding is important because it facilitates discussions about SB design problems and potential improvements.

Disadvantages are:

- The SB division on 4 types could, in some contexts, be confused for safety practitioners (example, if there is a legal requirement to put a physical barrier, is this a physical or a incorporeal barrier?),
- The diversity of possible SB makes it difficult to consider all types of accident modes; hence we opted for using a general framework.
- The method only gives an estimate of effectiveness and does not provide recommendations to improve SB design.

In summary, we believe that the proposed tool may reduce the subjectivity in assessing SB effectiveness by estimating their ability to achieve their purpose, ie., how well they can withstand the variability of the environment and not lead to accidents. Moreover, we presented illustrative examples to better clarify the usage of the proposed tool and how to interpret the results. In addition, since our proposed tool is quite versatile and adaptable, we believe it contributes to advances in determining the quality of the overall occupational risk assessment in construction sites.

Finally, the presented tool was developed for construction industry, however, with some minor adaptations, may also be applied in other industries (e.g., process industry).

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