sustainability

MDPI

Article

An Alternative Evaluation and Indicating Methodology for Sustainable Fire Safety in the Process Industry

Dorota Brzezińska *, Paul Bryant and Adam S. Markowski

Faculty of Process and Environmental Engineering, Lodz University of Technology, 90-924 Lodz, Poland
* Correspondence: dorota.brzezinska@p.lodz.pl

Received: 12 July 2019; Accepted: 22 August 2019; Published: 28 August 2019

Abstract: There is a mismatch between the desire to introduce greater levels of sustainability in engineering design and in the need to provide effective engineering solutions, particularly where issues of human safety and asset protection are involved. Sustainability engineering typically incorporates economic, environmental, and social factors, all of which are highly relevant and applicable to fire safety and the design of fire protection systems. The term fire strategy denotes a documented methodology to encapsulate a full range of such systems, within a single framework, for more complex risks such as those found in the process industry. The subject of fire safety is emotive and its application within building design may not change unless we refocus on a holistic and strategic approach, especially for complex building profiles. Fire is a recognized critical safety issue for most types of industrial plants. Due to the complexity of the processes, even a relatively small fire accident can lead to a chain of events that could be devastating, resulting in huge asset and continuity losses, damage to the local environment, and of course, the threat to life. More complex processes require a more flexible and relevant approach. The use of fire safety engineering and performance-based evaluation techniques, instead of prescriptive rules, continues to grow in prominence because of this. This is the case when specifying fire protection and safety for modern power generating plants. However, when it comes to critical infrastructure, such as is the case with power plants, it is sometimes not clear whether optimum fire safety engineering solutions have been applied. One of the ideas specifically developed for evaluating the most appropriate fire safety strategies and systems, especially for such infrastructure examples, is a method based upon the British Standard Specification PAS 911. This method is captured in a diagram and identifies eight main elements for fire safety and protection. The idea presented in this article is to allow assessment of a submitted actual fire strategy for a building or other form of infrastructure, against what has been predetermined as a standard baseline fire strategy for, in this case, a power plant building. The assessment makes use of a multi-level questionnaire, in this case specifically formulated for power plant fire safety needs. By comparing the actual fire strategy diagram against a baseline fire strategy, enforcement agencies, or other interested stakeholders, can recognize which fire safety factors play the most important part in the fire strategy, and determine whether proper levels of fire safety and protection have been applied. The fire strategy evaluation is realized by a team of engineers, which consists of independent fire strategist from a consultant office, internal fire and technical experts from the industrial plant, such as the person responsible for fire safety, person responsible for explosion safety, person responsible for housekeeping, and building manager. Additionally, there should be representatives of insurance companies and independent fire experts. Typically, the group consists of 7 to 12 people.

Keywords: sustainability; sustainable fire engineering; power plant safety; fire strategy; fire protection; fire safety

1. Introduction

Sustainability engineers have identified that there is a fundamental conflict between sustainable building design strategies [1] and current fire safety engineering methodologies. In the 1990s, the term *sustainable* was identified with environmental protection. Today, sustainability means much more and combines economic, environmental, and social factors, which are also highly relevant and fundamental for fire protection engineering. A fire strategy for a building or industrial plant has to take into account fire growth phenomena, human behavior, mitigating factors, control measures, and the involvement and reaction due to, and with, the environment. However, fire engineering typically demands that building spaces be compartmented in order to limit the spread of fire and smoke. Some forms of fire extinguishing media can be environmentally damaging yet continue to be specified. Even the use of water to fight fires can often lead to adverse local environmental consequences due to the runoff [1]. Consequently, there is a need to rethink the fire engineering process and apply a more holistic and strategic approach to the evaluation of fire safety engineering. This is particularly the case when we analyze more complex building profiles. Let us use the example of the industrial plant.

Industrial process plants face a range of critical safety issues, one of which is the consequence of a fire. Even a relatively small fire incident within such an environment can potentially result in uncontrolled fire propagation and a resultant *domino effect*, which can subsequently lead to huge property and process continuity losses and potential damage to the local environment [2]. This is in addition to the threat to life. Appropriate levels of fire safety and protection is therefore of fundamental concern for such forms of infrastructure. Fire accidents regularly occur in the process sector, with severe consequences to life, property, business, and the environment [3]. Focused consideration of loss prevention and safety in the process industries began actively in 1971 when the symposium 'Major Loss Prevention in the Process Industries' was organized for the first time. Since this time, industrial engineers, consultants, and scientists continuously strive to improve the process of safety performance [4]. However, the complexity and variation in industrial plants makes it difficult to impose generic fire protection rules or regulations. This creates the necessity to utilize more flexible, performance-based standards together with sophisticated fire safety engineering methodologies. Moreover, the innovation very often leads to new processes, introducing new potential hazards and continues the need for further research and development [5]. As revealed by recent high-profile accidents, fire risk also represents a noteworthy factor in the maritime transport sector. This has led to the development of a consequence-based framework incorporating elements such as impact, hazardous distance, and reaction time scale [6].

Fire safety engineering is recognized as a unique branch of engineering [7]. Whereas other engineering disciplines make use of known laws, fire safety engineering is rarely absolute in its science and application, especially in very complex buildings of industrial power plants. Traditionally, a strongly prescriptive approach has been applied to the fire safety and protection requirements of many types of building profiles, such as power generating plant buildings, as contained within the standards applied [8]. Furthermore, given that a typical power plant arrangement consists of a variety of building profiles and their associated risks, a range of fire safety and protection systems may be found to cater to this variation in risk profiles [9,10]. However, such a highly prescriptive approach has often restricted advances in building design [11] and may not be appropriate for ever more complex arrangements as is being seen in the development of modern power station arrangements, and with the increasing range of fuels used.

The general concepts behind a performance-based approach were introduced in the 1970s and onwards, to allow greater flexibility in the design and application of fire safety and protection systems. From the 1990s, standards were introduced to provide guidance regarding the application of a performance-based approach. The relevant standard introduced by BSI is the British Standard Specification PAS 911 [12]. This document was designed to provide a methodology for the preparation of fire strategies, whether they used prescriptive standards or a performance-based approach. It does not, in itself, give recommendations or requirements for the fire safety design of, for example, power plant buildings. What it does aim to do is to provide a consistent platform for fire strategies, such that they will follow a consistent format, whatever the building type is, and wherever the building is located [13,14].

With so much in the way of standardization and guidance in place, it could be considered that the fire safety community, as well as all relevant stakeholders, are well served. Many in the fire community do not believe that this is the case. A performance-based building regulatory system puts added responsibility on fire protection engineers, as they are generally expected to demonstrate that the proposed fire safety design solution satisfies the performance objectives [15–24]. There is another aspect, and that is the cost-benefit assessment of the impact and quantitative comparison of fire protection system designs systems [25,26]. This is a factor that should be considered in all fire strategies. The fire can be an outcome of an increasing array of threats. Despite this, many fire strategies still tend not to include a proper analysis of threats at the early project stages. Terms such as "extreme events are not considered" are still commonplace in many current fire strategies. Many others may not state this, but it will be implicit in the strategy's formulation. In fact, many fire standards have historically been written on the basis that only one distinct part of a building will succumb to a fire at any one time [26]. This may be the case for the vast majority of fires around the world. A properly considered threat analysis as part of the strategy evaluation may identify issues that could be probable and may have been missed without such an analysis [25].

Compliance with national regulations and standards is still seen as the key objective for most fire strategies. These standards have mostly evolved on the basis of human safety of the building's occupants. They rarely adequately address issues such as property and asset protection, business continuity, and the protection of the environment against fire, and the impact of fighting fires. With a changing world where these issues are becoming much more important, limited objectives setting is often an opportunity wasted. The British standard [12] identifies the potential for sixteen sub-objectives, four for each of the main objectives of human safety, property/asset protection, business continuity/protection, and protection of the environment. It is proposed that every fire strategy, when determining the objectives for the building, considers each of these points. As an example, it may be found that the firefighting of a major building fire could lead to firefighting water polluting local ecosystems, especially when the materials used or stored in the building could allow release of hazardous chemicals. With the increasing global appetite for litigation of those causing environmental damage, a solution to this possibility could be included within the fire strategy [7].

Accepting that there are many different methods used to assess fire risk, the authors observed that most of these methods could lead to a high degree of variability in approach and data access. One of the biggest limitations is a sparseness of reliable failure data, which is necessary for accurate risk calculation, as well as the lack of unified levels of risk acceptability, which very often precludes a credible risk assessment. Consequently, it was found that a complex fire risk assessment process can be replaced with any much simpler fire risk index method such as, for example, the Gretener method or Dow's Fire and Explosion Index [27]. The Gretener method, originally developed in Switzerland for risk assessment by insurers, is used here as a basis for a novel assessment method of fire strategies [28,29]. It was deemed a relevant method, in that it uses empirical figures, estimated individually for the building, based on the level of its fire protection, instead of theoretical numbers of failure, used in traditional risk calculation. The presented method also uses current fire engineering analysis ideas, for demonstration of the level of fire protection against a baseline fire strategy. The common example of such analysis can be found here using CFD calculations for smoke control systems evaluation.

It is highly recommended that the presented methodology of fire strategy evaluation is evaluated by a team of engineers, in order to reduce subjectivity.

The fire strategy evaluation should be undertaken by a team of engineering specialist stakeholders. This may consist of:

- Independent fire strategist consulting engineers,
- Internal fire and technical experts from the industrial plant,

- Persons responsible for fire safety including explosion risk,
- Persons responsible for housekeeping and building management,
- Representatives of the insurance company involved with the risk.

Typically, the group may consist of up to 12 people.

The methodology can be used both at the project stage of construction, or applied to existing infrastructure. This paper uses examples of the evaluation process, undertaken from 2017 to 2019, for two major Polish power stations:

- Polaniec Power Station in the East-South of Poland, which is a coal and biomass power station which consists of 8 units of 225 MW + one biomas unit "Green Block" of 205 MW;
- Dolna Odra Power Station in the North-West Poland, which is a coal power station which consists of 8 units of 232 MW.

During the validation workshops, the team of specialists (representatives of Lodz University of Technology, British fire experts and strategists, a team of Polish insurers from PZU Lab Sp z o.o. and the main risk and fire engineers from the power stations) were using the list of questions, segmented for specific fire safety factors, as presented in Tables 1 and 2. The calculus for fire risk index calculations, is given in Equations (1)–(5).

Table 1. Fire safety factors for a fire strategy.

Layer of Fire Protection	Fire Safety Factor (FSF)	Symbol	Score
Fire prevention and fire spread limitation	1. Organization and Management [ORG]	ORG	0–25
	2. Control of ignition sources and combustible materials [LIM]	LIM	0–25
Fire protection measures	3. Fire and smoke spread limitation—Passive systems [PAS]	PAS	0–25
	4. Detection and alarm communication [DET]	DET	0–25
	5. Fire suppression [SUP]	SUP	0–25
	6. Smoke control and evacuation [SC]	SC	0–25
	7. Maintenance of fire precautions and systems [MAI	MAI	0–25
Firefighting	8. Fire services intervention [FB]	FB	0–25

Table 2. Detailed questions for the fire strategy safety factors scoring method.

1. Organization and Management	**Score Scale**
1. Have internal procedures/instructions been implemented, which take into account the specific requirements for power plant facilities? For example: general instructions regarding the scope of fire safety management organization, procedures for hazardous work, fire safety instructions, explosion protection documentation, the rules concerning the operation of equipment and installations in case of fire,	0 ÷ 5
2. Are emergency and evacuation drills regularly conducted in line with emergency plans? Do fire and rescue service operatives participate in the exercises? How often are fire scenario drills conducted?	0 ÷ 4
3. Are systematic periodic and documented fire safety inspections carried out on facilities/grounds/areas as well as equipment, installations and fire safety and protection infrastructure and safeguards against disasters?	0 ÷ 4
4. Is round the clock protection of the power plant facilities operations ensured by its own or stationed on-site FRS (fire and rescue service)?	0 ÷ 6
5. Has an integrated system of coordination of all fire and explosion protection activities been implemented as well as for the scope of protection against disasters and local unspecified hazards?	0 ÷ 4
6. Is a fire fighting training program systematically conducted for company's staff? Have work conditions been established for external contractors with respect to fire and explosion protection?	0 ÷ 2
2. Control of Ignition Sources and Combustible Materials	**Score Scale**
1. Have procedures of flammable materials and industrial gases storage management been implemented?	0 ÷ 4
2. Have proper conditions been ensured for the storage and processing of fire-hazardous materials? For example: location, arrangement, fire load of a building/ground, access etc.	0 ÷ 4
3. Have organizational and technical measures been applied to reduce explosion hazards? For example: removal of accumulated dust, reduce emission of explosive agents, etc.	0 ÷ 4
4. Have possible ignition sources and other fire hazards been identified?	0 ÷ 3
5. Have proper detection systems been selected for the identified sources of ignition?	0 ÷ 5
6. Have appropriate ignition/explosion reduction systems been identified for the identified ignition sources?	0 ÷ 5
3. Fire and Smoke Spread Limitation—Passive Systems	**Score Scale**
1. Have the industrial buildings been properly divided into fire zones while observing their permissible size, which depends on: fire load, existence of explosive zones, status of automatic extinguishing and smoke ventilation systems?	0 ÷ 6
2. Has a strategy of fire compartmentation been used in the facility, adopting appropriate levels of fire resistance?	0 ÷ 5
3. Is the systematic monitoring of the condition of fire compartmentation carried out, for example, after repairs or alterations?	0 ÷ 4
4. Are periodic inspections of the condition of supporting passive fire protection installation carried out? For example: lightning connectors, vertical flues (e.g., chimneys), ventilation ductworks, etc.	0 ÷ 4
5. Is the process equipment fitted with devices ensuring limitation of fire/explosion spread?	0 ÷ 5
6. Are fire detection systems integrated with process system protection, especially taking into account domino effect possibilities?	0 ÷ 3
4. Detection and Alarm Communication	**Score Scale**
1. Have buildings/process systems been fitted with fully functioning fire detection and alarm system signaling to a central fire panel?	0 ÷ 6
2. Have the fire sensors been chosen to ensure optimum fire detection within the areas they are used?	0 ÷ 4
3. Does the arrangement of sensors comply with their specifications with regard to siting and spacing?	0 ÷ 4
4. Do detection circuit and communication cables have sufficient resilience against a fire and mechanical damage?	0 ÷ 3
5. Is the functionality of the fire detection and alarm system periodically checked against approved check-lists? Are records kept of this?	0 ÷ 5
6. Is the system and use of that system configured to minimize the impact of false alarms, equipment service point properly organized and equipped? Does the system require confirmation by local staff before contacting the fire brigade or is automatic coincidence-based fire detection used to communicate a fire without manual intervention?	0 ÷ 3

Table 2. *Cont.*

5. Fire Suppression	Score Scale
1. Are there fire water mains in place ensuring a sufficient and reliable supply of water (including reserve sources/intakes)? Have all requirements for the fire-water pump housings been met?	0 ÷ 5
2. Are all high risk facilities/process systems properly fitted with dedicated hydrant network? Is the hydrant network properly maintained?	0 ÷ 4
3. Are portable extinguishers properly arranged and labelled? Are extinguishers periodically inspected?	0 ÷ 2
4. Have localized fixed fire extinguishing devices and explosion protection systems been installed to protect specific risk areas? Are they designed and installed in accordance with established standards?	0 ÷ 4
5. Have systems been chosen to minimize delay in fire suppression and control?	0 ÷ 4
6. Will the choice and design of fire suppression systems ensure containment of a fire (and smoke) within a specific fire zone?	0 ÷ 6
6. Protection of Evacuation Routes (Smoke Control and Evacuation)	**Score Scale**
1. Have the required characteristics of escape routes and exits been implemented?	0 ÷ 6
2. Has it been ensured that staircases and lobbies are sufficiently fire separated from risk areas by walls of, say, at least 60 fire resistance?	0 ÷ 6
3. Are escape passages and exits labelled with safety signage complying with local standards? Have escape passages and exits been fitted with appropriate emergency escape lighting?	0 ÷ 4
4. Has the building been equipped with smoke and heat exhaust ventilation systems for horizontal escape routes to provide proper conditions for evacuation and for firefighting?	0 ÷ 3
5. Has the building been equipped with smoke and heat exhaust ventilation of staircases to provide proper conditions for evacuation and for firefighting?	0 ÷ 4
6. Are main spaces within the building covered by smoke and heat exhaust ventilation to provide proper conditions for evacuation and for firefighting together with structural protection?	0 ÷ 2
7. Maintenance of Fire Precautions and Systems	**Score Scale**
1. Has an inventory been taken, and criticality established, of fire protection and firefighting systems? This should also consider "EX"-rated devices, protection systems, and facilities to protect against environmental disasters and other local hazards, etc.	0 ÷ 4
2. Have the rules/procedures for regular maintenance and inspection of such systems been established?	0 ÷ 4
3. Are inspections, maintenance, repairs, and overhauls of fire protection equipment undertaken against the rules/procedures?	0 ÷ 4
4. Are there adequate documents and records confirming the maintenance regime is being properly attended to?	0 ÷ 3
5. Are support systems or methods to allow proper operation of these systems also regularly checked (e.g., room integrity testing for gaseous extinguishing systems)?	0 ÷ 6
6. Are changes in fire protection system design and arrangement recorded and monitored?	0 ÷ 4
8. Fire Services Intervention	**Score Scale**
1. Are awareness and skills of operational employees/staff sufficient to undertake or support firefighting and rescue operations?	0 ÷ 4
2. Is the arrangement and layout of facilities/installations conducive to fire-fighting and rescue operations? Considerations should include complexity of building layout, high-rise structures, availability of internal passageways, etc..	0 ÷ 4
3. What is the expected attendance time of the fire and rescue service: [s] (>900)/(>600, ≤900)/(>300, ≤600)/(≤300)?	0 ÷ 4
4. Is there a good internal fire-road network on any part of the site?	0 ÷ 3
5. Do facilities/installations have equipment to facilitate rescue operations: "dry risers", ladders, staircases to be used by firefighters, fire-proof staircase vestibules, cranes for rescue operations and other?	0 ÷ 4
6. Are there fire-fighting and rescue operations based on-site? Are they equipped with specialized equipment such as vehicles, special firefighting systems, etc.?	0 ÷ 6

Note that further validation meetings are planned in the Kozienice power station in the east of Poland, which includes a coal-fired thermal power station with one of Poland's tallest free standing structures, and two 200-m (660 ft) high flue gas stacks and consists of 8 units of 215 MW and 2 × 500 MW.

Holistic Fire Engineering

Holistic fire engineering (HFE) is an idea to cater to all the above concerns simultaneously. HFE does not seek to change fire science, or the application of fire engineering principles. What it does seek to do is:

- Provide a highly auditable framework, in which the key beneficiaries are represented by agencies around the world, worked in confidence of HFE based fire strategies.
- Provide a consistent approach and format, whether the power plant building design is based in different places of the world.
- Widen the scope of fire strategies to include threat assessment and objectives setting.

2. Fire Strategy Evaluation

The following method for fire strategy evaluation is originally based upon a British fire strategy methodology [7,13]. The method assumes scoring of eight fire safety factors and its presentation at the fire strategy value grid.

For each evaluated building (or its part, as for e.g., a fire zone), the methodology compares two fire strategies: the baseline strategy (default, based on the building risk profile or determined individually) and the actual strategy (real, realized for a new build project or for existing building). Figure 1 illustrates the flow chart of the evaluation sequence.

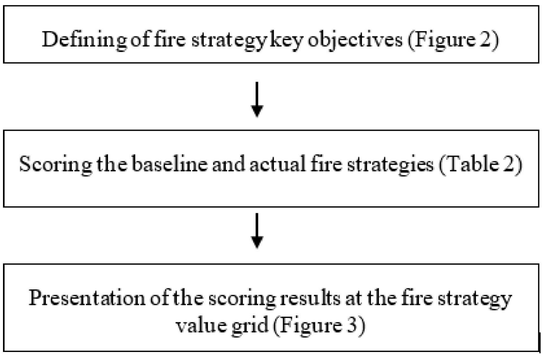

Figure 1. Fire strategy evaluation stages.

When reviewing the needs of the building, its owners, its occupants, and its processes, there may be a number of objectives relevant to the fire strategy. These may be over and above the requirements of the mandatory framework [13,14], which includes national legislation and fire safety codes. Figure 2 shows four key objectives which should be considered for a building fire strategy. Each of these objectives are broken down into four sub-objectives, what can be helpful in a more thorough objectives consideration.

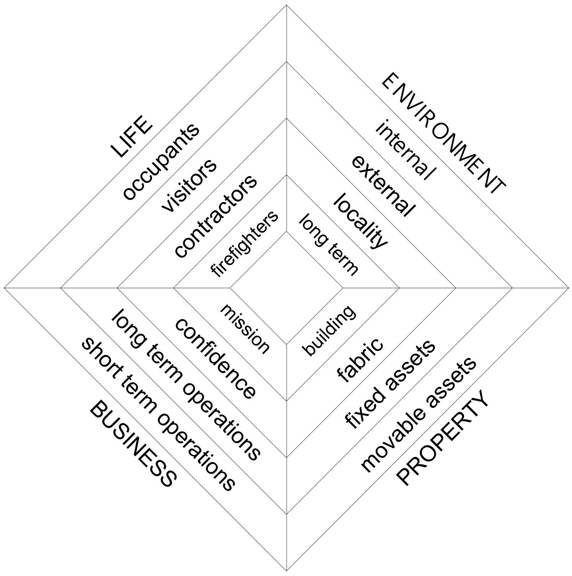

Figure 2. The fire strategy objectives matrix.

2.1. *Fire Safety Factors*

As mentioned earlier, the fire strategy is constructed of eight fire safety factors (FSF), which represent three fundamental layers of fire protection: fire prevention (including the organizational safety rules, ignition sources and combustible materials limitations), fire protection measures (compartmentation and using of automatic fire protection measures and systems) and fire service intervention. Each layer of fire protection is represented by appropriate fire safety factors. During the fire strategy evaluation process, the level (relevance) of each fire safety factor is scored from zero to twenty-five (Table 1). The scoring is realized separately for the baseline and the actual fire strategies and is helped with the special questions list [13,14].

2.2. *Baseline Fire Strategy*

The baseline fire strategy is the strategy which represents fire prevention and protection solutions acceptable as a minimum for the risk profile of a specific building type, or form of infrastructure. The suggested, default scores for baseline fire strategies, including consideration of the crucial fire strategy key objectives of life safety and property protection, are presented in Table 2.

2.3. *Actual Fire Strategy*

The actual fire strategy is the adopted or utilized strategy for a building project, or as applied for an existing building. The methodology requires the individual assessment and scoring of each fire safety factor, making use of typically the most relevant fire safety elements [13,14].

2.4. *Scoring of Fire Strategies*

In order to make all power plant fire strategies uniform, the building profile specific list of questions, representative for each of the fire safety factors were created and are presented in Table 2 [13,14].

2.5. *Fire Strategy Value Grid*

The fire strategy value grid is a spider diagram (radar graph) and presents all the fire safety factors scores together. The idea is to demonstrate the evaluation of actual fire strategy against the baseline one. This allows for very fast and easy assessment of the level for actual fire strategy and verifies which of the fire safety factors satisfy the requirements and which require additional protective measures. The strategy value grid diagram is shown in Figure 3 [13,14].

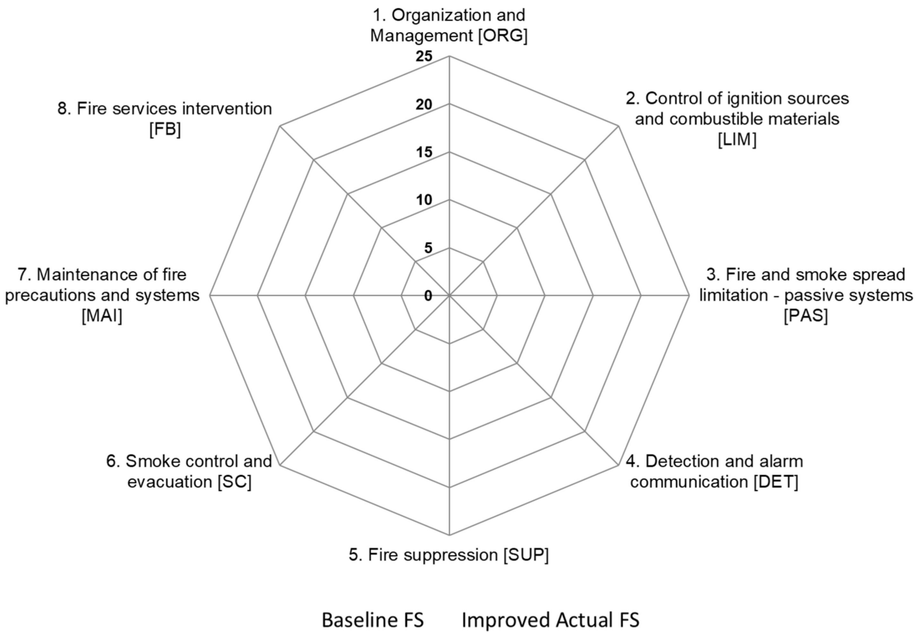

Figure 3. The fire strategy value grid.

2.6. Fire Risk Index Calculation

The last step of fire strategy evaluation—a fire risk index (FRI) calculation is based on the original Gretener method, where fire risk was assumed as a product of hazard severity and loss expectation represented by the fire frequency of ignition and here is presented in (Equation (1)) [13].

$$\text{Fire risk index (FRI)} = \text{Fire hazard index (FHI)} \cdot \text{Frequency of ignition (Fi)} \quad (1)$$

The hazard severity from Equation (1) is proportional to the potential hazard, reduced by protective measures (Equation (2)).

$$\text{Fire Hazard Index (FHI)} = \frac{\text{Potential Hazard (PH)}}{\text{Protective Measures (PM)}} \quad (2)$$

The original Gretener formula expressed empirically derived numerical factors for fire initiation and spread, with factors for fire protection. The idea used in the method presented here, is based upon the values achieved from scoring of each fire safety factor in accordance with Tables 3 and 4 for the baseline and actual strategies, respectively.

Table 3. Fire safety factors scores in Polaniec power plant turbine house fire strategy.

Layer of Fire Protection	Fire Safety Factor (FSF)	FS_{BAS}	FS_{AC} (Improved FS_{AC})
Fire prevention and fire spread limitation	1. Organization and Management [ORG]	20	20
	2. Control of ignition sources and combustible materials [LIM]	5	16
Fire protection measures	3. Fire and smoke spread limitation—passive systems [PAS]	15	9
	4. Detection and alarm communication [DET]	15	5 → (18)
	5. Fire suppression [SUP]	15	19
	6. Smoke control and evacuation [SC]	15	5
	7. Maintenance of fire precautions and systems [MAI]	15	21
Firefighting	8. Fire services intervention [FB]	15	15

Table 4. Fire risk index values for Polaniec turbine house fire strategy.

Parameter	FS_{BAS}	FS_{AC}
Potential Hazard (PH)	3.55	3.55
Protective Measures (PM)	3.55×10^2	3.18×10^2
Fire Hazard Index (FHI)	1.00	1.12
Frequency of ignition (Fi)	4.02	4.02
Fire Risk Index (FRI)	4.02	4.50

A total scoring for protective measures (PM) is obtained from the formula (Equation (3)) by aggregating the points obtained from the assessment of each fire safety factor adjusted by the appropriate.

$$PM = W_{ORG} \cdot E_{ORG} + W_{LIM} \cdot E_{LIM} + W_{PAS} \cdot E_{PAS} + W_{DET} \cdot E_{DET} + W_{SUP} \cdot E_{SUP} + W_{SC} \cdot E_{SC} + W_{MAI} \cdot E_{MAI} + W_{FB} \cdot E_{FB} \quad (3)$$

where:

E_{ORG}, E_{LIM}, E_{PAS}, E_{DET}, E_{SUP}, E_{SC}, E_{MAI}, E_{FB}—score of each fire safety factor,

W_{ORG}, W_{LIM}, W_{PAS}, W_{DET}, W_{SUP}, W_{SC}, W_{MAI}, W_{FB}—taken as 0.2 of point value for each baseline fire safety factor.

The value of the fire hazard index FHI, for both baseline and actual fire strategies, is to be calculated from the formula (Equation (4)).

$$FHI = \frac{PH}{PM} \cdot 100 \quad (4)$$

where:

FHI—fire hazard index,

PH—potential hazard,

PM—protective measures.

The potential hazard is applied, respectively, to the building risk profile [13].

The final step of the fire strategy assessment is the determination of the fire risk index from (Equation (5)).

$$\mathrm{FRI} = \mathrm{FHI} \cdot \mathrm{Fi} \quad (5)$$

where:

FRI—fire risk index,

FHI—fire hazard index,

Fi—frequency of ignition

Frequency of ignition value in the Equation (5) can be based on different statistical data, as for example PD-7974-7 [23].

3. Polaniec Power Plant Fire Strategy Evaluation

In order to facilitate an understanding of the methodology, an example of the fire strategy assessment was used on a Polish power generating plant. A workshop, entitled "Strategic Thinking", was conducted at the Polaniec Power Plant, from 26 to 30 July 2017 [30]. It provided an opportunity for exchanges of experience between participants, representing the scientific and insurance community, the operatives of the power plant, fire authorities, and other representatives of the energy industry.

Polaniec Power Plant Fire Strategy Value Grid

Table 3 illustrates an example of the fire strategy scoring, prepared for the turbine house of the Polaniec power plant in Poland. The baseline strategy design uses the "theoretical" values based on the scoring using the Polish fire regulations, whereas the actual strategy was based upon the evaluation of each of the fire safety elements currently found. Responses to the questionnaire are summarized in Table 3. The table presents sums of points, which were reached in the field of each fire safety factor. Because of limitation of the article size, the detailed list of points for each fire element is not presented here.

Values derived from scoring of each of the fire safety factors for both turbine house fire strategies (baseline strategy and actual strategy) listed in Table 3 are presented on a fire strategy value grid in Figure 4. The graphs of actual and baseline strategies allow for a quick and straightforward comparison of the main differences between the strategies.

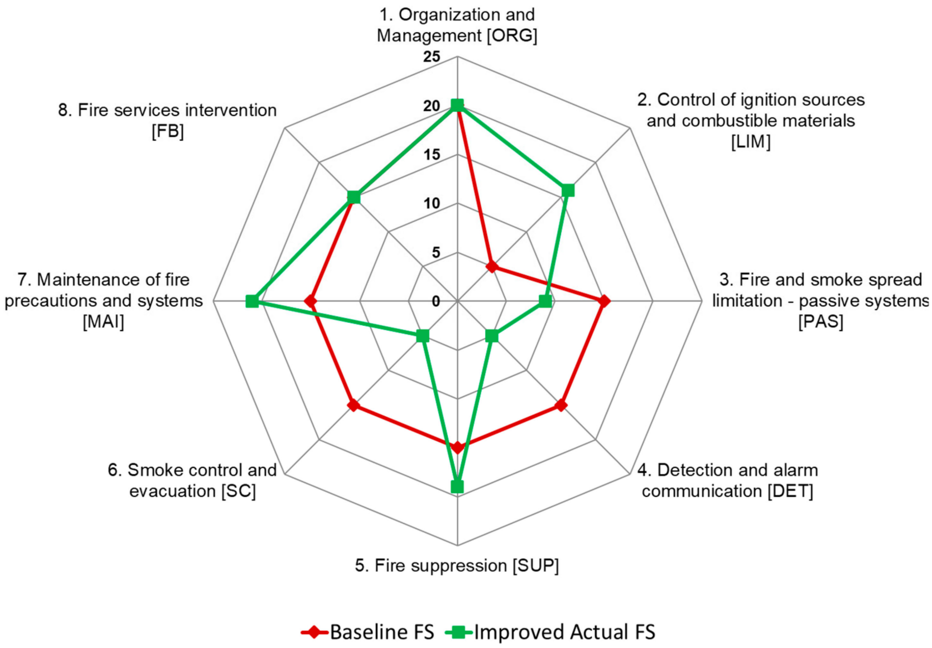

Figure 4. The fire strategy value grid for Polaniec turbine house.

The fire strategy value grid shows the differences between the actual fire safety and the optimum level as specified in the baseline strategy. It is noted that the organization and management of fire safety and protection meets with the expected level. Likewise, the protection measures implemented in the facility for fire detection and fire alarms and for fire suppression, including explosion and fire extinguishing systems, as well as smoke control systems and evacuation elements significantly different from the expected level. However, it should be noted that control of ignition sources and combustible materials exceed the baseline strategy and maintenance of fire precautions and systems are realized at above the expectations.

On the base of the presented above fire strategies scoring results (Table 3), the fire risk indexes were calculated, using Equations (1–5) (Table 4).

The results presented in Table 4 show that the actual fire risk index value (FRI_{AC}) is bigger than the baseline one (FRI_{AC}), which means that the actual fire strategy requires some improvements. Because the Polaniec turbine house is an existing building, and all significant building changes would be impossible for realization, the working group decided to implement new solutions in the area of detection and alarm communication factors. In those additional safety systems, the building was fitted with fully functioning fire detection and alarm system signaling to a central fire panel, the fire detection and alarm system was periodically checked against approved check-lists and the system was configured to minimize the impact of false alarms. In effect of this, the final score in this field was corrected from 5 to 18, what is presented in Table 3 and in Figure 5.

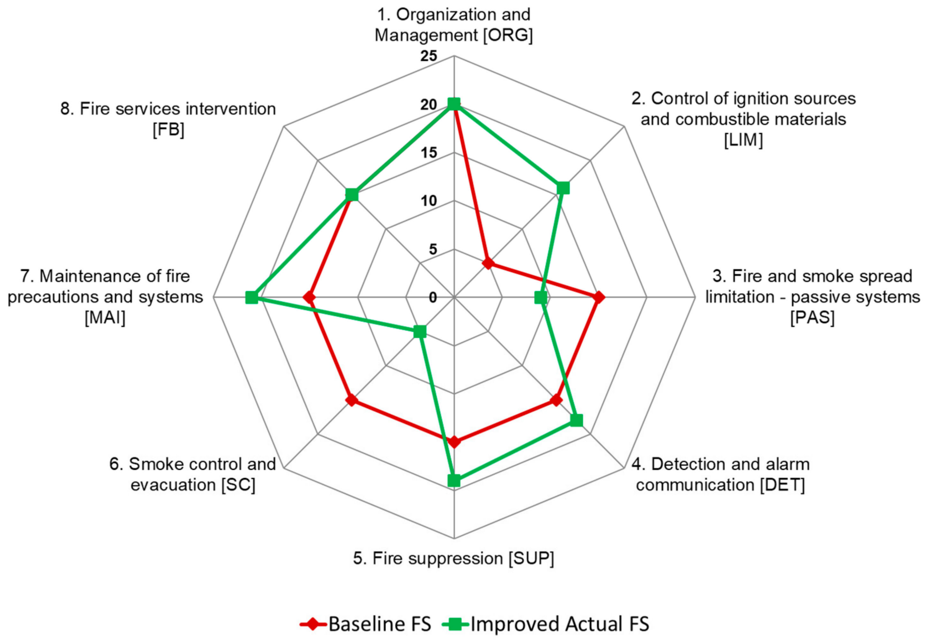

Figure 5. The fire strategy value grid for Polaniec turbine house after improvements of detection and alarm communication factors.

On the base of the presented above corrected fire strategies scoring results, the new fire risk indexes were calculated, using the same rules and equations as previously (Table 5).

Table 5. Fire risk index values for Polaniec turbine house fire strategy after improvements of detection and alarm communication factors.

Parameter	FS_{BAS}	FS_{AC}
Potential Hazard (PH)	3.55	3.55
Protective Measures (PM)	3.55×10^2	3.57×10^2
Fire Hazard Index (FHI)	1.00	0.99
Frequency of ignition (Fi)	4.02	4.02
Fire Risk Index (FRI)	4.02	3.98

The results presented in Table 5 show that the actual fire risk index value (FRI_{AC}) comes after the improvements of detection and alarm communication factors lower than the baseline one (FRI_{AC}), which means that the corrected actual fire strategy is now acceptable.

4. Conclusions

Fire safety engineering and performance-based evaluation techniques continue to grow in prominence, particularly for more modern complex building infrastructure such as that found within the processing industry. The presented methodology for fire strategies in process industry plants represents a sustainable approach to the application of fire safety and fire protection, and combines economic, environmental, and social considerations. However, this greater level of flexibility does not necessarily mean that there is a change of approach to the application of fire engineering principles. Given the increasing demand to incorporate sustainability within all branches of engineering design, there is also a need to improve strategic thinking, to provide for more relevant fire safety engineering designs that consider the environment, business continuity and asset protection as well as the protection of life. Strategic evaluation methods can assist with this goal, especially for more complex building environments.

The methodology described in this paper is captured in an indicative diagram and identifies eight main elements for fire safety and protection. With the use of a questionnaire, a detailed analysis of the key elements of a fire strategy can be determined against an idealized, optimal, baseline strategy. The concept was tested at a series of workshops entitled "Strategic Thinking" at industrial Polaniec and Dolna Odra power plants in Poland. Key stakeholders, including the power plant operators, the fire service, and the insurance company involved, found the method useful and highlighted possible deficiencies in the strategy.

Author Contributions: D.B.—Conceived and designed the analysis, Collected the data and, wrote draft of the paper; P.B.—Wrote the paper, Performed the analysis; A.S.M.—Consultancy.

Funding: This research received no external funding.

Acknowledgments: PZU Insurance Company S. A., ENEA Generation and ENEA Polaniec S.A. and PGE GiEK S.A. Dolna Odra are kindly acknowledged for the technical support and for the workshop of fire strategies organization and foundation.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. *Dublin Code of Ethics Design, Engineering, Construction & Operation of a Safe, Resilient & Sustainable Built Environment for All*; Sustainable Design International Ltd: Dublin, Ireland, 2016.
2. Genserik, R.; Valerio, C. *Domino Effects in the Process Industries: Modelling, Prevention and Managing*; Elsevier: Amsterdam, The Netherlands, 2013; p. 384.
3. Palazzi, E.; Caviglione, C.; Reverberi, A.P.; Fabiano, B. A short-cut analytical model of hydrocarbon pool fire of different geometries, with enhanced view factor evaluation. *Process Saf. Environ. Prot.* **2017**, *110*, 89–101. [CrossRef]

4. Fabiano, B. Loss prevention and safety promotion in the process industries: Issues and challenges. *Process Saf. Environ. Prot.* **2017**, *110*, 1–4. [CrossRef]
5. Fabiano, B. Loss Prevention and Safety Promotion in the Process Industries. *Process Saf. Environ. Prot.* **2014**, *92*, 277–279. [CrossRef]
6. Vairo, T.; Quagliati, M.; Del Giudice, T.; Barbucci, A.; Fabiano, B. From land- to water-use-planning: A consequence based case-study related to cruise ship risk. *Saf. Sci.* **2017**, *97*, 120–133. [CrossRef]
7. Bryant, P. *Fire Strategies—Strategic Thinking*; Kingfell: London, UK, 2013; p. 186.
8. Novozhilov, V. Fire Hazards of Some Modern Solid Fuels. *Energies* **2017**, *10*, 113. [CrossRef]
9. Brzezinska, D.; Markowski, A.S. Experimental investigation and CFD modelling of the internal car park environment in case of accidental LPG release. *Process Saf. Environ. Prot.* **2017**, *110*, 5–14. [CrossRef]
10. Huang, H.S.; Su, C.H.; Li, C.B.; Lin, C.Y.; Lin, C.C. Enhancement of Fire Safety of an Existing Green Building due to Natural Ventilation. *Energies* **2016**, *9*, 192. [CrossRef]
11. *Fire Precautions in the Design, Construction and Use of Buildings: Code of Practice for Residential Buildings (withdrawn)*; BS 5588-1; BSI: London, UK, 1990.
12. *Fire Strategies—Guidance and Framework for Their Formulation*; PAS 911; BSI: London, UK, 2007.
13. Brzezińska, D.; Bryant, P. *Strategies of Buildings Fire Protection*; Lodz University of Technology: Lodz, Poland, 2018; p. 209.
14. Brzezińska, D.; Bryant, P.; Markowski, A. Fire Risk Index Assessment as an Evaluation Method for Fire Strategies in the Process Industry. *Chem. Eng. Trans.* **2019**, 77.
15. *Application of Fire Safety Engineering Principles to the Design of Buildings: Code of Practice*; BS 7974; BSI: London, UK, 2019.
16. *Guide to Design Framework and Fire Safety Engineering Procedures*; PD 7974-0; BSI: London, UK, 2002.
17. *Application of Fire Safety Engineering Principles to the Design of Buildings: Initiation and Development of Fire within the Enclosure of Origin*; PD 7974-1; BSI: London, UK, 2019.
18. *Application of Fire Safety Engineering Principles to the Design of Buildings: Spread of Smoke and Toxic Gases within and beyond the Enclosure of Origin*; PD 7974-2; BSI: London, UK, 2019.
19. *Application of Fire Safety Engineering Principles to the Design of Buildings: Structural Response and Fire Spread beyond the Enclosure of Origin*; PD 7974-3; BSI: London, UK, 2019.
20. *Application of Fire Safety Engineering Principles to the Design of Buildings: Detection of Fire and Activation of Fire Protection Systems*; PD 7974-4; BSI: London, UK, 2003.
21. *Application of fire Safety Engineering Principles to the Design of Buildings: Fire and Rescue Service Intervention*; PD 7974-5; BSI: London, UK, 2019.
22. *Application of Fire Safety Engineering Principles to the Design of Buildings. Human Factors. Life Safety Strategies. Occupant Evacuation, Behaviour and Condition*; PD 7974-6; BSI: London, UK, 2019.
23. *Application of Fire Safety Engineering Principles to the Design of Buildings: Probabilistic Risk Assessment*; PD 7974-7; BSI: London, UK, 2019.
24. *Application of Fire Safety Engineering Principles to the Design of Buildings: Property Protection, Business and Mission Continuity, and Resilience*; Pd 7974-8; BSI: London, UK, 2012.
25. Park, H.; Meacham, B.; Dembsey, N.; Goulthorpe, M. Conceptual Model Development for Holistic Building Fire Safety Performance Analysis. *Fire Technol.* **2015**, *51*, 173–193. [CrossRef]
26. Worrell, C.; Rochon, C. Fire Probabilistic Risk Assessment and its Applications in the Nuclear Power Industry. *Fire Technol.* **2016**, *52*, 443–467. [CrossRef]
27. Albrech, C. Quantifying life safety Part II: Quantification of fire protection systems. *Fire Saf. J.* **2014**, *64*, 81–86. [CrossRef]
28. Watts, J.M., Jr. Fire Risk Indexing. In *SFPE Handbook of Fire Protection Engineering*; Hurley, M.J., Ed.; Society of Fire Protection Engineers; Springer: New York, NY, USA, 2016; pp. 3158–3182. [CrossRef]

29. Gretener, M. *Evaluation of Fire Hazard and Determining Protective Measures*; Association of Cantonal Institutions for Fire Insurance (VKF); Fire Prevention Service for Industry and Trade (BVD): Zurich, Switzerland, 1973.
30. Brzezińska, D.; Bryant, P.; Nowak, S.; Januszewski, J.; Kuczkowski, R. *Fire Strategies—The Workshop Report On Fire Protection In Power Facilities Carried out on The Site of The Polaniec Power Plant, 26–30 July 2017*; PZU: Warsaw, Poland, 2017.