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Syed M. Ahmed East Carolina University, United States





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## ARTICLE Effect of Acids and Alkalis on the Resistance of a Polypropylene Geotextile Against Thermo-oxidation

#### José Ricardo Carneiro<sup>1</sup>\* Paulo Joaquim Almeida<sup>2</sup> Maria de Lurdes Lopes<sup>1</sup>

Construct-Geo, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
 Requimte, Faculty of Sciences, University of Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal

ARTICLE INFO	ABSTRACT
Article history:	The long-term behaviour of geosynthetics is one of the most important topics in the research
Received: 19 October 2018	about these materials. This work studies the effect of some liquids (water, sulphuric acid 0.1
Accepted: 12 February 2019	$mol.L^{-1}$ and sodium hydroxide 0.1 $mol.L^{-1}$ ) on the resistance of a polypropylene
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2	

Keywords: Geosynthetics Geotextiles Durability Thermo-oxidation Resistance against liquids Reduction factors Interactions The folg-term behaviour of geosynthetics is one of the most important topics in the research about these materials. This work studies the effect of some liquids (water, sulphuric acid 0.1 mol.L<sup>-1</sup> and sodium hydroxide 0.1 mol.L<sup>-1</sup>) on the resistance of a polypropylene geotextile against thermo-oxidation. For that purpose, the geotextile was (1) exposed in isolation to the liquids (immersion tests) and to thermo-oxidation (oven-ageing tests) and (2) exposed consec-utively to both degradation tests (combined effect). The damage suffered by the geotextile in the degradation tests was evaluated by monitoring changes in its tensile behaviour. Based on the changes occurred in tensile strength, reduction factors were determined. The reduction fac-tors obtained in the successive exposures to liquids and thermo-oxidation were compared with the reduction factors determined by the traditional methodology for the combined effect of those agents. The results, among other findings, showed the existence of an effect of sulphuric acid 0.1 mol.L<sup>-1</sup> on the resistance of the geotextile against thermo-oxidation. Indeed, the successive exposure to sulphuric acid 0.1 mol.L<sup>-1</sup> and thermo-oxidation. Due to the interaction occurred between the degradation agents, the traditional methodology was unable to predict correctly (by underestimating) the reduction factor for the combined effect of sulphuric acid 0.1 mol.L<sup>-1</sup> and thermo-oxidation.

#### 1. Introduction

eosynthetics are polymeric materials used in the construction of many civil engineering structures, such as waste landfills, roads, railways, hydraulic structures or coastal protection structures. These materials provide an excellent alternative to more traditional construction materials due to their high efficiency, low cost, ease of installation and low environmental impact. There are many types of geosynthetics, being the geotextiles the most used ones due to their ability to perform many different functions: filtration, drainage, protection, separation or reinforcement.

<sup>\*</sup>Corresponding Author:

José Ricardo Carneiro,

Construct-Geo, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal Email: rcarneir@fe.up.pt,

For being suitable for use in civil engineering structures, the geosynthetics must have a good resistance against many degradation agents. The most common degradation agents of these materials include: liquids (like acids or alkalis), high temperatures, oxygen, ultraviolet (UV) radiation and other weathering agents, creep and abrasion<sup>[1,2]</sup>. The installation process can also provoke damage to the geosynthetics<sup>[3]</sup>.

The polymers most used for the production of geosynthetics include polyolefins (like polypropylene (PP) or polyethylene), polyesters and polyamides. PP (polymer most used for producing geotextiles) has a good resistance against many chemical substances, like acids or alkalis<sup>[4,5]</sup>. However, it has a relatively poor resistance against oxidation<sup>[6,7]</sup>. The oxidation process of PP follows a complex chain reaction mechanism that can be induced by UV radiation (photo-oxidation) or by temperature (thermo-oxidation) (detailed description of the oxidation process  $in^{[6,8,9]}$ ). The damage caused by photo and thermo-oxidation can be retarded by adding chemical additives (such as antioxidants and/or UV stabilisers) to PP<sup>[9][10][11]</sup>. In the absence of UV radiation, the oxidation process of PP is relatively slow at ambient temperatures<sup>[12]</sup>. However, it cannot be neglected when considering products for long-term use, like geosynthetics.

The long-term behaviour of geosynthetics is normally predicted based on data obtained from laboratory tests where the materials are exposed (often under accelerated conditions) to degradation agents<sup>[13][14][15]</sup>. For that purpose, the organisations for standardisation (like the European Committee for Standardization or the American Society for Testing and Materials) have developed many methods. For example, the resistance of geosynthetics to liquids can be evaluated by EN 14030<sup>[16]</sup>, EN 12447<sup>[17]</sup> or ASTM D6389<sup>[18]</sup>. EN ISO 13438<sup>[19]</sup> and ASTM D5721<sup>[20]</sup> can be used to evaluate their resistance against thermo-oxidation. The resistance of geosynthetics against degradation can also be evaluated by field tests (degradation under real conditions)<sup>[21,22,23]</sup>. However, these tests are often very time consuming (months or years), being unsuitable when quick results are needed.

The damage that occurs in geosynthetics during the degradation tests is often evaluated by monitoring changes in their mechanical properties (mainly in their tensile behaviour). In order to take into account the resistance changes that geosynthetics suffer over time, reduction factors (RF) are often used in the design phase<sup>[24,25]</sup>. For example, for reinforcement applications, the tensile strength of geosynthetics is typically affected by a set of reduction factors accounting for the effects of installation damage, creep, weathering and chemical and biological agents<sup>[24,25]</sup>.

The actual design methods, the standard degradation tests for durability evaluation and most studies found in literature about the durability of geosynthetics consider the isolated action of the degradation agents, not accounting for possible interactions between them<sup>[26]</sup>. However, the combined effect of the degradation agents (which happens in real cases) can be much different (more severe) from the sum of their isolated actions. For example, Carneiro et al. (2014)<sup>[15]</sup> and Carneiro et al. (2018)<sup>[26]</sup> showed the existence of interactions between chemical degradation agents of geosynthetics. The occurrence of interactions between mechanical degradation agents has also been reported in literature<sup>[27,28]</sup>. The occurrence of the previous interactions can lead to inaccurate global reduction factors, which are traditionally obtained by multiplying relevant partial reduction factors (each determined in isolation)<sup>[26]</sup>. Therefore, the identification and quantification of interactions between the different degradation agents may lead to a better prediction of the long-term behaviour of the geosynthetics.

This work studies the effect of some liquids in the thermo-oxidation process of a PP geotextile. For that purpose, the geotextile was (1) immersed on liquids (water, sulphuric acid 0.1 mol.L<sup>-1</sup> and sodium hydroxide 0.1 mol.  $L^{-1}$ ), (2) exposed to thermo-oxidation and (3) immersed in liquids followed by thermo-oxidation (combined ac-tion). The main goals of the work included: (1) determi-nation of the effect of the degradation tests on the tensile behaviour of the geotextile, (2) evaluation of the effect of the immersion tests on the resistance of the geotextile against thermo-oxidation (identifying possible interactions between the degradation agents) and (3) comparison of the reduction factors obtained by the traditional methodology for the combined effect of liquids and thermo-oxidation (determination of the reduction factors in isolation for each degradation agent and further multiplication) with those obtained in the successive exposure to those agents.

#### 2. Experimental Description

#### **2.1 Geotextile**

This work studied a nonwoven needle-punched PP geotextile stabilised with 0.2% (percentage in weight) of the additive Chimassorb 944 (C944). C944 is a UV stabiliser belonging to the HALS (hindered amine light stabilisers) family. Besides acting as UV stabiliser, C944 is also highly effective in protecting PP geotextiles against thermo-oxidation<sup>[12]</sup>. The main properties of the geotextile can be found in Table 1.

(Ondumaged Sample)				
Property	Test standard	Mean value		
Mass per unit area (g.m <sup>-2</sup> )	EN ISO 9864 <sup>[29]</sup>	272 (±15)**		
Thickness at 2 kPa (mm)	EN ISO 9863-1 <sup>[30]</sup>	3.16 (±0.10)**		
Tensile strength* (kN.m <sup>-1</sup> )	EN ISO 10319 <sup>[31]</sup>	13.12 (±0.55)**		
Elongation at maximum load* (%)	EN ISO 10319 <sup>[31]</sup>	112.5 (±4.3)**		

 
 Table 1. Main Properties of the Geotextile (Undamaged Sample)

\*determined in the machine direction of production

\*\*95% confidence intervals in brackets

The sampling process (for the characterisation and degradation tests) was carried out according to EN ISO 9862<sup>[32]</sup>. The specimens (machine direction of production) were collected from positions evenly distributed over the full width and length of the geotextile (supplied in a roll), but not closer than 100 mm to the edges. The specimens for the same characterisation or degradation test (total of 5 specimens for each test) were taken from different longitudinal and transverse positions of the roll. The specimens were 200 mm wide and 300 mm long.

#### 2.2 Degradation Tests

First, the geotextile was exposed in isolation (single exposure) to immersion in liquids and thermo-oxidation (description of the tests in the following points). Then, the geotextile was exposed consecutively to the action of liquids and thermo-oxidation (multiple exposures). Table 2 summarizes the degradation tests carried out in this work.

Single exposure	Multiple exposure
H <sub>2</sub> O	$H_2O + TO$ (28 days)
$H_2SO_4$	$H_2O + TO$ (56 days)
NaOH	$H_2SO_4 + TO (28 \text{ days})$
TO (28 days)	$H_2SO_4 + TO (56 \text{ days})$
TO (56 days)	NaOH + TO (28 days)
	NaOH + TO (56 days)

Table 2. Degradation Tests.

(TO – thermo-oxidation)

#### 2.2.1 Immersion Tests

The geotextile was immersed at room temperature (about 20 °C) in deionised water (H<sub>2</sub>O) (pH  $\approx$  7), in sulphuric acid (H<sub>2</sub>SO<sub>4</sub>) 0.1 mol.L<sup>-1</sup> (pH  $\approx$  1) and in sodium hydroxide (NaOH) 0.1 mol.L<sup>-1</sup> (pH  $\approx$  13). These conditions were chosen to represent strong acid and alkaline environments (the neutral medium was intended for comparison). The immersion tests were carried out in the dark and had a duration of 150 days. Sulphuric acid (p.a. grade) and sodium

hydroxide (p.a. grade) were obtained from Merck. Water was treated microbiologically and purified by reverse osmosis followed by deionisation on ionic exchange columns.

The specimens immersed in sulphuric acid 0.1 moL.  $L^{-1}$  and sodium hydroxide 0.1 mol. $L^{-1}$  that were subsequently exposed to thermo-oxidation (multiple exposures) were not washed after the immersion tests (in order to be contaminated with remains of the acid or alkali) and were dried at room temperature in the absence of light. The subsequent thermo-oxidation tests were carried out in a short period of time (a few days or weeks) after the drying process.

#### 2.2.2 Thermo-oxidation Tests

The thermo-oxidation tests were carried out in an oven (*Heraeus Instruments*, model T6120) and consisted in exposing the geotextile at 110 °C in a normal oxygen atmosphere (21%  $O_2$ ) without forced air circulation. The exposure period lasted for 28 and 56 days. The exposure period of 28 days corresponds to method A2 of EN ISO 13438<sup>[19]</sup>. The increase of the exposure time from 28 to 56 days was intended to harshen the degradation conditions and thereby enhance the effects of thermo-oxidation.

## **2.3 Evaluation of the Damage Suffered by the Geotextile**

The damage suffered by the geotextile during the degradation tests was evaluated by monitoring changes in its tensile behaviour (tensile tests according to EN ISO  $10319^{[31]}$ ). The tensile tests (velocity of 20 mm.min<sup>-1</sup>) were carried out in an equipment from *Lloyd Instruments* (model LR 50K) equipped with a load cell of 5 kN (from *Lloyd Instruments*). Each tensile test included the analysis of 5 specimens (in the machine direction of production) with a length of 100 mm (between grips) and a width of 200 mm.

The mechanical parameters obtained in the tensile tests included tensile strength (T, in kN.m<sup>-1</sup>) and elongation at maximum load ( $E_{ML}$ , in %). Elongation was determined by expressing the relative displacement of the grips as a percentage of the original length (100 mm). The results obtained for tensile strength and elongation at maximum load (mean values of 5 specimens) are presented with 95% confidence intervals determined according to Montgomery and Runger<sup>[33]</sup> (Equation 1).

$$\mu = x \pm t_{\alpha/2, n-1} \frac{s}{\sqrt{n}} \tag{1}$$

Where  $\mu$  is the population mean, *x* is the sample mean, *t* is Student's *t*-distribution value for the confidence level  $\alpha$  and *n*-1 degrees of freedom, *n* is the number of specimens

tested for each sample and *s* is the sample standard deviation. The changes occurred in tensile strength are also presented in terms of retained tensile strength ( $T_{\text{Residual}}$ , in %), obtained by dividing the tensile strength of the damaged samples ( $T_{\text{Damaged}}$ ) by the tensile strength of an undamaged sample ( $T_{\text{Undamaged}}$ ) (Equation 2).

$$T_{\text{Residual}} = \frac{T_{\text{Damaged}}}{T_{\text{Undamaged}}} \times 100$$
 (2)

#### 2.4 Determination of Reduction Factors

The reduction factors for the effects of immersion in liquids ( $RF_L$ ), thermo-oxidation ( $RF_{TO}$ ) and immersion in liq-uids followed by thermo-oxidation ( $RF_{L+TO}$ ) were obtained by the following equation:

$$RF = \frac{T_{\text{Undamaged}}}{T_{\text{Damaged}}}$$
(3)

Where,  $T_{Undamaged}$  and  $T_{Damaged}$  represent, respectively, the tensile strength of the geotextile before and after the degradation tests. The reduction factors obtained by the traditional methodology for the combined effect of immersion in liquids and thermo-oxidation (RF<sub>L+TO Trad</sub>) were determined by multiplying the reduction factors obtained in isolation for each degradation agent (RF<sub>L</sub> and RF<sub>TO</sub>, re-spectively) (Equation 4).

$$RF_{L+T0 Trad} = RF_L x RF_{T0}$$
(4)

The reduction factors presented in this work correspond to particular degradation conditions and cannot be generalized or applied directly in the design. For being used in the design, the reduction factors must be analysed case by case, taking into consideration the particular conditions of each construction.

#### 3. Results and Discussion

#### **3.1 Single Exposures to Liquids and Thermo-oxidation**

The tensile properties of the geotextile had no relevant changes after the immersion tests in water, in sulphuric acid 0.1 mol.L<sup>-1</sup> and in sodium hydroxide 0.1 mol.L<sup>-1</sup> (Table 3), which is in accordance with the good resistance reported in literature for PP geotextiles against liquids. The minor variations observed in tensile strength and elongation at maximum load can be attributed to the heterogeneity of the geotextile (nonwoven geotextiles typically have some heterogeneity arising from their manufacturing process).

**Table 3.** Tensile Properties of the Geotextile After the Single Exposures to Liquids and Thermo-oxidation.

Degradation test	T (kN.m <sup>-1</sup> )	E <sub>ML</sub> (%)	T <sub>Residual</sub> (%)	RF
$H_2O$	13.06 (±1.44)	125.6 (±10.3)	99.5	1.00
$H_2SO_4$	13.10 (±1.60)	110.4 (±14.3)	99.8	1.00
NaOH	13.74 (±1.71)	122.6 (±12.0)	104.7	1.00
TO (28 days)	12.64 (±1.24)	89.2 (±4.7)	96.3	1.04
TO (56 days)	12.76 (±1.82)	83.4 (±4.1)	97.3	1.03

(95% confidence intervals in brackets)

Similarly to the immersion tests, the thermo-oxidation tests also did not cause relevant changes in the tensile strength of the geotextile (retained tensile strengths very close to 100%) (Table 3). However, they caused a reduction in elongation at maximum load (decrease from 112.5% to 89.2% and to 83.4% after, respectively, 28 and 56 days of thermo-oxidation). The decreases in elongation at maximum load may be related with the occurrence of some shrinkage (about 2.5%) in the geotextile during the exposure to thermo-oxidation, which led to a reduction of the deformability of the nonwoven structure.

## **3.2 Multiple Exposures to Liquids and Ther-mo-oxidation**

The specimens immersed in sulphuric acid  $0.1 \text{ mol}.\text{L}^{-1}$  (originally white) acquired a brown colour during the exposure to thermo-oxidation (Figure 1), which readily indicated the occurrence of some damage in the geotextile. Besides the colour change, no other changes were detected (by the naked eye) in the geotextile. By contrast, the colour of the specimens immersed in water and in sodium hydroxide 0.1 mol.L<sup>-1</sup> (white in both cases) remained practically unaltered during the thermo-oxidation tests.



**Figure 1.** Geotextile Immersed in Sulphuric Acid 0.1 mol. L<sup>-1</sup> Before (Left) and After Thermo-oxidation (Right).

The tensile behaviour of the geotextile after the thermo-oxidation tests was similar for the specimens previously immersed in water (multiple exposure) and for the specimens without immersion (single exposure to thermo-oxidation) (Table 4). Indeed, no relevant differences were found in tensile strength and in elongation at maximum load when comparing the single exposure to thermo-oxidation with the multiple exposure to water and thermo-oxidation. Therefore, the immersion in water (during 150 days at about 20 °C) had no effect on the resis-tance of the geotextile against thermo-oxidation.

**Table 4.** Tensile Properties of the Geotextile After the

 Multiple Exposures to Liquids and Thermo-oxidation.

	Т	Eng	Τ	
Degradation test	(kN.m <sup>-1</sup> )	(%)	(%)	RF
$H_2O + TO (28 \text{ days})$	13.00 (±2.30)	85.7 (±6.2)	99.1	1.01
$H_2O + TO$ (56 days)	13.04 (±1.63)	82.4 (±4.3)	99.4	1.01
$H_2SO_4 + TO$ (28 days)	11.16 (±0.91)	71.2 (±6.6)	85.1	1.18
$H_2SO_4 + TO$ (56 days)	10.20 (±1.99)	62.7 (±7.6)	77.7	1.29
NaOH + TO (28 days)	12.51 (±1.73)	84.6 (±2.5)	95.4	1.05
NaOH + TO (56 days)	12.28 (±1.19)	89.2 (±6.0)	93.6	1.07

(95% confidence intervals in brackets)

Contrarily to the immersion in water, the immersion in sulphuric acid 0.1 mol.L<sup>-1</sup> led to a reduction in the resistance of the geotextile against thermo-oxidation (the occurrence of some damage had already been indicated by the colour change). Indeed, the specimens immersed in sulphuric acid 0.1 mol.L<sup>-1</sup> had a retained tensile strength of 85.1% after 28 days of thermo-oxidation (Table 4). The increase of the exposure time led to a further decrease in tensile strength (retained tensile strength of 77.7% after 56 days of thermo-oxidation). Elongation at maximum load (after the thermo-oxidation tests) was also lower for the specimens immersed in sulphuric acid 0.1 mol.L<sup>-1</sup> (multiple exposure) than for the specimens without immersion (single exposure to thermo-oxidation). This way, two degradation agents that individually did not cause relevant damage (retained tensile strengths between 96.3% and 99.8% in the single exposures), together led to some degradation in the geotextile.

The reduction in the resistance of the geotextile against thermo-oxidation after the immersion in sulphuric acid 0.1 mol.L<sup>-1</sup> may have some possible explanations: (1) the remains of sulphuric acid catalysed the thermo-oxidation process (the specimens were not washed after the immersion test in order to be contaminated with remains of sulphuric acid), (2) occurrence of losses and/or consumption of the HALS-type UV stabiliser during the immersion in sulphuric acid 0.1 mol.L<sup>-1</sup>, leaving the geotextile less protected against thermo-oxidation (in the absence of the additive, the geotextile would be totally destroyed after 9 days at 110 °C<sup>[12]</sup>) or (3) the protective mechanism of the HALS-type UV stabiliser was affected by the remains of sulphuric acid. Further studies are needed to undoubtedly explain the influence of sulphuric acid in the thermo-oxidation process. These studies are mainly related with polymer chemistry, falling outside the area of civil engineering.

The multiple exposure to sodium hydroxide 0.1 mol.  $L^{-1}$  and thermo-oxidation caused a slight reduction in the tensile strength of the geotextile (retained tensile strengths of 95.4% and 93.6% after 28 and 56 days of thermo-oxidation) (Table 4). However, and having into account the 95% confidence intervals, it is not possible to conclude if these small decreases are due to some effect of sodium hydroxide on the thermo-oxidation process or if they only reflect the typical heterogeneity of non-woven geotextiles. Regarding elongation at maximum load, no relevant differences were found when comparing the multiple exposure to sodium hydroxide  $0.1 \text{ mol.L}^{-1}$  and thermo-oxidation with the single exposure to ther-mo-oxidation. Although not evident in the experimental conditions used in this work, the existence of an effect of sodium hydroxide on the thermo-oxidation process was identified (under different experimental conditions) by Carneiro et al.  $(2014)^{[15]}$ .

## **3.3** Comparison of Reduction Factors: Multiple Exposure vs. Traditional Methodology

The reduction factors obtained in the multiple exposures to liquids (water, sulphuric acid 0.1 mol.L<sup>-1</sup> or sodium hydroxide 0.1 mol.L<sup>-1</sup>) and thermo-oxidation were compared with the reduction factors determined by the traditional methodology (Equation 4) for the combined effect of both degradation agents (determination of reduction factors in isolation for each degradation agent and further multiplication). The reduction factors obtained directly from the single and multiple exposures to the degradation agents can be found in Tables 3 and 4, respectively.

The reduction factors determined by the traditional methodology for the combined effect of (1) immersion in water and thermo-oxidation and (2) immersion in sodium hydroxide 0.1 mol.L<sup>-1</sup> and thermo-oxidation were not much different from those obtained in the multiple exposures to both degradation agents (Table 5). By contrast, the multiple exposure to sulphuric acid 0.1 mol.L<sup>-1</sup> and thermo-oxidation led to slightly higher reduction factors (1.18 and 1.29 after, respectively, 28 and 56 days of thermo-oxidation) than those predicted by the traditional methodology for the combined effect of both agents (1.04 and 1.03 after, respectively, 28 and 56 days of thermo-oxidation) (Table 5).

<b>Table 5.</b> Reduction Factors for the Combined Effect of
Liquids and Thermo-oxidation Obtained by the Traditional
Methodology (RFL+TO Trad) and in the Multiple Exposures to
the Degradation Agents $(RF_{L+TO})$ .

0		-10/
Multiple exposure	RF <sub>L+TO</sub>	$RF_{L^{+}TO \; Trad}$
$H_2O + TO$ (28 days)	1.01	1.04
$H_2O + TO$ (56 days)	1.01	1.03
$H_2SO_4$ + TO (28 days	) 1.18	1.04
$H_2SO_4$ + TO (56 days	) 1.29	1.03
NaOH + TO (28 days	) 1.05	1.04
NaOH + TO (56 days)	1.07	1.03

The differences found between the reduction factors for the combined effect of sulphuric acid 0.1 mol.L<sup>-1</sup> and thermo-oxidation (obtained by the traditional methodology or in the multiple exposure to both degradation agents) can be attributed to the interaction that occurred between the degradation agents (which the traditional methodology was unable to account for). This way, when interactions occur between the degradation agents, the multiplication of reduction factors (each representing the isolated effect of a degradation agent) may not represent correctly (by underestimating) the combined effect of those agents. Other examples of interactions between degradation agents of geosynthetics (which led to inaccurate reduction factors when using the traditional methodology) can be found in Carneiro et al. (2014)<sup>[15]</sup>, Dias et al. (2017)<sup>[28]</sup> and Carneiro et al. (2018)<sup>[26]</sup>.

#### 4. Conclusion

The isolated exposures to liquids (water, sulphuric acid 0.1 mol.L<sup>-1</sup> or sodium hydroxide 0.1 mol.L<sup>-1</sup>) and to thermo-oxidation did not cause relevant changes in the tensile strength of a PP geotextile (retained tensile strengths very close to 100%). By contrast, elongation at maximum load suffered a reduction after thermo-oxidation (no relevant changes occurred after the immersion tests). Globally, the geotextile presented a good resistance against the immersion tests and against thermo-oxidation.

The damage occurred in the geotextile in the multiple exposures to liquids and thermo-oxidation was not always equal to the sum of the damage caused by each agent individually. Indeed, the multiple exposure to sulphuric acid 0.1 mol.L<sup>-1</sup> and thermo-oxidation (two agents that individually did not cause relevant damage), led to some degradation. Under similar experimental conditions, the effect of sulphuric acid 0.1 mol.L<sup>-1</sup> (pH $\approx$  1) on the resistance of the geotextile against thermo-oxidation was higher than the effect of sodium hydroxide 0.1 mol.L<sup>-1</sup> (pH  $\approx$  13). However, under different experimental conditions (higher

immersion temperature), the effect of sodium hydroxide  $0.1 \text{ mol.}L^{-1}$  can be higher than the effect of sulphuric acid  $0.1 \text{ mol.}L^{-1}$ <sup>[15]</sup>.

The identification and quantification of interactions between the degradation agents is crucial to understand and predict the behaviour of geosynthetics under real conditions (where the agents do not act in isolation). In the existence of relevant interactions between the degradation agents, the reduction factors obtained directly from the multiple exposures may be different from those determined by the traditional methodology (determination of reduction factors in isolation for each degradation agent and further multiplication). Indeed, the traditional methodology was unable to predict with accuracy (by underestimating) the reduction factor for the combined effect of sulphuric acid 0.1 mol.L<sup>-1</sup> and thermo-oxidation. The definition of more reliable reduction factors (taking into consideration the interactions that may occur between the degradation agents) may contribute for a better design and thereby allow a better application of geosynthetics in Civil Engineering.

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#### **Abbreviations and Symbols**

- $\alpha$  Confidence level
- $E_{ML}$  Elongation at maximum load
- HALS Hindered amine light stabiliser
- n Number of specimens
- PP Polypropylene
- RF Reduction factor
- $RF_{L}$  Reduction factor for the action of liquids
- $RF_{TO}$  Reduction factor for thermo-oxidation

 $RF_{L+TO}$  – Reduction factor for the combined effect of liquids and thermo-oxidation

 $RF_{\text{L+TO Trad}}-$  Reduction factor for the combined effect of

liquids and thermo-oxidation (traditional methodology)

s – Sample standard deviation

- t Student's t-distribution value
- T Tensile strength
- T<sub>Damaged</sub> Tensile strength of exposed samples

T<sub>Residual</sub> – Retained tensile strength

 $T_{Undamaged}$  – Tensile strength of undamaged sample (unexposed)

TO – Thermo-oxidation

 $\mu$  – Population mean

UV – Ultraviolet

x – Sample mean

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## ARTICLE A Practical Study on Reducing CO<sub>2</sub> Concentration in Educational Buildings in North-East China

Lingyun Li<sup>1</sup> Changfeng Fu<sup>2</sup>\* Angela Lee<sup>3</sup>

1. Dalian University of Technology, No.2 Linggong Road, Ganjingzi District, Dalian City, Liaoning Province, 116024, China

2. The School of Computing and Engineering, University of West London, St Mary's Road, Ealing, London, W5 5RF, United Kingdom

3. University of Salford, Maxwell Building, 43 Crescent, Salford M5 4WT, United Kingdom

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#### ABSTRACT

Indoor air quality is a major contributor to the quality of people's lives. Notwithstanding pollutants that are becoming increasingly prevalent from new building materials, furnishings and consumer products, CO2 concentration in educational buildings has been identified as a significant issue affecting students' performance. This study measures and addresses how serious the CO<sub>2</sub> levels are in differing educational facilities in north-east China during the winter period when windows have remained typically always closed to minimise heat loss. The research is based on indoor air quality measurement with the CO<sub>2</sub> and temperature & humidity data log, and also the users' experience. The negative impacts of CO<sub>2</sub> concentration are demonstrated to affect students' decision-making capabilities, and the relevant Chinese building regulations related to the requirements of indoor air exchange have also been reviewed. The paper also proffers practical solutions from architects' point of views to improve indoor air quality, specifically related to CO<sub>2</sub> concentration in educational buildings. A brief comparison of the indoor air quality with a specific focus of CO<sub>2</sub> concentration in educational buildings in China, and other countries around the world based on literature has been addressed. This intends to highlight the severe situations in Chinese education buildings.

#### **1. Introduction**

pproximately, 90% of our lives is spent within indoor environments<sup>[1][2][3]</sup>. Thus, the quality of indoor air is a major contributor to human health<sup>[4]</sup>. Indoor air pollution may cause or aggravate illnesses<sup>[5][6]</sup>, increase mortality<sup>[4]</sup>, and have a major economic and social impact<sup>[7]</sup>. Further, it has been proven that a number of respiration related diseases are directly caused or developed by poor indoor air quality (IOQ) by means of pollutants<sup>[5][6][8]</sup>. Exposure to pollutants may cause a variety of effects ranging in severity from perception of unwanted odors through to cancer<sup>[9]</sup>. Examples of health effects are dispersal of airborne infectious disease, micro-organisms in air humidifiers

<sup>\*</sup>Corresponding Author:

Changfeng (Charlie) Fu,

The School of Computing and Engineering, University of West London, St Mary's Road, Ealing, London, W5 5RF, United Kingdom Email: Charlie.fu@uwl.ac.uk

causing pneumonia and humidifier fever, mould increasing risk of allergy, and an increased risk of lung cancer through exposure to environmental tobacco smoke (ETS) and radon. Sensory effects include:

• Adverse health effects on sensory systems

•Adverse perceptions such as annoyance reactions and triggering of hypersensitivity reactions

• Sensory warnings of harmful factors such as irritation due to formaldehyde.

The rapid development of new building materials, furnishings and consumer products over the past 50 years has resulted in a subsequent increase in new chemicals in the built environment<sup>[10]</sup>. The increase is an accumulation of the number of chemicals manufactured and used in household and building products, including construction materials, interior finishing materials, cleaning agents, furnishings, computers and office equipment, printers and supplies. In addition, buildings and HVAC (heating, ventilation and air conditioning) systems have deteriorated as a result of ageing and inadequate maintenance, or become obsolete as a result of technological advances. Added to this, the amount of fresh air being brought into buildings has decreased in order to reduce the amount of energy needed to heat or cool it. Thus, there is less fresh air available to dilute indoor air contaminants/ pollutants. Indoor concentrations are largely uncharacterised, but they have likely increased over time as a wider mix of chemicals are used and air exchange rates in the buildings decrease to improve energy efficiency<sup>[10]</sup>. Chemical concentrations are often highest indoors because many of the sources are indoors, and because of limited degradation indoors compared with outdoors. In addition, people who may be exposed to indoor air pollutants for the longest periods of time are often those most susceptible to the effects of indoor air pollution, and are namely the young, the elderly, and the chronically ill.

There have been many definitions provided for appropriate IAQ, one definition describes the absence of air contaminants which may impair the comfort or health of building occupants<sup>[11][3]</sup>. Another defines indoor air pollution as chemical, physical or biological contaminants in the breathable air inside a habitable structure or conveyance, including workplaces, schools, offices, homes and vehicles. Other general factors influencing IAQ to those aforementioned includes temperature and humidity comfort, lighting and acoustic condition. A popular method to measure IAQ is to measure CO<sub>2</sub> levels in indoor air using CO<sub>2</sub> meters or monitors. CO<sub>2</sub> is commonly used as a sentinel indicator of IAQ to demonstrate relative levels of other pollutants, typically like NO<sub>2</sub>, CO, SO<sub>2</sub>, and VOC (volatile organic compounds) and body odor <sup>[12,13,14]</sup>. It has to be clarified that the  $CO_2$  concentration in general outdoor air is around 400-600ppm. This is not harmful to human health. However, there are some regulations regarding  $CO_2$  level in certain types of buildings in the world. For instance, the British Health and Safety Legislation<sup>[15]</sup>, which apply to school and educational buildings (ibid), state that long term exposure (less than 8 hours) to  $CO_2$  should not exceed 5000ppm, and short term exposure (15 minutes or less) should not exceed 15000ppm.

Notwithstanding pollutants, many researchers have investigated the relationship of IAQ with regards to CO<sub>2</sub> levels. A significant study in this area was carried out at the Lawrence Berkeley National Laboratory and SUNY Upstate Medical University<sup>[16]</sup>. The research demonstrated that the concentration of CO<sub>2</sub> in indoor air significantly affects people's decision-making performance where 2500ppm CO<sub>2</sub> is reached in an indoor environment (Figure 1). Satish et al. demonstrated that when the  $CO_2$  level is between 1000ppm and 2000ppm, occupants may feel that the air is un-fresh and often start to feel drowsy; when the CO<sub>2</sub> level is raised to between 2000ppm to 4000ppm, occupants in this environment may feel difficulty breathing, their faces often turn red and they may start to feel convulsion; when CO<sub>2</sub> levels reach between 4000ppm and 6000ppm, occupants may experience permanent brain damage, and often lose consciousness, and more seriously, may die if they stay in such an environment for a extended period of time<sup>[16]</sup>.





In recent years, the indoor air quality issues have been addressed as a very important factor to the building performance, especially in school and education buildings which may affect collective young people. Similar research has been done around world, such as central Italy<sup>[12][13][18][19]</sup>.

Johnsona et. al. demonstrated that school classrooms,

especially those located in extremely cold or hot weather, where windows are usually kept closed during teaching sessions, often face poor air IAQ<sup>[12]</sup>. Thus, IAQ has been proven to impact upon students' performance, and as such, many countries around the globe have indoor air quality management (IAQM) strategies for educational facilities that aid the management of IAQ during occupancy<sup>[20][21]</sup> <sup>[22]</sup>. Whilst such strategies exist, they are not commonly monitored as in the case of China. The Chinese Indoor Air Quality Standard (GB/T18883-2002) states that the CO<sub>2</sub> level should be kept below 1000ppm. As one adult usually exhales about 22.6 litres of CO<sub>2</sub> per hour, how are classrooms affected, where are large quantity of persons are expected to concentrate for fixed time periods? This research investigates CO<sub>2</sub> concentration in educational facilities in north-east China. Data collection will involve measurements on CO2 levels in learning facilities, and calculated against student numbers, size of facility and window openings. Analysis of the results against the relevant building regulations will then be used to proffer practical design solutions.

#### 2. Research Methods

Building Performance Evaluation (BPE) is a practical method of evaluating a buildings performance with Post Occupancy Evaluation (POE) being a major component. A Building Performance Evaluation may be carried out on new, refurbished or existing buildings. It can test building fabric, building services, energy use, water use, user satisfaction, to name a few. The outcomes may be used to better understand how to make the building more efficient.

Post Occupancy Evaluation is becoming recognised as an important tool to develop better designs and to obtain important feedback on a building and how well it performs, in many cases buildings do not meet their expectations and this can have an impact on human comfort, running costs, user satisfaction, health and safety. Post Occupancy Evaluation is defined as "the process of evaluating any type of building in a systematic and rigorous approach after they have been built and occupied"<sup>[23]</sup>. The RIBA also defines a Post-Occupancy Evaluation in the RIBA Plan of Work as an "Evaluation undertaken post occupancy to determine whether the project outcomes, both subjective and objective, set out in the Final Project Brief have been achieved."<sup>[24]</sup>.

In this research, the POE exercise mainly focuses on the human comfort and health and safety issues, specifically the indoor air quality, including  $CO_2$ concentration and associated temperature and humidity. Two detailed methods were applied. One was mainly environmental data collection with equipment, another was to gather users' experience feedback. For the indoor air quality environmental data collection, Following 3 types of data logs with integrated sensors were used:

• Tinytag  $CO_2$  TGE-0011, which can be setup for collecting  $CO_2$  concentration (ppm) for minimum one minute. As this  $CO_2$  data log needs a power supplier, it has to be placed near to a power socket.

• Tinytag Ultra 2 TGU-4500 is an indoor thermal data logger which can capture both temperature and humidity data for minimum one minute in indoor environments. It is powered by a battery. So it can be placed anywhere.

• Tinytag Plus 2 TGP-4500 is an outdoor thermal data loggers which can capture both temperature and humidity data for minimum by minute in outdoor environments. It is also powered by a battery.

The users' experience investigation was mainly via a questionnaire survey of students in the classrooms, and a semi-structured interview to the people in the facility management team. The questionnaire mainly covers the students' feelings on air quality, temperature and humidity, class and break time, and their concentration in classes. The semi-structured interviews mainly focus on building operation management, especially for the ventilation systems in the buildings.

#### 3. Sample Area

Dalian is one of the largest cities in north-east of China, located at the south most point of the Liao-Dong peninsula. The coordinates are 38.9140°N,121.6147°E. Dalian is classified as a Class A Cold Zone area according to the Chinese Building Regulations, and requires at least 152 days of heating supply per year. The lowest average outdoor temperature for 5 days per year (heating calculation temperature) is - 9.8°C. The average outdoor temperature during the winter period is - 0.7°C. In winter, usually all windows of all buildings in Dalian remain shut to minimize any heat loss. With the everincreasing standard of energy efficiency for buildings, the air tightness of windows has been improved significantly over the years. The Design Standards for Public Building (GB50189-2005) requires that the air tightness of a window must not be below Level 4 (2.0< & <2.5 m3/M.H), which means that the cold air penetration for each meter of window gaps in each hour is 2.0-2.5 m<sup>3</sup>. However, contrary to this, the National Energy Efficiency Standards for Public Buildings (GB50189-2015) requests the air tightness not below Level 6 ( $1 \le \& \le 1.5 \text{ m}^3/\text{M.H}$ ).

From the end of 1990s, due to the growing demand of students, there was a significant surge in the refurbishment and construction of new universities across Dalian; notably, only 6 out of a total of 42 university buildings in Dalian which stand today were constructed before 2000.

The 6 pre-2000 university buildings have no mechanical or passive ventilation systems in place. Of the remaining 36 university buildings, most do not have mechanical ventilation systems. Only one building has a mechanical ventilation system, but it is rarely used as it is not viewed as necessary. Notably, the majority of the lecture theatres windows have large divisions, and therefore, it is usually impossible to operate/ open windows easily. In addition, the majority of school buildings in Dalian are not equipped with any ventilation systems, and too consist of large windows that are difficult to operate/open.

#### 4. CO<sub>2</sub> Measurement in Classrooms

CO<sub>2</sub> measurements were carried out during winter 2018, where the outdoor temperature ranged between 1°C and 6°C. Measurements were taken in a 'typical' large lecture theatre (A) with 250 seats in a university building constructed in 2007 (Figure 2), and another was in a 'typical' classroom (B) with 40 seats of a high school building constructed in 2005 (Figure 3). The measurements usually started few minutes before the classes began, when most students were in the classrooms. Although the measurements were taken over a whole week, the CO<sub>2</sub> concentration results were averaged for a typical day, as per Figure 4 and 5.



Figure 2a. The Floor Plan Figure 2b. Internal Photograph



Figure 2c. Window Openings of the Lecture Theatre





Figure 2. A Typical Lecture Theatre (A)





Figure 3a. The Floor Plan

Figure 3b. Internal Photograph



Figure 3c. Window Openings of the Classroom



Figure 3d. Indoor Layout of the Classroom Figure 3. The School Classroom (B)



Figure 4. CO<sub>2</sub> Measurements in a University Lecture Theatre (A) Across a Typical Day During Winter 2018





The results presented demonstrates that CO<sub>2</sub> levels vary significantly during lesson times, and this is also impacted by the opening of windows. The CO<sub>2</sub> in the university lecture theatre (A) increased rapidly from around 600ppm to 2855ppm during the first 90 minutes of the session, with all of the doors and window shut (Figure 4). Meanwhile, the  $CO_2$  level in the secondary school classroom reached to 2022ppm within 40 minutes (Figure 5). The height of the lecture theatre (A) is 5.1m and the designed concentration is  $1.22 \text{ person/m}^2$ , with each person occupying 4.18m<sup>3</sup> of space; the height of the secondary school classroom (B) is 3.6m, and the designed concentration is  $0.8 \text{ person/m}^2$ , with each person occupies  $4.5m^3$  space. The windows of the lecture theatre (A) are aluminum-framed double-glazed sliding windows, with an overall window opening area of 42.2m<sup>2</sup>. The rate between the window areas to the floor area of the theatre is 1:4.8, and the window opening length is 77m; the window's opening area to the floor area is 5.97%. For the school classroom (B), the windows are aluminum-framed double-glazed windows. The overall window area is  $11.895m^2$ . The rate between the window areas to the floor area is 1:5.29, and the window opening length is 8.4m; the window's opening area to the floor area is 5.05%. Based on the above information, it indicates that, if the school class session lasts for 90 minutes, the actually indoor air quality environment in the school classroom may be worse than the lecture theatre. The comparable results are presented in Table 1.

 

 Table 1. Comparable CO2 Concentration Results of Classroom Facilities in Typical Day During Winter 2018

	Highest recorded concentration	Concentration of space	Person occupancy concentration	Overall window opening	Rate of window area of
	of CO2		of space	area	floor area
Lecture theatre (A)	2855 ppm during 90 minutes	1.22 person/m <sup>2</sup>	4.18m <sup>3</sup>	42.2m <sup>2</sup>	1:4.8
Secondary school classroom (B)	2022ppm within 35 minutes	0.8 person/m <sup>2</sup>	4.5m <sup>3</sup>	11.895m <sup>2</sup>	1:5.29

According to the Chinese Building Regulations (GB50352-2005), in order to ensure that there is adequate natural ventilation in a building, the window opening area of a room against that of the floor area of the room should be greater than 1:20, of (A) 1:4.8 and (B) 1:5.29 respectively. Thus, both the university lecture theatre and the high school classroom meet this criterion. However, as the windows are not usually opened during the winter, the exchange of fresh air cannot be guaranteed. In this case, the lecture theatre had 288.75m<sup>3</sup> air exchange over 90 minutes; the school classroom had 26.8m<sup>3</sup> over

40 minutes. According to the building regulations for building services (GB50736-2012), every person in a classroom should have at least 22 to 24 m<sup>3</sup> fresh air. Based on this standard, the lecture theatre should have at least 5500m<sup>3</sup> fresh air exchange over 90 minutes and the school classroom should have at least 880m<sup>3</sup> air exchange as well. Neither facility met this standard, as windows largely remained closed and there were no additional mechanical ventilation systems present.

In the North-East of China, occupants very rarely open any windows during the entire winter period. Therefore, it is foreseen that the results presented in Figure 4 and 5 are typical of educational facilities whereby there is a high CO<sub>2</sub> concentration during use/operation. Although  $CO_2$  is not an air pollutant that directly causes harm to people's health, it does indicate the presence of other pollutants including human odor, and is associated with uncomfortable temperature and humidity which affect students' concentration as concluded by another research <sup>[16]</sup> demonstrated that when the  $CO_2$  level is between 1000ppm and 2000ppm, people may feel that the air is stale and often start to feel drowsy (see Figure 1). Further, such high levels of  $CO_2$  in educational facilities can also cause headaches, stomach aches, and other irreversible damage to people's health. Thus, good indoor air quality and artificial/mechanical ventilation is essential for educational buildings in the north-east of China. The following section proffers a number of practical solutions to address this concern.

#### 5. Users' Experience

#### **5.1 Questionnaire Survey**

The following five questions are designed to collect the students' experience in the classrooms:

Table 5.1 The Questionnaire Surveying in the Lecture Theatre

1.	Do you feel the air quality getting bad over the class time?	• Yes • No	•	78 5
2.	lf so, in terms of what? (sllow nxdtiple selection)	<ul> <li>Breathing problem including block note,</li> <li>basdische,</li> <li>tlæpy;</li> <li>cal'rouscennate</li> <li>Other, specify</li> </ul>		17(20.5%) 27(33%) 43(51%) 36(67%) 5 (6%)
3.	If so, when you start to have such symptom?	Within first 30 mins     Within first 60 mins     After 1 hour     After 1 5 hour     Or specifymins	• • • • •	5 24 37 17 0
4.	You think how long of each section you thould have a break?	30 minu     45 minu     60 minu     90 minu     Or specify minu	••••	12 27 37 7 0
5.	What do you feel about the temperature in the clausroom?	Fina     Good     Sounchimes too hot     sounchimes too cold     from cold to hot     from hot to cold	• • • • •	22 15 24 3 20 1

<ol> <li>Do you feel the air quality getting bad over the class time?</li> </ol>	<ul> <li>Yes</li> <li>No</li> </ul>	• 28 • 7
<ol> <li>If so, in terms of what?</li> <li>(allow multiple selection)</li> </ol>	Breathing problem including block nose, kasdachs, daspy, can't concentrate Other, specify (no shows feeling) 	<ul> <li>3(0.85%)</li> <li>2(6%)</li> <li>9(26%)</li> <li>27(77%)</li> <li>8(23%)</li> </ul>
<ol> <li>If so, when you start to have such symptom?</li> </ol>	Within first 30 mins     Within first 60 mins     After 1 hour     After 1 5 hours     Or specify <u>120</u> mins	• 1 • 7 • 22 • 3 • 2
<ol> <li>You think how long of each session you should have a break?</li> </ol>	30 mins     45 mins     60 mins     90 mins     0r specifymains	• 9 • 17 • 11 • 1 • 0
<ol> <li>What do you feel about the temperature in the elastroom?</li> </ol>	<ul> <li>Fina</li> <li>Good</li> <li>Sometimes too hot</li> <li>sometimes too cold</li> <li>from cold to bot</li> <li>from hot to cold</li> </ul>	<ul> <li>15</li> <li>12</li> <li>4</li> <li>1</li> <li>2</li> <li>1</li> </ul>

Table 5.2 The Questionnaire Surveying in the School Classroom

83 questionnaire forms were collected from the university lecture theatre (Table 5.1) and 35 were collected from the school classroom (Table 5.2). Although the students in both classrooms could feel the indoor air quality getting worse over their class time, the students in the university theater had stronger reaction to such changes. This was because that more people (proportions) had the listed symptoms. This outcome is also consistent to the collected data that the  $CO_2$  concentration, temperature and humidity in the lecture theatre were relatively higher than the school classroom. It also can be identified that the length of each class session should not be more than 45-60 minutes. The temperature of the classroom looks like another key factor affecting the students' human comfort. As all of these classrooms are heated with community heating systems, the temperature in the classroom with full of the students, the temperature and humidity can easily go up to over 24°C, and 70% humidity. Based on the Chinese design regulations, the designed temperature and humidity in classroom should be 20°C-22°C and the humidity should be 30-70%, ideally 50%-60%<sup>[14]</sup>. In this study, it has been identified that the temperature and humidity will increase when the  $CO_2$  concentration increases in these classroom. It was observed that when the CO<sub>2</sub> concentration was over 1400ppm, the temperatures in both the lecture theatre and the classroom are over 24°C. From the measurements of both classrooms, it can be told that the  $CO_2$  concentration increased from 1000ppm to 1500ppm in about 15-20 minutes, and to 2000ppm in about 30-40 minutes. Thus, if people want to control the CO<sub>2</sub> concentration below 2000ppm in during the winter time in North-East China,

each class session should be controlled within 40 minutes.

#### 5.2 Interview of the Building Management Team

The building facility management teams of both the university and school were interviewed regarding the ventilation systems and the knowledge of the indoor air quality. The outcomes of the interview are very negative. Most people in the facility operation and management teams have little knowledge about either indoor human comfort or the indoor air quality. As mentioned earlier, one building in this study has an artificial ventilation system. The building facility management usually do not turn it on. There is no guidance regarding when the ventilation system should be turned on. The facility teams also claimed that they have never received any complaint about the indoor air quality issues, or have been asked to turn the ventilation system on, but they are very interested in the outcomes of this research. This interview has fully reflected that some conclusions addressed in other previous studies<sup>[25]</sup> that the reasons causing such issues are a lack of awareness of IAQ amongst all stakeholders (i.e. architects, users/ occupiers, general public etc.), a lack of responsibility, and a lack of communication between stakeholders during the building process.

#### 6. Practical Solutions to Mitigate High Concentration CO<sub>2</sub> in Educational Facilities

#### 6.1 Window Openings

Users/occupants in educational facilities should open winders more frequently during the winter period. The frequency should follow the requirement of the air exchange rate for each person which stands at a minimum of 22 to 24 m<sup>3</sup> fresh air per person (GB50736-2012). Students should be also be encouraged venture out of the lecture theatre/classroom as much as possible during break times, not just for them to personally enjoy fresh air, but also to reduce the CO<sub>2</sub> level in the learning environment. Based on the above calculated figures, it is proposed that educational facilities should open windows every half hour on average. The openable sections on windows should be designed appropriately so that they can be easily operated and are of an adequate scale, especially for very large windows. This can encourage people to open windows more frequently, but also ensure that those who sit close to windows do not feel too cold.

## 6.2 Reducing CO<sub>2</sub> Concentration Through Improved Timetabling

The results of  $CO_2$  concentration in the lecture theatre (A), Figure 4, are more complex in nature than the secondary classroom (B). As typical in an university lecture theatre, classes are often timetabled consecutively

with different groups of students in each timetabled lecture. It was witnessed that students of a following lecture were aware immediately of poor air quality on entering the lecture theatre, and often opened the window on entry. This action significantly reduced the  $CO_2$  level. Therefore, the timetable of different classes in the same facility is encouraged to support adequate  $CO_2$  levels.

Another noticeable finding in the  $CO_2$  concentration measurement for the lecture theatre (A) was that the  $CO_2$ concentration increased rapidly for the last lesson before 5pm (Figure 6). This was concluded that the students thought they could bear the bad air quality in last hour before the class finished, and also coincided with the drop in air temperature externally. This indicates that poor air quality is also related to users' psychology and habit.



**Figure 6.** CO<sub>2</sub> Concentration Increased Rapidly in the Late Afternoon in the University Lecture Theatre

#### 6.3 Enable Convectional Currents

A separate measurement was carried out in two lecture theatres (Classroom A and Classroom F) with differing numbers of windows (Figure 2). The same group of students stayed in the two rooms for 90 minutes each with all windows and doors shut on same test-day. Classroom F has two more windows with 7.25% of the window opening area and the floor area rate, and 115m opening edges than the classroom A, with the same variables of 5.78% and 77m. The highest CO<sub>2</sub> concentration captured in the classroom F within 90 minutes was 1842ppm; and the highest reading from the classroom A within the same time frame was 2882ppm.

In addition, the researchers observed that the majority of classrooms in the old buildings constructed before 2000 are rectangular in shape, with window opening located along both the longer walls of the classrooms. This arrangement of windows permit greater convective air flow, with no unapproachable corner. Thus, the air quality in such rooms will undoubtedly be greater, and should be encouraged for future designs. Further, the height of a classroom can affect the air quality, as larger headroom impacts upon air pressure affect ambient temperature which can also enhance air exchange in a room (Figure 7)





## 6.4 Installing Mechanical Ventilation and Passive Ventilation Systems

Generally, electric fans located on or by windows can improve air exchange in classrooms (see Figure 8), but this makes too much cold air coming into classrooms directly. Passive roof vents, based on air flow and thermal pressure, can also enhance air exchange (Figure 9). Another option if vents or openings are not permissible in the wall is to install electrical roof vents (Figure 10), but it is not necessarily convenient for users to manually control roof vents during classes; sensor controlled electric roof vents would be a better solution. The thermal collectors can be installed to compensate from heating lost during air exchange. In this case, the relevant costs and issues of maintenance and operation of such ventilation equipment should be carefully considered and managed at design and construction stages.



Figure 8. Classroom Cross-Section – Electric Fans Located On or By Windows Can Improve Air Exchange in Classrooms



Figure 9. Classroom Cross-Section – Mechanical or Passive Ventilation Can Also Enhance Air Exchange



Figure 10. Classroom Cross-Section – Electric Roof Vents

#### 6.5 Compensating with Fresh Air via Corridors

In very cold areas, if it is not possible to open windows during winter, particularly in educational facilities whereby those located close to the window will often find it too cold, another solution is to ensure that fresh air can come from corridors via the windows or doors in corridors. This has been identified an effective way in practice (Figure 11).



Figure 11. Classroom and Corridor Cross-Section – Openings in Corridors Can Support Air Exchange in Classrooms

#### 6.6 Vent Windows

In recently years, tilt and turn windows (Figure 12) have been widely incorporated in educational buildings across China. However, due to their large opening areas, they are rarely used/opened during winter. It has been demonstrated in practice that small vent windows are effective and efficient for air exchange in winter in such cold zones (Figure 13). Vent windows, with small opening areas, are foreseen to be highly effective particularly if they are installed in high up on external walls. The advantages of vent windows are effective air exchange, easily controllable, and they prevent cold outdoor air being blown directly to those sitting adjacent to windows. However, such (small) window vents may not be able to support the large air exchange required in classrooms.



Figure 12: Profile of Tilt and Turn Windows



Figure 13. Profile of Tilt and Turn Windows that Incorporate a Vent Opening

#### 6.7 Buffer Areas on the North Sides of Classrooms

In Scandinavian countries, educational building designs often incorporate buffer areas on the north sides of classrooms (Figure 14) where wind direction is at its greatest, which can be used as cloakrooms, for instance. This can support fresh air exchange but also limit the degree of the cold air directly coming into the learning space.



Figure 14. Plan of Classroom with Buffer Area at North to Support Improved Air Exchange

#### 7. Conclusion

It is more commonly accepted that outdoor air pollution can damage human health, but indoor air pollution can equally impact<sup>[26]</sup>. The risk of poor IAQ is increased by a lack of proficiency and knowledge of how the numerous factors can contribute to poor IAQ, both during design and construction and after occupancy. In many cold zones across China, particularly north-eastern China, the windows in many high concentration educational facilities are rarely opened during winter months to minimize any heat loss. Further, the majority have no mechanical ventilation systems. This contributes to increased CO<sub>2</sub> concentration levels, which has been proven to effect students' performance and even their health. This research has provided the empirical evidence to substantiate this by conducting a series of CO<sub>2</sub> measurements in different teaching spaces. It reveals the serious situations (2800+PPM at peak) in the educational buildings in north-eastern China. Based on the literature review, the CO<sub>2</sub> concentration are normally not more than 2000ppm at peak points in the similar educational facilities in the developed countries<sup>[19][13][27][28]</sup>. The research also implicates that, although the designs of such educational buildings have fulfilled the relevant design and building regulations which are partially reviewed here, the actually usage of the buildings with their facilities, such as windows and artificial ventilation systems are matter to the indoor environment and human comfort of classrooms. This could be a driver to improve the relevant design principles and regulations, and to enhance the building facility management policies in future. This work also offers a number of practical solutions to address IAQ. Further studies on indoor air quality with the development of feasible and effective sensor controlled ventilation systems for education buildings is much needed.

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## ARTICLE A Tale of Two Roofs: A Large Private Organization Achieves High Performance but Reverts to Traditional Procurement Practices

#### Alfredo Rivera<sup>1</sup>\* Jacob Kashiwagi<sup>1</sup>

1. Leadership Society of Arizona, 2429 E Hermosa Vista Dr, Mesa, AZ 85213, USA

ARTICLE INFO	ABSTRACT
Article history Received: 1 April 2019 Accepted: 10 June 2019 Published:	The Best Value Approach (BVA) is a new project delivery method that has been documented to increase performance and value. It does this by changing the traditional project delivery characteristics of managing the expert and focusing on the technical side of the project, to utilizing the expertise of the experts and using performance information and risk mit-
Keywords: Best Value Approach Roofing Facility Management Large private organization Innovation Culture	igation to manage the project. Large organizations have had difficulty in sustaining the BVA. A large private organization agreed to test the BVA on the replacement of a roofing system on one of its facilities. A case study research was performed on this project, using the grounded research approach, to identify if a large supply chain stakeholder can utilize the BVA to sustain high performance, value, and low price at the same time in a highly competitive marketplace. The research proposal is to docu- ment issues and benefits of utilizing the BVA. Identifying why large orga- nizations have an issue with sustaining the approach and being utilized on more projects. The results of the paper will identify issues organizations have with implementing the BVA and the benefits in using the delivery system on construction services. The case study utilizes a stakeholder in the roofing industry supply chain and shows an approach to construction

#### 1. Introduction

The construction industry has been having difficulty delivering services on time, on budget and with high customer satisfaction<sup>[1][2][3][4][5]</sup>. This has been verified by literature research. This portion of the paper will identify the results of what has been found.

Despite improvements, according to a study conducted

in 2015 by the Construction Industry Institute, the following was identified regarding worldwide construction performance<sup>[6][7]</sup>:

• 2.5% of projects defined as successful (scope, cost, schedule, & business).

• 30% of projects completed within 10% of planned cost & schedule.

<sup>\*</sup>Corresponding Author:

Alfredo Rivera,

Leadership Society of Arizona, 2429 E Hermosa Vista Dr, Mesa, AZ 85213, USA Email: alfredo.r@leadaz.org

• 25 to 50% waste in coordinating labor on a project.

• Management inefficiency costs buyers between \$15.6 and \$36 billion per year.

• Rework by contractors is estimated to add 2-20% of expenses to a contractor's bottom line.

• An estimated \$4 billion to \$12 billion per year is spent to resolve disputes and claims.

This has been observed and documented around the world<sup>[8][9]</sup>. Interestingly, this issue is not unique to the construction industry<sup>[5][10][11][12][13][14][15]</sup>. Table 1 shows the delivery of services performance in multiple industries.

A Few Major PM Industries	On Time	On Budget	Customer Satisfaction	Quality
Information Technology	40%	43%	3.6/10	Fair
Construction	25%	32%	N/A	Poor
Health Sector	N/A	N/A	6/10	Poor
Aerospace and Defense	14%	38%	N/A	N/A
Manufacturing	67%	50%	7/10	N/A
Energy	59%	59%	7/10	N/A

Table 1: Performance in Numerous Industries<sup>[8]</sup>

This is echoed by a recent presentation conducted bThis is echoed by a recent presentation conducted by Bechtel President and COO Brendan Bechtel in the construction industry, which he identified that mega-projects within construction services (projects larger than \$100M USD) are 98% cost overrun and delayed, with an 80% average cost increase<sup>[16]</sup>.

The issue is that the industry does not understand the source of the poor performance<sup>[4]</sup>. Although, efforts have attempted to resolve non-performance in the construction industry for the past 25 years, only a few approaches developed in the last decade for the delivery of services have performance documentation showing an increase in customer satisfaction and value (schedule, budget, flexibility, and quality) on construction and nonconstruction projects<sup>[3][17][18]</sup>. Three studies were conducted to identify which approach had the most documented performance information<sup>[4]</sup>:

1. In 2006, the International Council for Research and Innovations in Building and Construction (CIB), one of the largest global organizations that bring international and government research institutes to collaborate on the building sector, sanctioned Task Group 61, to investigate construction performance, with an objective to stimulate global research efforts from its findings, to improve construction overall on a global scale.

2. In 2008, Task Group 61 [later elevated to a working commission called W117 at the end of 2008] conducted a worldwide study to identify any innovative construction methods that used performance measurements as a means to increase project performance. The study filtered through 15 million articles and reviewed over 4,500

articles. Out of the 4,500 articles, it found 16 articles that identified three construction methods being used that showed how customer satisfaction and value on projects, were improved through numerous tests. The Performance Assessment Scoring System (PASS), and the City of Fort Worth Equipment Services Department (ESD - FT), two out of the three systems and after further investigation, were found to either have performance measurements with no identification of its structure and how well it worked, or could not show exactly how it improved project performance through performance measurements<sup>[3]</sup> <sup>[17][18]</sup>. The final system the CIB Task Group identified was a delivery/risk management system called Performance Information Procurement System / Performance Information Risk Management System (PIPS/PIRMS) [also known as the Best Value Approach], developed by an international research group (Performance Based Studies Research Group (PBSRG)) out of the Arizona State University. The Best Value Approach was the only system that had documented performance of industry impact and added value, and how it was structured to implement the advancements it found during test cases in industry.

3. In 2013, PBSRG sanctioned a follow-on worldwide study to the CIB worldwide study in 2008 by Task Group 61. The study's objective was to identify all efforts [research or industry] around the world that are like the international research group, as well as the current construction performance. The study sifted through hundreds of papers, websites, and personal industry contacts, and did not find any approach to delivering services with more documentation showing high performance than the Best Value Approach in the world<sup>[4]</sup>.

#### **1.2 Best Value Approach**

The Best Value Approach (BVA) was developed by Dr. Dean Kashiwagi in 1991. Since then it has undergone multiple name changes including: Performance Information Procurement System (PIPS), Performance Information Risk Management System (PIRMS), and Best Value Procurement. The approach has been applied and investigated by organizations all over the world including: University of Botswana, Brunsfield, Democratic Republic of Congo, NEVI (Netherlands), United States Medical Command, Hazim Consulting: Saudi Arabia, and Simon Frasier University (Canada). The majority of the BVA implementations have been performed with the assistance of the Performance Based Studies Research Group (PBSRG). PBSRG was originally housed under Arizona State University (from 1992 to 2016), but then moved under the International Council for Research and Innovations in Building and Construction Working Commission 117 (CIBW117) in 2017. In the last 26 years more than 130 organizations have used the BVA to improve efficiency in their organizations and receive higher performing services.

The documented performance of the BVA is as follows<sup>[8][9]</sup>:

• Founded in 1992 [26 years of operation] and has documented performance on over 2000 projects and services delivered (construction and non-construction).

• \$6.6B of projects and services delivered with a 98% customer satisfaction and 9.0/10 client rating of process.

• \$17.6M in research funding generated, due to the effectiveness of decreasing buyer cost of services on average by 31% [57% of the time, the highest performing expert was selected and was the lowest cost].

• Contractors/vendors could offer the client/owner 38% more value and decreased client efforts by up to 79%.

• Change order rates were reduced to as low as -0.6%.

• 130 unique clients [both government and private sector] and received 12 National/International Awards.

• The most licensed technology out of Arizona State University [60 licenses].

• It is internationally recognized through repeated testing [Canada, Netherlands, Sweden, Norway, Finland, Botswana, Malaysia, Australia, Democratic Republic of Congo, France].

• Some of the largest projects documented were: \$100M City of Peoria Wastewater Treatment DB project (2007); \$53M Olympic Village/University of Utah Housing Project (2003); \$1B Infrastructure project in Netherlands (2009).

• Some of the highest performing projects documented include: ASU tested BVA in their business services and procurement department, resulting in \$100M of revenue. Changed the entire procurement service industry in the Netherlands through the success of a \$1B infrastructure test that cut procurement cost by 50% and help the project finish 25% faster. As a result, the Rijkswaterstaat won the most prestigious procurement award in the Netherlands, the 2012 Dutch Sourcing Award, and now NEVI [Dutch Professional Procurement Group] is licensing BVA technology and certifying in the Netherlands<sup>[9]</sup>.

The BVA has been audited multiple times in the last 26 years. Two of the audits identified the impact and effectiveness of the BVA in detail:

• The State of Hawaii Audit<sup>[19][20]</sup>.

• The two Dutch Studies on the Impact of PIPS<sup>[21][22]</sup>.

These studies confirmed all BVA performance claims were accurate. Duren and Doree's study found the following results for projects performed in the United States:

• 93.5% of clients who worked with BVA identified that

their projects were delivered on time.

• 96.7% of clients who worked with BVA identified that their projects were delivered within budget.

• 91% of the clients stated that there were no charges for extra work.

• 93.9% of the clients awarded the supplier's performance with greater than an 8 rating (on a scale from 1-10, 10 being the highest performance rating).

• 94% of clients would hire the same supplier again.

The other groups that conducted audits were COE PARC, 2008; Zuyd University & University Twente, 2008; WSCA/NASPO Agreement, 2011<sup>[9]</sup>.

Interestingly, though documenting high performance, one of the major issues identified with the BVA has been the difficulty for organizations to sustain implementation. Out of the 130 organizations that have implemented the BVA, less than 1% have been able to sustain the effort for more than 6 years. The longest implementing organization being Neogard, who have used the BVA for more than 20 years. This issue is more prominent in large organizations. In many cases the BVA was stopped before the organization even tested the process.

Some of the major issues organizations have experienced in following the process and sustaining it are as follows<sup>[9]</sup>:

1. Resistance to the process from client personnel.

2. Client's personnel making decisions to modify the process.

3. Inability to explain the value of the process to the C-Suite.

4. The BVA supporter in the organization retires or leaves the organization.

Interestingly, it has still been difficult for organizations to take full advantage of the BVA, despite having projects that experienced high performing results. This could be due to how different the BVA and current traditional project practices are when delivering services.

The traditional practices (Figure 1 – Quadrant I: Price Based) involve the following when delivering a project/ service:

1. The client develops the technical requirements for a project.

2. Technical information is reviewed by the client to determine the best vendor for the project.

3. The client develops the contract for the project.

4. The client and the vendor partners to deliver the project.

5. The client controls and makes the decisions for the project.

The BVA practices (Figure 1 – Quadrant II: Best Value Approach) involve the following:

1. The vendor develops the technical requirements for a project.

2. Technical information is only shared with the client when a vendor is selected.

3. The vendor develops the contract for the project.

4. The client and the vendor do not partner to deliver the project.

5. The vendor has total control of the project and the client only approves the actions.



Figure 1. Industry Structure

The industry structure diagram in Figure 1, developed by researcher and Dr. Dean Kashiwagi, identifies that the major difference between the price based (low bid) environment and the Best Value quadrant, is that the client utilizes the expertise of the vendor to increase performance instead of trying to manage, direct, and control (MDC) the vendor. The opposite nature of the BVA from the traditional project delivery approaches, may contribute to organizations having difficulty implementing and sustaining it.

To assist organizations to overcome the resistance of the BVA's new ideas and project practices to delivery services, it has been adjusted over the last 10 years. The focus has been on continually simplifying the process and automating normal project delivery methods, to minimize the decision making of the client and ensure the process is followed and can show its value.

#### 1.3 Large Private Organization

In the Spring of 2017, the global facility management director for large private organization (LPO), identified an opportunity within his organization to implement the BVA and be able to document its value, the issues and difficulties with running it, and the reaction of the technical personnel utilizing the process.

The LPO needed to replace their 18-year-old Roof "A". Roof "A" was 70,000 square feet and covered many important upper management personnel (i.e. lawyers and C-suite executives). Between 2013 - 2017, 30

unique reports were filed with the facilities management department (FMD) on leakage. Over the course of four years, the FMD had to replace many damaged ceiling tiles, repair light fixtures, and dry out wet carpet. The occupants became more concerned with massive roof failures at the end of 2016, due to the roof approaching its 20-year life and warranty. The concern was heightened, due to Arizona's impending monsoon season (June to September) 6 months away. Replacement of roof "A" became a high priority project for the FMD.

Although PBSRG had the support of the FMD, it still needed to convince the LPO project management staff to use the BVA and allow PBSRG to support them.

#### 2. Methodology

PBSRG, planned to take the following steps to implement and document the BVA for the LPO's Roof "A" project:

1. Propose using the BVA to the LPO's project management team.

2. Provide education to the LPO's internal staff and roofing contractors.

3. Run BVA.

4. Document issues and difficulties:

a. Review each phase of the BVA and how it was implemented.

b. Identify how the organization dealt with the differences.

5. Analyze the documented information.

#### 2.1 BVA Proposal to LPO

The LPO's FMD invited consultants to bid on the Roof A project. They only had two weeks to choose a consultant. Two consultants expressed interest in bidding on the project. PBSRG was one of the consultants. The FMD requested both parties submit a cost, scope of work and performance information. Table 2 identifies the difference between the two proposals:

1. PBSRG's scope provided more value to the client for the same cost.

2. PBSRG could complete the project 10% quicker.

3. PBSRG's provided past performance information that showed they were experts:

a. 34 years roofing experience (started in 1983 with U.S. Airforce).

b. 20 roofing journal articles.

c. 6 books on roofing.

d. 19 roofing conference publications.

e. Over 2,000 site walks of roofs.

f. Over 100 roofing projects in State of Hawaii alone

g. Over 100 roofing projects at DISD over 4 million square feet

h. Ran projects for: Motorola Scottsdale, Motorola Arlington Heights, IBM, Intel Corp., United Airlines, Honeywell, Facilities Management Group, PECO Nuclear Facility, IPI, State of Hawaii, Dallas Independent School District, Raytheon (Tucson), GSA Region 6).

i. Customer satisfaction is 98%.

j. Saved customers between 10-30% of the cost of projects.

Consultant A	PBSRG
Cost: \$15,000	Cost: \$25,000
Scope of Work	Scope of Work
Review the Owner's Requirements and related information, including schedule, budget, service life expectations, warranties, history, building usage, and contractor insurance requirements.	<ul> <li>Would perform the same scope of work (SOW), but would also include the following:</li> <li>Provide education to internal personnel and vendors.</li> <li>Hold a roof site inspection for all potential vendors.</li> <li>Help write the RFP</li> <li>Hold a clarification phase the ensures the vendor will plan the entire project before an award is given.</li> <li>Require the vendor to submit a weekly risk report that track all project performance metrics with impacts to cost, time, and quality.</li> <li>Provide a close-out report to the LPO that documents the entire project from beginning to end.</li> <li>Help on with any meditation that is needed during the project.</li> </ul>
Schedule:	Schedule:
January: Contract negotiation period	January: Start immediately
February 20: Create request for proposal	February 1: Create request for proposal
March 1: Bid	February 16: Bid
March 20: Evaluation	February 17: Evaluation
March 23: Identify contractor	February 22: Identify contractor
April 20: Anticipated authorization to proceed	March 20: Anticipated authorization to proceed
July 15: Project completion	May 31: Project completion
n/a	June 16: Project report
Performance Information: no documentation was provided	Performance Information: Documentation was provided

PBSRG used the BVA to respond to the bid request and showed clear performance metrics that it was the highest performing vendor. However, for PBSRG to convince the LPO management to award them the project, they had to lower their cost to \$15,000.

Clients focusing on cost instead of performance, is one of the issues with implementing the BVA. Although research on more than 2,000 projects show that large cost savings when delivering services come by hiring an expert, traditional clients continue to hire the lower costing vendor or attempt to force the high performing vendor to lower their cost.

Most organizations do not understand the detrimental impact [in terms of cost, time and quality] of hiring a low performing vendor or forcing a high performing vendor to perform a service, with less cost, then they usually need.

#### **3. Best Value Approach (BVA) Implementa**tion

The Best Value Approach has four phases (see Figure

2):

1. Prequalification: Educates vendors and client stakeholders on the Best Value Approach. Explains to vendors how to be successful in the bidding process. During this time PBSRG also helps the client collect any information required to enable the vendors to bid for the project.

2. Selection: uses a decision-less structure to rate contractors based on level of expertise (performance) and selects the high prioritized one.

3. Clarification: the highest prioritized contractor is required to create a non-technical plan from begin to end that creates transparency for all stakeholders.

4. Execution: the awarded contractor begins the plan they set forth in clarification and measures themselves throughout the entire project.



Figure 2. Best Value Approach

This section will review each step of the BVA and identify how each step was implemented at the LPO.

#### **3.1 Prequalification**

The BVA uses prequalification differently than traditional project delivery models. Instead of the owner identifying what requirements make a vendor qualified, it assumes all vendors are qualified if they decide to bid on the project. The prequalification phase focuses more on educating the vendors on the BVA to ensure they understand what the expectation of the client is and determine for themselves if they are qualified and can deliver the service. The BVA is designed so that a nonqualified vendor will never make it through the process. Thus, non-qualified vendors will only be wasting their own time and resources. The education performed in the prequalification helps them to understand this clearly. This involves explaining expectations of the client, current condition of the service (Roof A, see Figure 8), and the BVA process.

The first group on the Roof A project that PBSRG educated was the ON internal management team. This

was performed in 2 meetings. From these meetings it was documented that the technical workers on the team had a very difficult time accepting the process. Since the BVA minimizes the technical participation of the client, the role of the technical personnel was minimized, which they had a difficult time accepting.

The information PBSRG proposed to provide the vendors were as follows:

1. Budget of the roof (\$8/sq. ft.).

2. Size of the roof and date installed (70,000 sq. ft., reinforced single ply roof in 1995 and modified bitumen roof in 1998).

3. Client Satisfaction of the Roof (client was unsatisfied with previous roofs due to leaking).

4. Deck Composition (North side, insulation is unknown but mechanically fastened down, and South side insulation is glued down on a proposed stainless-steel deck).

5. Number of penetrations [equipment/material on the roof that protrudes from the surface] that the LPO would like removed.





Figure 3. Roof "A" Full Facility View

The LPO's technical personnel felt that more information needed to be given to the vendors and required PBSRG to set up a moisture scan for the roof. A moisture scan identifies what percentage of the total roof has moisture in it. The reason PBSRG proposed to not perform the moisture scan, is because the awarded vendor would have to do it anyway, before being awarded a contract. In addition, performing the scan at that early point in the process would add a couple of weeks to the schedule. They also wanted the contractors to be able to take core samples [see Figure 5] from the roof to verify the roof's layer composition. This caused PBSRG to not only hold an educational session for the vendors but also hold a 2 more roof walk meetings for the vendors.



Figure 4. Roof "A" North Side



Figure 5. Roof "A" North Side

The moisture scan discovered that only 8.4% of the roof detected moisture. See Figure 7 below for results. Neither the core sampling or the moisture scan changed the contractor's pricing. In fact, the expert contractor already knew what percent of the roof had moisture and previously prepared for it. In the end, none of the technical information the LPO wanted to provide the contractors was needed, but due to the traditional way of doing things, the technical people still required it.



#### 3.2 Selection Phase

The selection phase was delayed by a couple of weeks

due to the changes in the prequalification phase. The LPO management team did agree to not create requirements for the vendors but allow the vendors to propose the best roofing system. This was identified in the Request for Proposal sent to the vendors. To select the best value vendor, the vendors were asked to submit bid proposals that included the following components:

• Key personnel proposal form (1 page) – leadership team with references.

• Level of expertise plan (4 pages) – performance claims about roofing project ability, supported with verifiable performance information, and a roof list [includes warranty length, leakage performance, and customer satisfaction].

• Risk management plan (2 pages) – claims about risks that could occur on a project, their experience with it and variable performance information to support.

• Value added plan (2 pages) – options that identify schedule and cost impact.

• Project cost proposal – roof system proposed, its specifications and cost.

• Project schedule (2 pages).

• A proposal for also doing Roof B.

The following evaluation weights were applied to the criteria:

- Level of Expertise, 35%
- Price, 35%
- Interview, 20%
- Risk and Risk Mitigation, 5%
- Value Added, 5%

In total, six bid proposals were submitted by four roofing contractors. Table 3 identifies what the contractors submitted followed by a comparison of the systems in Table 4.

Table 3.	<b>Bid Pro</b>	nosal Reo	uirements	Matrix
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Requirements	Vendor A [10-year coating option]	Vendor B [25 year]	Vendor C [20 year]	Vendor D [20 year]
RFP Cover page/Checklist	х		Х	
Key Proposal Form	х		х	
LE Submittal (LE, RMP, VA)	х		х	
Schedule			х	
Roof Performance List	х	х	х	Х
Actual Performance Info				х
Asbestos		х		Х
Performance Bonding		х		
Penetration/steel platform components removal		х		х
Roof B		х	Х	Х

**Table 4. Roofing System Comparison** 

Company	System	Cost	\$/sq. ft.	Annual \$	Age of Roofs	# of References	Warranty
Vendor B	System 1 (BUR)	\$761K	\$10.74	\$31K	Avg: 2 yrs. Max: 4 yrs.	3	25 years [QA]
Vendor B	System 1 (BUR)	\$659K**	\$9.30	\$27K	Avg: 2 yrs. Max: 4 yrs.	3	25 years [QA]
Vendor C	System 2 (PVC)	\$630K	\$8.53	\$32K	Avg: 2 yrs. Max: 4 yrs.	5	20 years [NDL]
Vendor D	System 2 (SPF)	\$528K	\$7.54	\$27K	Avg: 4 yrs. Max: 5 yrs.	Surveys: 94 Roof list: 47	20 years [NDL]
Vendor D	System 3 (PVC)	\$504K	\$7.19	\$26K	Avg: 5 yrs. Max: 15 yrs.	30	20 years [NDL]

An analysis on the proposals identified the following:

• None of the vendors turned in all the information requested from the Request for Proposal.

• 2 (out of 6) proposal costs were below the budget.

• One vendor was disqualified for turning in a roof system that was only warranted for 10 years (Client wanted a 20-year warranty).

• Only one vendor turned in adequate performance information on their roof system to verify their roof system met the performance expectations of the client.

After seeing the information, it minimized thinking and decision making by the selection committee to determine that the Vendor D System 3 and the Vendor C PVC roof systems as the two options that would move on to the interview stage.

After the interview of both contractor's and their systems, Table 5 shows their final evaluation ratings.

Table 5. Final Evaluation Ratings

No	Criteria	Vendor C PVC	Vendor D System 3
1	Level of Expertise rating	17.5	17.5
2	Risk Management Plan rating	2.5 2.5	
3	Value Added rating	2.5	2.5
4	Interview rating	18.3	19.5
5	Cost	28.0	35.0
	Total Score	69.0	77.0

Vendor D System 3's option was identified as the best value. It was \$70K below budget, \$127K below competing PVC roof, and had greater documented performance information [30 references, average age of roof is 5 years, maximum age is 15 years].

#### **3.3 Clarification Phase**

The clarification kick-off meeting is the first time the vendor brings in their entire leadership team to discuss the details of the project with the LPO. The vendor was expected to have the following documents prepared to present:

1. Full draft plan.

2. A detailed schedule by roof area.

3. A detailed cost estimate, including the requested value-added items. Any removal activities and costs should be separated from the installation of new material. The rational is that the LPO is charging the project from two different sources of money.

4. Detailed specifications with any changes proposed.

5. Manufacturer's warranty with any changes proposed.

The contractor did not come prepared with all the above requirements. This led to the LPO identifying numerous documents missing:

• Safety plan.

· Copy of warranty.

• Letter that roof system meets FM Global requirements [NAV #].

• Roof system section, attachment pattern, and all flashing details and cap work.

- City of Phoenix Permit.
- Steel removal plan.
- Roster for safety training and completion of it.
- Updated cost breakout to include above items.

The Vendor proposed a start date of 3/27/2017 with an end date of 5/22/2017, which would meet the deadline requirement of 5/31/2017. Interestingly, in the clarification kick off meeting, the LPO identified a new requirement previously unknown to anyone. They identified that their facilities are insured by FM Global and need to maintain an FM Global standard rating that meets their minimum. Currently, the contractor felt comfortable they would meet the requirement, but the LPO's technical staff required the contractor to perform a pull test in order to show the roof would maintain the FM Global minimum standard. A pull test is when a screw is drilled into the deck, and a machine pulls the screw out of the deck. The pressure that was required to extract the screw out of the roof deck is recorded and compared to the standards to identify if it meets the minimum. The LPO was concerned that the screws holding down the roof would not meet the minimum. The pull test results showed that the strength requirement to screw (fasten) down the roof system met the FM Global minimum standard (see Figure 8).



Figure 7. Pull Tester

In addition, the LPO required the contractor to bring in a professional structural engineer to verify if their plan to remove the steel structure (far left pop out in Figure 9) would not compromise the integrity of the roof.

The additional requirements from the LPO were not necessary, but the LPO's technical personnel made a decision to require them. Their decision making did not change the vendor's plan but did delay the start of the project by a month, putting the project at risk of not completing before monsoon season.

## **3.4 Execution Phase and BVA Roof "A" Project Results**

Despite the contractor not submitting a full plan until weeks after the project started, the roof was completed and the LPO was satisfied. The project was completed one month after the intended deadline but was 100% due to the LPO. Despite the schedule delay, the monsoon season was not in effect in Arizona at that time. In total, the LPO saved \$270,000 on roof "A" and rated it 10/10. See comparison of before and after in Figures 9 and 10.



Figure 8. Roof "A" Before



Figure 9. Roof "A" After

#### 3.5 Analysis of Issues in Implementing BVA

Throughout PBSRG's implementation of the BVA at the LPO, the biggest issue was the resistance from its technical personnel. If PBSRG did not bring in Dr. Dean Kashiwagi, who had been running BVA since 1992, the technical personnel would not have even tried the approach. Many times, the technical personnel would challenge the BVA ideas, and even after it was proven correct on the project, they still would claim the ideas was flawed. In fact, even after the success of Roof "A", the LPO team immediately made a decision to deviate from fully following the BVA and revert to their traditional way of doing business on their secondary roof project [Roof "B"]. The next section will explain the results of Roof "B".

Additional issues documented while implementing the

BVA were the following:

1. The need to convince multiple stakeholders and gain their approvals.

2. The BVA practices are different than the traditional way of doing things; it is difficult for the personnel to follow them.

3. Current relationships with vendors. Traditional project delivery is based upon creating a relationship between the client and the vendor. BVA requires the client to minimize the relationship and base the selection and execution off identifying the expert and letting them do their job.

#### 3.6 Traditional Roof "B" Comparison

Due to the cost savings from Roof "A", the LPO decided to also complete another roof that was in need of replacement, Roof "B". Roof "B" was similar to Roof "A". The layers of Roof "B" were as follows:

- GBS granulated top layer.
- SP4 (smooth inner ply).
- Vented Base sheet.
- 2 polyisocyanurate.

Although, Vendor D was identified as the high performing vendor for Roof "B", the LPO decided to not follow the BVA prioritization and chose Vendor C [roof incumbent] to deliver the roof (see Table 6), due to their history with the contractor. The LPO did try to follow the BVA steps, however, after the initial clarification steps they stopped coordinating with PBSRG. Without the help of PBSRG, the LPO began falling back into the traditional model of management, direction, and control (MDC). PBSRG Director Dr. Dean Kashiwagi warned the LPO to stick with the structure and beware of developing a relationship with the contractor and the importance of sticking with the BVA process.

Table 6.	. Roof "B"	Bid	Proposal	Comparisons
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Company	System	Cost	\$ / s q . ft.	Warranty
Vendor B	N/A	\$ 81,382.00	\$1.85	n/a
Vendor C	60 Mil Fleeceback TPO	\$ 167,000.00	\$3.80	20 years [NDL]
Vendor D	GAF Acrylic/Silicon Coating	\$ 97,960.00	\$2.23	15 years [Emerald Pledg Limited]

The LPO project management team spent time working with the vendor on the technical aspect of the proposed roofing system, requiring the contractor to perform a moisture scan and do an adhesive test [test how much wind is needed to uplift the top layer of the roof system from the deck] of the roofing material with the existing modified bitumen system. The LPO team also was concerned with the manufacturer's lack of warranty for the existing roof system. These issues along with waiting to get a budget for Roof "B" approved from internal management, caused a project start date of 5/24/2017 delay by 2 weeks [initial end date of 6/16/2017].

The contractor started the project on 6/7/2017 and projected to finish it on 7/15/2017. The major risk of this adjusted time frame was monsoon season. The last two weeks of the project had a high chance of rain storms. The contractor was awarded the project without successfully completing the clarification phase, and did not consistently submit a weekly risk report, which required them to report on the project each week.

Most of the project went well, and was looking to be completed on 7/3/2017, 12 days quicker than the adjusted schedule. The day before the contractor would finish the roof (7/2/2017) a major rain storm swept through Phoenix and uplifted 20% of the new TPO roof system (see Figure 11), destroying the existing modified bitumen system underneath as well. It was proposed that this issue occurred because the contractor does not normally seal up the ends of the roof until the very last step. This enabled a storm to come through and have the ability to get underneath the new TPO roof system and uplift a portion of it.

Roof "B" would end up completing, 3 months over schedule in October. The decision was made to remove the entire existing Roof "B" and replace it with a new roof. Insurance would end up covering the cost of the roof.



Figure 10. Roof "B" After Storm

#### 4. Conclusion

The Best Value Approach (BVA) is a new approach that has been documented to improve the performance and efficiency of delivering services and projects. However, it has been difficult to sustain at organizations, especially larger ones. This paper documented a case study of a large private organization (LPO) that utilized the BVA on the replacement of a roofing system as a test to document its value, the issues and difficulties with running it, and the reaction of the technical personnel utilizing the process. To select, hire and deliver the project was done in record time and with high performance.

Despite the high performance and decrease in management, PBSRG identified that the biggest issue in implementing BVA at large organizations is due to the resistance caused by the technical personnel not wanting to switch their traditional approach of management, direction, and control (MDC) of the vendor to the utilization of their expertise.

However, despite the technical personnel not agreeing with the BVA and even making minor adjustments to it, it is able to override their resistance and deliver amazing performance. It requires the BVA implementers to be an expert at using information and metrics to simplify the project and create transparency, to minimize any decisions that the technical personnel would make.

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#### ARTICLE

## Energy Analysis of a Real Industrial Building: Model Development, Calibration via Genetic Algorithm and Monitored Data, Optimization of Photovoltaic Integration

Salvatore Ardizio<sup>1</sup> Fabrizio Ascione<sup>1</sup> Nicola Bianco<sup>1</sup> Gerardo Maria Mauro<sup>2\*</sup>

#### Davide Ferdinando Napolitano<sup>3</sup>

1. Università degli Studi di Napoli Federico II, Department of Industrial Engineering, Piazzale Tecchio 80, 80125 Napoli, Italy

2. Università degli Studi del Sannio, Department of Engineering, Piazza Roma 21, 82100 Benevento, Italy

3. Università degli Studi di Bergamo, Via Salvecchio, 19, 24129 Bergamo, Italy

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#### ABSTRACT

This study performs the energy analysis of a real industrial building, located near Naples (South Italy). The used approach includes three phases: development of the energy model, model calibration based on monitored data and optimization of photovoltaic (PV) integration. Monitored data provide the monthly overall electricity demands of the facility for different years, while the load factors of industrial devices are not available. Thus, the assessment of hourly and daily trends of electricity demands and internal heat loads is not possible from monitored data. In order to solve such issue, the energy model of the building is developed under EnergyPlus environment, taking account of the existing PV system too. A genetic algorithm is run by coupling EnergyPlus and MATLAB® to properly calibrate the hourly load factors of the devices in order to achieve a good agreement between simulated and monitored values of monthly electricity demands. Finally, the installation of further PV panels is investigated to optimize the photovoltaic integration with a view to cost-effectiveness. The robustness of the optimization process is ensured using the calibrated energy model, which provides reliable hourly values of building electricity demand. Results show that the electricity produced by the additional PV panels is around 160 MWh per year, while the payback period is around 10 years demonstrating the financial viability of PV integration.

#### 1. Introduction

B uildings are responsible for about 36% of total world energy consumption and for about 40% of CO<sub>2</sub>-equivalent emissions<sup>[1]</sup>. At EU level, the

situation is similar<sup>[2]</sup>. For this reason, one of the main routes to follow in order to preserve the world we live in is the sustainable development of the building sector, with the aim of reducing both polluting emissions and energy

Gerardo Maria Mauro,

<sup>\*</sup>Corresponding Author:

Università degli Studi del Sannio, Department of Engineering, Piazza Roma 21, 82100 Benevento, Italy Email: germauro@unisannio.it

consumption. As mentioned, a large share of the latter is due to building facilities, from residential to industrial ones. The optimization of building energy performance is crucial to pursue sustainability. That is why, many countries have embarked on a common path for decades, in order to reduce the environmental impact of the building sector<sup>[3][4][5][6]</sup>. For the same reason, over the last decades, there have been several studies focused on building energy modeling, calibration and optimization<sup>[7]</sup> <sup>[8]</sup>, using different approaches, methodologies and optimization algorithms, in particular, numerical evolutionary ones, such as genetic algorithms<sup>[9][10]</sup>, particle swarm optimization<sup>[11][12]</sup>, and ant colony optimization<sup>[13]</sup> <sup>[14]</sup>. Indeed, evolutionary algorithms are particularly suitable for building optimization problems, since reliable whole-building performance simulation tools usually do not provide continuous and differentiable objective functions, thereby rendering the use of analytical/ classical optimization methods<sup>[15][16]</sup> extremely difficult. Definitely, the robustness of the optimization procedure is strictly related to the accuracy of the developed building energy model, which should be properly calibrated based on real data – to provide reliable outcomes<sup>[17]</sup>. Therefore, the optimization success strongly depends on the accuracy in model development and calibration. In other words, modeling (and thus simulation), calibration and optimization are fundamental inter-dependent aspects when addressing building energy performance<sup>[18]</sup>.

In 2005, Wright & Alajmi (2005) investigated the robustness of a genetic algorithm (GA) search method in solving an unconstrained building optimization problem<sup>[19]</sup>, concluding that it is possible to find near-optimum solutions with a competitive (low) number of building performance simulations. In 2011, Banos et al., proposed a review of the state of the art in matter of computational optimization methods applied to renewable and sustainable energy systems<sup>[20]</sup>, showing that the number of research papers using optimization methods to solve renewable energy problems had increased dramatically in recent years. The study concluded that the use of heuristic approaches, Pareto-based multi-objective optimization and parallel processing are promising research areas in the field of renewable and sustainable energy. In 2012, Heo et al. focused on the calibration of building energy models<sup>[21]</sup>. They introduced a probabilistic methodology – based on Bayesian calibration - supporting large scale investments in buildings' energy retrofit. This methodology permits to assess the risks associated with each of the retrofit options considered. In 2015, Ascione et al. proposed a new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy

performance<sup>[22]</sup>. The optimization procedure was based on the coupling between MATLAB®<sup>[23]</sup> and EnergyPlus<sup>[24]</sup> by implementing a GA and supported the evaluation of profitable and feasible packages of energy efficiency measures applied to buildings. Thermal comfort was also taken into account as constraint and, finally, a ranking of the retrofit measures based on the intervention priority was estimated by identifying the most cost-effective and energy-efficient measures. In 2016, Royapoor and Roskilly performed the calibration of a 5-storey office building EnergyPlus model using energy and environmental data, collected through environmental sensors and a weather station<sup>[25]</sup>. According to the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) guideline 14-2014<sup>[26]</sup>, the model was calibrated to achieve Mean Bias Error (MBE) values within  $\pm$  5% and Cumulative Variation of Root Mean Square Error (CV(RMSE)) values below 10%. In the same vein, in 2017, Hong et al. carried out the calibration of a building energy model by using an optimization algorithm to minimize the CV(RMSE), set as objective function<sup>[27]</sup>. A similar approach was used by Lara et al., who compared the results obtained through the brute-force approach and an evolutionary optimization method adopted with the aim to calibrate an educational building model located in the North of Italy<sup>[28]</sup>. In 2017, Fan and Xia implemented a multi-objective optimization model for energy-efficiency building envelope retrofit with rooftop photovoltaic systems<sup>[29]</sup>. The optimal solutions were characterized as concerns economic indicators too, e.g., net present value and payback period, in order to support the decision-makers. In the same year, Cacabelos et al. proposed a novel building calibration approach, which consisted into dividing the building into several sub-models and calibrating them separately<sup>[30]</sup>. The results of the multi-stage calibration showed really good agreement as for energy consumption and temperature trends with lower values of MBE and CV(RMSE) on both hourly and monthly basis compared to standard calibration methodologies. Very recently, in 2019, Gao et al. investigated the different levels of data transformation between building information modeling (BIM) and building energy simulation process, including geometry (step 1), material (step 2), space type (step 3), thermal zone (step 4), space load (step 5), and HVAC system (step 6)<sup>[31]</sup>. The accuracy in data transformation is fundamental in achieving a reliable building energy model using the increasingly widespread BIM platforms. In recent times, the efforts for improving building energy efficiency are often focusing on renewable energy source systems, especially solar ones, given the high cost-effectiveness that such technologies ensure compared to the past. In 2019, Venkateswari and

Sreejith presented a comprehensive review on the factors affecting the efficiency of a solar photovoltaic (PV) cell, focusing on employed materials, maximum power point tracking (MPPT) techniques and devices used for DC-AC conversion<sup>[32]</sup>. In this regard, silicon is widely used as cell material because of its abundant availability and low cost. However, several promising multi-junction solar cell technologies ensure significantly higher values of energy efficiency and good economic indicators. Al-Addous et al. investigated the influence of weather conditions on PV power production and proposed reliable experimentally derived models to assess PV actual efficiency as a function of different temperature and radiation<sup>[33]</sup>. In addition, El Baz et al. focused on the development of a model that was capable to accurately assess the output power of a PV system according to the weather forecasts<sup>[34]</sup>. Van der Meer et al. studied the probabilistic forecasting of a residential PV power generation by means of the application of Gaussanian Processes<sup>[35]</sup>. Camilo et al. investigated the economic profitability of different PV system configuarions and concluded that storage systems are not a profitable solution, because the investments required are too high, despite the cost reduction produced, thus, the injection of the surplus into the grid is more convenient<sup>[36]</sup>.

To this background, the proposed study concerns energy modeling, calibration and optimization through a comprehensive approach, which addresses a real industrial building located near Naples (South Italy). The aim is to develop a reliable building energy model in order to perform a robust optimization of photovoltaic integration. The methodology used includes three phases, as detailed in the following section: development of the energy model, model calibration based on monitored data and optimization of photovoltaic integration.

#### 2. Methodology

The methodology used includes the following three phases:

I. Development of the energy model of the investigated industrial building, including all devices used for industrial processes;

II. Model calibration by means of the implementation of a genetic algorithm and the comparison of simulated data with real monitored data;

III. Optimization of the photovoltaic integration with the aim of minimizing global costs.

#### 2.1 Energy Model Development

Firstly, the well-known graphical interface Design-Builder is used in order to realize the geometrical model of the industrial building and its subdivision into thermal zones<sup>[37]</sup>. It is fundamental to properly define the stratigraphy of the different elements constituting the envelope of the building, because they strongly affect the heating and the cooling demand.

Consequently, the dynamic energy simulator Energy-Plus is used for the development of the energy model of the building, since it ensures high accuracy and detail in modelling<sup>[24]</sup>. Great attention should be paid to the definition of:

1. the usage profiles for each thermal zone - i.e., the hourly schedules of occupation, people activity, clothing resistance, and so on;

2. the typology and the availability of the HVAC system;

3. the typology of the photovoltaic generator and its size.

Once the building model has been defined, EnergyPlus is used to run simulations. In order to do so, it is important to properly set the main boundary conditions of the simulations. These latter are described as per follows:

• Conduction Transfer Functions as heat balance algorithm;

- six timestep per hour;
- 20 maximum iterations for the HVAC system.

Finally, to run the dynamic energy simulations proper climatic data are necessary. The ones used are those of the authoritative ASHRAE IWEC<sup>[38]</sup> and are encoded in a proper ".epw" weather file, available at the EnergyPlus online database<sup>[39]</sup>.

#### 2.2 Energy Model Calibration

The model calibration is fundamental to achieving the schedules related to industrial devices' operation and load factors over a typical year. The accurate modeling of such devices is fundamental to obtaining reliable outcomes from simulations because the devices strongly affect building electricity consumption and internal heat loads, and thus cooling demand. In this regard, energy models of buildings can be very complex and contain a large number of input data. The accuracy of an energy model, especially when it comes to calibration, depends on the user's ability and experience in defining the input data. These parameters must, in fact, lead to a model whose energy performance reflects as closely as possible to the measured energy performance of the existing building being calibrated. The high number of input data that are required for the definition of a detailed thermal energy model makes the calibration a problem with an undefined number of solutions. The most typical approach used in the calibration of a model is the empirical one, based on the modification of the parameters "by trial and error" based on experience<sup>[40]</sup>.

The steps of a correct calibration can be delineated as follows:

• Step 1: Develop an initial model of the investigated system with input data based on experience, expertise and consistency with the real system;

• Step 2: Perform an iterative procedure to improve the developed model in order to minimize error indicators, denoted as calibration indices, achieved by comparing the model outputs with real data or outputs provided by another validated (and thus reliable) model. This iterative procedure can be carried out "by trial and error" or by using optimization algorithms. In this latter case, the objective function to be minimized is provided by the mentioned error indicators. The proposed methodology uses a genetic algorithm for this purpose.

• Step 3: When a stop criterion is satisfied the iterative procedure stops and the calibrated model is achieved.

The mentioned calibration indices (i.e., error indicators) are generally achieved by comparing outputs related to energy consumption, because the real values are generally known from the building bills. For example, Pan et al. used data on electricity consumption from the sub-meter to calibrate the internal loads of the energy model of a high-rise commercial building in Shanghai<sup>[41]</sup>. Therefore, calibration methodologies generally consider monthly data related to electricity consumption to assess the error indicators of the developed model. This information is generally available for most buildings, though not all. Concerning the used metrics for calibration indices, the proposed methodology refers to ASHRAE Guideline 14-2014<sup>[26]</sup> by assessing the Mean Bias Error () and the Coefficient of Variation of Root Mean Square Error (), which are defined by equations (1) and (2), respectively:

$$MBE = \frac{1}{m} \sum_{i=1}^{m} \frac{(I_i - y_i)}{y_i} \quad (1)$$
$$CV(RMSE) = \frac{\sqrt{m \sum_{i=1}^{m} (I_i - y_i)^2}}{\sum_{i=1}^{m} y_i} \quad (2)$$

where:

•  $I_i$  is the simulated energy consumption of the *i*th month;

•  $y_i$  is the measured energy consumption of the *i*th month;

• *m* is the number of months, set equal to 12 because a whole year is considered.

According to ASHRAE Guideline 14<sup>[26]</sup>, when the absolute values of the MBE and the CV(RMSE) are smaller than 5% and 15% respectively, the model can be considered to be well-calibrated.

As mentioned, the iterative improvement of the energy model is performed by running a genetic algorithm (GA), as shown in Figure 1. The aim is to calibrate the schedules related to industrial devices' operation and load factors. The objective function (F) to be minimized is the absolute difference (*dEE*) between the simulated electricity consumption and the real monitored one (F=dEE). The decision variables are provided by the hourly load factors of industrial devices during a typical working day. They are encoded by the vector of bits <u>x</u>. The GA stops when it is achieved a maximum number of generations ( $g_{max}$ ), i.e., iterations. After that, the MBE and the CV(RMSE) are assessed according to equations (1) and (2), because the model can be considered calibrated if these values are lower than 5% and 15%, respectively.

The GA conducts a smart search within the solution domain, since it permits to investigate only a limited number of solutions, which are chosen by the optimization engine. In particular, the evolution, i.e., improvement, of a population of individuals (i.e., solutions) is performed, through successive generations (i.e., iterations) according to the processes of selection, mutation and crossover<sup>[42]</sup> <sup>[43]</sup>. The logic improvement is the minimization of the objective function. The GA allows to strongly reduce the computational effort compared to an exhaustive search or a "trial and error" procedure. In this study, most GA parameters take the same values employed by Ascione et al in 2016 and 2017<sup>[42][43]</sup>. Regarding the population size s and the number of generations, they should be properly set, as the reliability of the results and the computational time are crucially affected by them. Ascione et al. assessed that reliable s values are included in the range 2-6 times the number of decision variables<sup>[42]</sup> – in this study, it is set equal to 4 - whilst reliable values are 10-100 generations - in this study, it is set equal to 30.



Figure 1. Flowchart of the Genetic Algorithm Implemented for Model Calibration

#### 2.3 Optimization of Photovoltaic Integration

In this phase, the optimization of the photovoltaic (PV) integration is performed by considering the existing PV system, installed on the building roof. The energy model calibration, performed in the previous phase, is essential in order to achieve a robust optimization.

Initially, the existing photovoltaic system is accurately modeled under EnergyPlus environment, in order to have a simulated PV electricity production as close as possible to actual monitored data.

Then the PV integration is optimized in order to achieve cost-optimality, i.e., the minimization of global costs.

The Global Cost (GC) of a durable good is composed by the purchase cost, by all the necessary expenses supported for its use during its useful life, as well as by the residual value that the good possesses at the end of its useful life. The assessment of the global cost aims in assisting decision makers in choices regarding the opportunity to invest in the process building, considering the phases of conception, construction, building management. The useful life of a building can be divided into three main phases:

• *Initial phase:* from programming the intervention up to his realization;

Intermediate phase: phase of occupation and management of the building;

• Final phase: demolition or sale of the property.

The structure of the global cost is also closely connected to these three phases, as stated by the European Union guidelines<sup>[4][44]</sup>:

$$GC = AF * RC + IC - IN - RV$$
 (3)

where:

• *AF* is the annuity factor. It is used to calculate the present value of any future cash flow until the year "n", taking into account the discount rate "a" – usually, set equal to  $3\%^{[4][44]}$ . Furthermore, the AF is assessed by the following equation (4):

$$AF = \frac{1}{a} \left( 1 - \frac{1}{(1+a)^n} \right) \quad (4)$$

• *RC* is the annual running cost;

• *IC* is the initial cost. It is the fund needed to start up the "business";

• *IN* is the incentive that usually the Governments give to the stakeholders in order to make certain "businesses" more affordable. In this case it was assumed equal to 0;

• RV is the residual value. It is the value after deprecia-

tion, which is the book value of the asset. This value, in this study, was assumed equal to 0 for precautionary reasons, because RV is calculated from now to 20 years and for this reason it is close to 0.

Another critical element in the calculation of the global cost is represented by the *useful life* (n) of the building. Usually, differential useful lives are considered depending on the different building types, the different technological subsystems or the subject performing the analysis. In this study, the calculation period is assumed equal to 20 years as recommended for non-residential buildings by EU guidelines<sup>[4][44]</sup>.

For a complete analysis of the investment regarding the enhancement of the photovoltaic system, besides global cost savings, further meaningful financial indices are assessed to support the decision maker: SPB, DPB and NPV.

The *simple payback period (SPB)* is the length of time required to recover the cost of an investment. It is an important determinant of whether to undertake the investment, and can be assessed according to equation (5).

$$SPB = \frac{Investment Cost}{Annual Cash Inflows}$$
(5)

The discounted payback period (DPB) is similar to the SPB, but it takes account of discounted (and not constant) cash flows, therefore it is higher than SPB and provide a more reliable metric of the investment profitably. It can be assessed according to equation (6):

$$DPB = -\frac{\log(1 - SPB * AF)}{\log(1 + AF)} \quad (6)$$

A general rule to consider when using the discounted payback period is to accept projects that have a payback period shorter than the target timeframe.

#### 3. Description of the Case Study

The considered case study is an industrial building (Figure 2 and Table 1), a metalworking plant, located near Naples (South Italy). The gross floor area of the building is about 4800. The glazing area represents about 5% of the floor area and about 10% of the external wall area. The plant consists of three blocks:

• the first one is divided in two floors and it is occupied by the offices and the production line;

• the second one is a one-storey block, used for the warehouse and the workshop;

• the last one was recently purchased and it is a shed that will soon be put into operation as workshop and to extend the production line.



Figure 2. Rendering of the Investigated Building

Case study					
Location	<b>District</b> of Naples				
Category	Industrial building				
Gross Floor Area	4800				
Conditioned Floor Area	1700 m <sup>2</sup>				
Levels	2				
Level Height	4 m				
Thermal Zones	27				
Glazing Area	235				

Table 1. Overview About the Case Study

In the first block, each storey has an internal height of 4 m and are connected by a staircase. There are windows on all the facades with the aim to achieve the total building windows' surface (i.e., about 235 ). The geometrical model of the building has been realized with the graphical interface DesignBuilder®<sup>[37]</sup>. It has been subdivided in several thermal zones, which are different from its real subdivision in zones. In fact, a thermal zone is a part of the building that has a sufficient spatial uniformity in the temperature (and possibly in the humidity) of the air and for which there is a single and common predetermined value of the controlled variable (temperature and, possibly, set-point humidity). In addition, a thermal zone has the same type of occupation and intended use, and is served for the purpose by a single type of system, or by two complementary types. In this building, 27 thermal zones can be identified: in the first block, 10 are located at the first storey and 12 at the second one; in the storage area, there are 4 thermal zones; finally, the third block is supposed to be constituted by only one thermal zone (the shed). In order to conduct an accurate dynamic simulation, it is necessary to accurately define the geometry model and all the time-schedules concerning the end-use of each thermal zone as well as the operation parameters of the HVAC (heating, ventilation and air conditioning) systems.

The present study addresses only the first building

block because the second one is characterized by very low and occasional energy consumption, while the third one has no energy consumption at all as it is an empty space, as mentioned previously.

Regarding the energy model, it is very important to consider the elements that have the highest energy consumption of the whole facility. Therefore, the consumption related to the chiller for space cooling and to the machines of the production line were assessed, other than the lights. A diesel fuel boiler is present as a heating system. However, as the main aim of this study concerns the economical convenience of a PV integration, the diesel consumption related to the heating system - which is negligible compared to the other consumption voices - is not considered. Thus, it is supposed that fan coils are used only for cooling. The building is equipped with an electric air-cooled chiller, which has a nominal coefficient of performance (COP) equal to 3.14. It is important to outline that not all the thermal zones are equipped with elements of the HVAC system.

In the firm there are 63 industrial devices, divided as follows: most devices relating to the production line are located at the groundfloor, while the rest of the devices are situated in the warehouse; these, however, are manual machines. The most extended thermal zone is the "spark erosion" one, situated at the groundfloor. As expected, as this is the biggest zone with the highest number of machines, it is, consequently, the zone with the greatest energy consumption.

#### 4. Results and Discussion

#### 4.1 Calibration

In order to have a reliable energy model of the building, the proper calibration of the operation of the industrial devices of the production line is fundamental. Unfortunately, there is no data on the manufacturability on a monthly basis of the devices because the facility works on commission, thus it is very difficult to establish a precise energy consumption for each device. Therefore, as explained in Methodology, a calibration process making use of the coupling between the dynamic energy simulator EnergyPlus and the optimization engine MATLAB® is used in order to evaluate the schedules of load factors for such devices. More in detail, a genetic algorithm is implemented in MATLAB® to identify the combination of load factors that month by month assures the lowest difference in terms of electricity consumption between the simulation results and real monitored data related to 2017. Table 2 compares real monitored data of the electricity consumption of industrial devices for 2017 and 2018 against simulated outputs of the calibrated model, reflecting very good model consistency with real data.

Table 2. Electricity Consumption of I	ndustrial Devices: Simulated Outputs of
the Calibrated Model vs Real	Monitored Data of 2017 and 2018

	Electricity demand					
Month	Simulated data [kWh]	Real data of 2017 [kWh]	Discrepancy: Simulated vs Real 2017	Real data of 2018 [kWh]	Discrepancy: Simulated vs Real 2018	
January	112'352	112'303	0.044%	120'406	-6.69%	
February	103'794	103'723	0.068%	109'731	-5.41%	
March	106'449	106'349	0.094%	121'411	-12.32%	
April	105'016	104'915	0.096%	117'637	-10.73%	
May	116'824	116'745	0.068%	132'896	-12.09%	
June	126'866	126'819	0.037%	134'868	-5.93%	
July	134'076	133'994	0.061%	147'477	-9.09%	
August	121'603	121'576	0.022%	113'676	6.97%	
September	116'511	116'487	0.021%	124'731	-6.59%	
October	113'744	113'736	0.007%	119'956	-5.18%	
November	113'008	112'894	0.101%	114'147	-1.00%	
December	117'962	118'016	-0.046%	119'822	-1.55%	
Total	1'388'205	1'387'557	0.047%	1'476'758	-6.00%	

Table 2 shows the measured values of electricity consumed by the facility, around 100 MWh per month, and compares them with the result of EnergyPlus simulation making use of the optimal combination of load factors for the industrial devices. Differences are very low, especially for 2017, which means that the model has been properly calibrated.

Overall, in 2017, the electricity required is around 1'388 MWh. The non-linearity of the electricity demand, which is due to the fact that the firm does not work in series but works on commission, leads to a non-linearity of the energy values required month by month. In fact, the devices of the production line do not work every day, every hour and with the same work shifts, but there are variations of processing day by day depending on the requests. As mentioned, the load factors of each machine are obtained by means of an optimization process making use of a genetic algorithm, which provides the processing coefficient of each device. The load factors of each device are very low. In fact, they are generally equal to 0.30 or 0.40, and in some cases, they are 0.00. In few cases, peaks of 0.80 or 0.90 are reached. This is due to the main feature of the company that works on commission, therefore this does

not allow to have a calibration linearity. Furthermore, each process requires an alternate use of several devices, which is why the load coefficients are often low, since a single product to be processed is subject to a machining chain (eg, turning, milling, erosion, etc.).

The results of the simulation are compared with the measured data for 2018 too, in order to evaluate the goodness and the robustness of the calibration. Table 2 shows that electricity consumption has slightly increased compared to the previous year, probably due to a change in processing fees and the implementation of new processing industrial devices. In fact, in 2018 it is noted that on average the monthly values settle around 110/120 MWh and a total of 1'477 MWh per year. It is possible to note an increase of around 10% compared to the previous year. This involves a greater variation than the simulated values even if they are always very low percentages around 3-4%. Here, too, it can be noted, for example, that in July the demand for electricity is around 148 MWh, while for other months it is around 30 MWh less, demonstrating that the industrial devices do not work linearly month by month but are dependent on customer requests.

#### 4.2 Photovoltaic Integration

On the main surface of the first block, the facility presents a photovoltaic system on a surface of approximately 1710. This photovoltaic system has a peak power of 224.64 kWp and is connected to the electricity grid, Enel, in medium voltage (MT). The plant is made of monocrystalline silicon panels with peak power of 150 W per panel, maximum power point voltage of 18.5 V, maximum power point current intensity of 8.62 A, open circuit voltage of 22.75 V, short circuit current intensity of 8.62 A, module efficiency of 15%, panel surface around 1 m<sup>2</sup>.

The roof on which the system is built is flat and for the installation of the modules an inclined structure of 5° (Tilt) has been built and oriented to the south to optimize the production of the plant itself. The modules are firmly anchored to aluminum structures attached to concrete supports resting on the roof. The PV generator consists of 864 photovoltaic modules, eight string inverters each of which has two independent MPPT (Maximum Power Point Trackers). Three strings are connected to each MPPT of each inverter and each string is composed of 18 modules connected in series.

The existing PV system produced around 305 MWh in 2017 and 285 MWh in 2018, and this electricity was self-consumed with 0% injected into the network. Table 3 shows the electricity production of the existing photovoltaic plant by comparing simulated outputs against real monitored data of 2017 and 2018.

	Electricity production of existing Photovoltaics						
Month	Simulated data [kWh]	Real data of 2017 [kWh]	Discrepancy: Simulated vs Real 2017	Real data of 2018 [kWh]	Discrepancy: Simulated vs Real 2018		
January	10'865	11'758	7.59%	10'758	0.99%		
February	14'498	12'544	15.58%	10'411	39.26%		
March	23'076	21'205	8.82%	19'400	18.95%		
April	28'663	32'224	-11.05%	31'669	-9.49%		
May	38'582	39'547	-2.44%	33'600	14.83%		
June	38'057	40'833	-6.80%	38'700	-1.66%		
July	40'578	41'211	-1.54%	39'678	2.27%		
August	36'084	37'026	-2.54%	32'076	12.50%		
September	26'307	27'667	-4.92%	28'089	-6.34%		
October	19'409	22'894	-15.22%	18'854	2.94%		
November	11'888	11'937	-0.41%	11'667	1.89%		
December	9'640	7'907	21.92%	9'723	-0.85%		
Total	294'920	306'753	-3.86%	284'625	3.62%		

 Table 3. Electricity Production of the Existing Photovoltaic Plant: Simulated

 Outputs vs Real Monitored Data of 2017 and 2018

The electricity production of the PV system depends on some factors, which can explain the difference between years 2017 and 2018:

• the sun radiation is clearly the main factor affecting electricity production and it is not the same for all years;

• the temperature makes the difference and affects the yield. The optimal temperature is generally estimated at around 25 °C. In this case the classic photovoltaic panel has the best conditions to produce energy. Excessive overheating or an insufficient level of ventilation causes a proportional decrease in production;

• the presence of dust and dirt on the modules hinders the full receptivity of the solar irradiation on the photovoltaic cells;

• the passage, or worse the constant presence, of shadows during the day. A typical example is the shade of chimneys, antennas or trees that can cover part of the panels during the day, hindering the efficiency of the entire system.

During the summer months, the production of the PV system is higher than winter months because the days present more hours of sun. It is possible to see that there is a low difference between the values related to the measured production and to the simulated one. The

percentage absolute difference (%) is around 3-4% for both 2017 and 2018. The simulated value of PV electricity production, as shown in Table 3, is placed right in the middle between the data of 2017 and 2018.

The electricity production of the existing PV system is lower than facility electricity demand, given the high values of energy demands by industrial devices and space cooling equipment. Thus, the study addressed the optimization of a further PV integration with a view to cost-optimality. Indeed, the enhancement of the PV system can be highly cost-effective given the huge values of facility electricity consumption.

The new PV panels have the same characteristics of existing ones and are installed on the building roof with the same orientation and tilt angle. Different sizes are considered in terms of coverage of the non-occupied roof surface (around 830 m<sup>2</sup>) by photovoltaics, set equal to:

• around 25% coverage of roof area, corresponding to 210 panels and to a peak power of 31.5 kWp;

• around 50% coverage roof area, corresponding to 400 panels and to a peak power of 60 kWp;

 around 75%, corresponding to 600 panels and to a peak power of 90 kWp;

• around 100%, corresponding to 825 panels and to a peak power of 123.75 kWp.

The panel numbers have been chosen in order to ensure complete strings. The financial benefits of PV integration are assessed in terms of global cost reduction. In order to investigate the sensitivity to investment cost variation, two values are considered for PV purchase cost, i.e., 1200  $\epsilon/kWp$  (case A) and 1700  $\epsilon/kWp$  (case B), respectively, according to current market prices.

For example, Figure 3 shows the PV productions of both the existing PV system and the integrated one, which takes into account the cover of 100% of the roof area.





The performance of PV integration covering the different percentage of the roof area considered in Tables 4, 5, 6 and 7 - i.e., 25%, 50%, 75% and 100%, respectively – by reporting:

• the electricity production of existing PV systems;

• the electricity production of PV integration;

• total electricity production of PV;

#### • electricity sold to the grid.

The electricity production of existing PV system is reported in each of the following summentioned tables, in order to make any comparison clearer for the readers.

Table 4. Production of PV Panels Covering the 25% of the Non-occupied Roof Area

Month	Electricity pro- duction of existing PV [kWh]	Electricity production of PV integration [kWh]	Total Electricity pro- duction of PV [kWh]	Electricity sold to the grid [kWh]
January	10'865	1'613	12'478	0
February	14'498	2'133	16'631	106
March	23'076	3'342	26'418	164
April	28'663	4'048	32'711	780
May	38'582	4'891	43'743	2'137
June	38'057	5'083	43'140	3'199
July	40'578	5'271	45'849	1'120
August	36'084	4'680	40'764	1'477
September	26'307	3'562	29'869	293
October	19'409	2'697	22'106	64
November	11'888	1'731	13'619	0
December	9'640	1'431	11'071	0
Total	294'920	40'482	335'402	9'340

Table 5. Production of PV Panels Covering the 50% of the Non-occupied Roof Area

Month	Electricity pro- duction of existing PV [kWh]	Electricity production of PV integration [kWh]	Total Electricity pro- duction of PV [kWh]	Electricity sold to the grid [kWh]
January	10'865	3'072	13'937	0
February	14'498	4'062	18'560	240
March	23'076	6'365	29'441	445
April	28'663	7'710	36'373	1'386
May	35'852	6'586	45'168	3'388
June	38'057	9'681	47'738	4'479
July	40'578	10'039	50'617	2'128
August	36'084	8'915	44'999	2'475
September	26'307	6'785	33'092	752
October	19'409	5'137	24'546	239
November	11'888	3'297	15'185	0
December	9'639	2'724	12'364	0
Total	294'916	74'373	369'293	15'633

Table 6.	Production of PV	<b>Panels Covering</b>	the 75%	of the Non-	occupied Roof
		Area			

Month	Electricity pro- duction of existing PV [kWh]	Electricity production of PV integration [kWh]	Total Electricity pro- duction of PV [kWh]	Electricity sold to the grid [kWh]
January	10'865	4'608	15'473	0
February	14'498	6'092	20'590	563
March	23'076	9'548	32'624	1'041
April	28'663	11'565	40'228	2'319
May	38'582	11'244	49'826	5'136
June	38'057	14'521	52'578	6'379
July	40'578	15'059	55'637	3'236
August	36'084	13'372	49'456	3'548
September	26'307	10'178	36'485	1'377
October	19'409	7'705	27'114	559
November	11'888	4'946	16'834	4.1
December	9'640	4'086	13'726	0
Total	294'920	112'924	407'844	24'162

Table 7. Production of PV Panels Covering the 100% of the Non-occupied Roof Area

Month	Electricity pro- duction of existing PV [kWh]	Electricity production of PV integration [kWh]	Total Electricity pro- duction of PV [kWh]	Electricity sold to the grid [kWh]
January	10'865	6'335	17'200	5
February	14'498	8'377	22'875	1'139
March	23'076	13'129	36'205	2'017
April	28'663	15'903	44'566	3'728
May	38'582	16'485	55'067	7'456
June	38'057	19'967	58'024	8'819
July	40'578	20'706	61'284	4'539
August	36'084	18'387	54'471	4'796
September	26'307	13'995	40'302	2'296
October	19'409	10'594	30'003	1'111
November	11'888	6'801	18'689	39
December	9'640	5'618	15'258	0
Total	294'920	160'297	455'217	35'944

Concerning the 25% PV coverage, the electricity production increases of around 40 MWh per year and the sold electricity is around 9 MWh per year. Considering the existing PV system, the production capacity complexively rises to 335 MWh per year. During warm months, the integration system guarantees an electricity production between 4-5 MWh per month, while during the rest of the year its production is between 0 and around 3 MWh per month. Finally, the sold energy is equal to 2-3 MWh per month in warm periods, while it assumes values included between 0 and 1 MWh per month for the rest of the year.

When the PV integration covers the 50% of roof area, the electricity production increases of around 74 MWh per year and the sold electricity is around 16 MWh per year. Overall, a production of 369 MWh per year is achieved. Considering exclusively the PV integration system, this latter produces around 9-10 MWh per month during the warmer period, while its production is included between 3 and 7 MWh per month for the rest of the year, with the exception of April, when the electricity production has a peak equal to around 8 MWh. Concerning the sold energy, it is possible to observe that it reaches about 3-4 MWh per month in the warm months and values between 0 and 2 MWh per month in the other months.

Concerning the 75% PV coverage, the electricity production increases of around 113 MWh per year and the sold electricity is around 24 MWh per year. Considering the existing PV system, the production capacity complexively rises to 408 MWh per year. During warm months, the integration system permits to produce around 15 MWh per month. Finally, the sold energy is equal to 5-6 MWh per month in the warm period, while it assumes values included between 0 and 3 MWh per month for the rest of the year.

In conclusion, when the PV integration covers the 100% of roof area, the electricity production increases of around 160 MWh per year and the sold electricity is around 36 MWh per year. In this case, a total production capacity of 455 MWh per year is achieved, reaching with the second plant about 20 MWh per month in the warm months and 6-16 MWh per month during the rest of the year. The sold energy is equal to 7-8 MWh per month during the warmer period, while it is included between 0 and 4 MWh per month for the rest of the year. Finally, such PV integration can reduce (to close to zero) the electricity taken from the grid by supporting the facility self-sustainability.

Table 8 shows the cost/financial analysis of the proposed solutions by reporting the global cost saving compared to the baseline for cases A (panel purchase cost of 1200  $\epsilon/kWp$ ) and B (panel purchase cost of 1700  $\epsilon/kWp$ ).

It is clear, for both scenarios, the cost-optimal solution is the 100% PV integration, which can yield a global cost saving between 134 k $\in$  (case A) and 70 k $\in$  (case B) during the facility lifespan, with simple payback (SPB) between 7.3 and 10.4 years, discounted payback (DPB) between 8.4 and 12.7 years.

Table 8.	Cost	Analysis	of New	PV	Panels
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Roof covering	Global Cost Saving for Case A	Global Cost Saving for Case B
100%	133.840 k€	69.837 k€
75%	97.252 k€	51.252 k€
50%	67.199 k€	35.699 k€
25%	32.783 k€	23.778 k€

#### 5. Limitations and Further Developments

Despite the effectiveness of the calibration method, and the robustness of the results, which was confirmed by the comparison with the measured data related to the year 2018 too, the study here proposed presents a limit.

The lack of data related to on-site measurements concerning the energy consumption of each device and to the local weather conditions has obliged the authors to make some simplifications, in order to calibrate the energy model and investigate the cost-effectiveness of the PV integration for the firm. In usual conditions, the normalization of the bill consumptions would have been required as well as the use of on-site monitored weather data. However, the latter were unavailable, especially the productivity of each device, due to the fact that the company works on commission. For this reason, the only way to proceed was to calibrate the energy model based on typical weather conditions and by considering the energy consumptions reported on the bills. This operation was performed referring to the energy bills of the year 2017. As verification, the monthly energy consumption values assessed by the model were compared with the ones monitored the following year 2018. Being the main calibration indexes limit values - evaluated on the yearly global energy performance - respected also for this different year, the model was considered "calibrated". This approach was adopted also for modelling and calibrating the existing PV system.

The unavailability of data concerning the piece production of each device, and in turn, their individual electricity consumption, has obliged the authors to use the genetic algorithm, in order to estimate the load factors of each device. However, the assessed load factors could be different from the real one – if measured –, even if the global electricity consumption of the production site resulting from the energy simulations is approximately the same of the measured one. As further development, it would be interesting to measure on site the load factors of the devices, if possible, and, consequently, re-calibrate the energy model. In fact, with the re-calibrated model, it would be possible to investigate also the thermal comfort of the workers, because it would be known the exactly disposition of the internal gain sources, and so it would be also possible to optimize the operation of the HVAC (heating, ventilation and air conditioning) system, considering the thermal comfort and the running costs as objective functions.

In addition, another interesting improvement that could be done to the energy model is the calibration of the  $CO_2$ emissions and, more in general, of the environmental impact – from the energy point of view. Once done, a genetic algorithm could be performed, in order to evaluate the optimal energy retrofit strategy for the firm, considering the cost-effectiveness and the environmental sustainability as main targets.

#### 6. Conclusion

The study investigated the energy performance of an industrial building. The facility energy model was developed under EnergyPlus environment by considering all industrial devices, which deeply affect electricity consumptions and cooling needs. Since the operation and load schedules of the devices were not available, an accurate calibration procedure was performed based on the implementation of an optimization genetic algorithm and on the comparison between simulated data and real monitored data concerning electricity consumption. The calibration procedure provided optimal results because the calibrated model presented very low values of the calibration coefficients, i.e., error indicators, suggested by ASHRAE guideline 14-2014. Indeed, the MBE (mean bias error) was around 0.05% and the Coefficient of Variation of Root Mean Square Error (CV(RMSE)) was around 0.20%, whereas the limit values recommended by ASHRAE to have a calibrated model are 5% and 15%, respectively.

After the model calibration, the integration of the existing photovoltaic (PV) system is investigated in order to achieve cost-optimality. Indeed, the facility is characterized by the huge electric loads, given the industrial devices, and the existing PV system can be enhanced with high financial benefits. The study showed that the cost-optimal measures is the installation of a full-roof PV system, since this provide global cost savings I 20 years between 70 and 134 k€ (depending on the purchase cost) with payback times around 10 years.

Generally speaking, even if the results could appear quite obvious, it is important to remark that an accurate model calibration is always fundamental to achieve robust optimization results. In fact, having a well-calibrated energy model, even other energy retrofit measures concerning the power system could have been easily taken into account, in order to reduce the environmental impact of the building. This could be another interesting point to investigate further.

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## ARTICLE Developing a Holistic Fire Risk Assessment Framework for Building Construction Sites in Hong Kong

#### John F. Y. Yeung<sup>1\*</sup> Daniel W. M. Chan<sup>2</sup>

 Division of Business, College of International Education, Hong Kong Baptist University, Hong Kong, China
 Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

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#### ABSTRACT

Amongst all types of construction accidents, industrial practitioners tend to pay less attention to the prevention of fires at construction sites. Although fires may not occur frequently on construction sites, statistics show that when they do, the consequences are very serious; involving fatalities, injuries, serious project delays and financial loss. There are many reasons why fires occur on sites, but a simple lack of awareness of the risks of fire is a major contributor. Fire risk assessment is not commonly performed on sites. Hence, it is believed that an appropriate assessment method for evaluating potential fire risk is required in order to improve the awareness of fire risk on construction sites. This paper reports on the key findings of a research project which aims to develop a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites based in Hong Kong. A comprehensive list of those factors (or conditions) which may constitute a fire risk was compiled using desktop research and structured face-to-face interviews with experienced site personnel. This list of factors was then used to develop a questionnaire survey form and the Reliability Interval Method (RIM) was used to analyse the survey results and determine the relative importance and rankings of the various fire risk factors at a broad level and risk sub-factors at a detailed level. It was found that the fire risk factor of "Fire Services Equipment and Installations" has the greatest impact on construction site fire safety, with "Means of Escape in Case of Fire" being the second, and "Attitude of Main Contractor towards Fire Safety" being the third. In fact, it is the main contractor who plays the pivotal role in maintaining construction site fire safety, which is in line with the high ranking given to the fire risk factor of "Attitude of Main Contractor towards Fire Safety". The proposed fire risk assessment framework can be used to develop a useful checklist for assessing the overall level of fire risk for a construction site, and to identify any areas needing improvement. Although the fire risk assessment framework was developed locally in Hong Kong, the research methodology could be replicated in other countries to produce similar frameworks for international comparison. Such an extension would aid the understanding of the management of fire risk on construction sites and help discover differences between countries.

\*Corresponding Author:

John F. Y. Yeung,

Division of Business, College of International Education, Hong Kong Baptist University, Hong Kong, China Email: jfyyeung@hkbu.edu.hk

#### 1. Introduction

isk management is used to identify, evaluate, and prioritize risks, and it is followed by a coordinated and economical application of resources to minimize, manage, and control the likelihood and/or severity of ill-fated events or to maximize the realization of opportunities<sup>[1]</sup>. Risks can come from uncertainty in financial markets, project failures, legal liabilities, credit risks, accidents, natural causes and disasters as well as deliberate attacks from an adversary. Fire risk management is an important area of risk management in which risk assessment of building conditions usually includes economic risk, social risk, natural risk (including fire risk of buildings), construction risk, and operation risk. In fact, fire risk management in construction sites is an important research area that is lacking systematic investigation. To fill this research gap, this paper aims to develop a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites in Hong Kong. The focus of the fire risk problem in this research study is on a combination of life safety risk due to fire, property loss risk due to fire, and business interruption risk due to fire. For example, the fire risk factor of "Means of Escape in Case of Fire" (reported later) has been identified to prevent life safety risk due to fire; and the fire risk factor of "Storage of Combustible Materials or Dangerous Goods" has been identified to minimize physical damage and business interruption.

The construction accident rate in Hong Kong is the highest amongst major industries despite a decreasing trend since 2001 as shown in Table 1. Although construction site fires may be infrequent, their consequences are usually severe. Recent statistics from the Hong Kong Labor Department show that when construction site fires occur (Figure. 1), damage is not only very serious in respect of fatalities and injuries, but also lead to serious project delay and financial loss. Two recent serious construction site fires in Hong Kong illustrate these significant risks<sup>[2][3]</sup>. There are many reasons why fire accidents occur on sites and one of the most important is the lack of awareness of the risks as evidenced by the fact that site supervisory teams usually do not conduct regular and formal fire risk assessments. This may be due to a lack of an appropriate fire risk assessment method for evaluating fire risk on site. To help overcome this deficiency, this paper reports the findings of a research project which aims to develop a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites in Hong Kong. The proposed framework with ranking of the associated fire risk factors assists safety officers and related construction personnel to objectively assess the overall fire risk level of an individual construction site and to prioritize improvements to reduce risk. Although the framework was developed locally in Hong Kong, the research method may be applicable to other countries, for the production of similar frameworks and subsequent international comparisons.





Figure 1. Numbers of Fire Accidents in the Hong Kong Construction Industry<sup>[46]</sup>

Note: The information is unavailable in year 2019.

#### 2. Research Methodology

The research methods employed included: (1) desktop research; (2) structured face-to-face interviews with experienced site professionals; (3) questionnaire survey; and (4) weights assessment relating to the questionnaire survey results using the Reliability Interval Method (RIM).

#### Figure 2 shows the process of this research stage.





Figure 2. Research Process in this Study

#### 2.1 Desktop Research

The desktop research covered: (1) a comprehensive literature review of fire risk assessment systems, assessment of weighting methods and site evacuation models; and (2) studies of legislation and current practices regarding fire safety in construction sites and of major past accidents. Through these studies, an initial checklist of fire risk factors and sub-factors was developed<sup>[4]</sup>.

The search engines "Scopus" and "Google Scholar" were used to conduct the literature search under the "Title/ Abstract/Keyword" field. Search keywords included "Fire risk", "Fire risk assessment", "Fire safety", "Fire safety assessment", "Construction sites accidents" and "Construction site safety". Publications related to construction and fire safety from local government offices were also examined. The initial literature review demonstrated a lack of well-established fire risk assessment systems and the associated fire risk factors for construction sites. It should be noted that there are minimum safety and health requirements for construction sites issued by the EU Council (the EU Council Directive 92/57/EEC (of 24 June 1992) on the implementation of minimum safety and health requirements at temporary or mobile construction sites)<sup>[5]</sup>. The role of health and safety requirements in this context is that it is important to make sure that construction sites are maintained with adequate health and safety measures for combating potential fire risks. Some other organizations, such as the National Fire Protection Association (NFPA) in the US, the Fire Protection Association (FPA) in the UK, and the UK Health & Safety Executive, have also had guidelines on fire safety during building construction for several years. The National Fire Protection Association (NFPA) provided guidelines and standard for safeguarding construction, alternation, and demolition operations<sup>[6]</sup>. The UK Fire Protection Association (FPA) had similar guidelines in order to achieve similar interpretation in the European countries and to give examples of acceptable solutions, concepts and models<sup>[7]</sup>. The UK Health & Safety Executive provided guidelines for clients, designers, and those managing and carrying out construction work involving significant fire risks<sup>[8]</sup>.

The significant fire risk factors identified from the desktop literature review included: (1) Law Enforcement and On-site Supervision; (2) Means of Access for Firefighting and Rescue Purpose; (3) Means of Escape in Case of Fire; (4) Storage of Combustible Materials and Dangerous Goods; (5) Electricity Management; (6) Characteristics of Construction Site; (7) Fire Services Equipment and Installations; (8) Safety Procedures for Evacuation; (9) Site Environment during Fire; and (10) Safety Behaviors of On-Site Staff. Since there is not much literature related to fire risk assessment on construction sites, the literature search was broadened to include fire risk assessment systems for existing buildings and building evacuation models. When fire risk is assessed on a construction site, Chan (2007) advised that it is not appropriate for practitioners to solely consider fulfilling the minimum fire services installations and equipment requirements stated in legislation<sup>[9]</sup>. The author suggested taking a wider view, adopting a fire risk assessment method comprising many relevant factors. This approach is in line with Watts'(1997) and Lo's (1999) research work which consists of a fire risk hierarchy comprising a number of risk factors for conducting a fire risk assessment for an existing building<sup>[10][11]</sup>. Watts stated that fire risk assessment is built by assigning values to fire risk attributes based on "professional judgment and past experience and then aggregated by some arithmetic function" to derive a safety index value<sup>[10]</sup>. In other words, fire risk assessment considers the multi-attribute characteristics of fire safety and could be developed into a standard tool for assessment. In fact, fire risk assessment systems for existing buildings and karaoke establishments in Hong Kong have been developed on the basis of fire risk ranking<sup>[11][12][13]</sup>. It should be noted that fire risk ranking systems are heuristic models of fire safety, and they originated with the insurance rating schedule<sup>[14]</sup>. For instance, a Fire Safety Evaluation System (FSES) has been developed based on fire risk ranking in the United States<sup>[10][15]</sup>. Gretener (1973, 1980) developed an arithmetical assessment of fire risk ranking and this approach constitutes different processes of analyzing and scoring hazard and other risk parameters to generate a rapid and simple estimate of relative fire safety level<sup>[16][17]</sup>.

Lo (1999) developed a fire risk assessment system using a fuzzy set theory approach to assess the overall fire safety level of existing buildings<sup>[11]</sup>. The system allowed

fire risk factors to be prioritized so that improvement works could be carried out at areas with higher risks. This system also forms a part of the "Building Safety Inspection Scheme (BSIS)". The BSIS sets out the mandatory safety assurance requirements enacted by the Hong Kong government in 1997. A trial application of this fire safety assessment system was conducted by the Hong Kong Housing Department. Figure 3 shows the systematic approach for the identification of fire safety factors proposed by Lo (1999)<sup>[11]</sup>, and Chow & Lui<sup>[12]</sup> using a 20-point system. This application of the technique is guite different from those of Lo's (1999) research work<sup>[11]</sup>. The study focused on karaoke establishments because of their special risk features, including: (1) boxespartitioning; and (2) often crowded long corridors. The objective of this ranking system was to identify where immediate action is needed for improvements in fire safety in karaoke establishments.





Lo (1999) considered research on fire safety to be complicated because of its multi-factor nature<sup>[11]</sup>. It was insufficient, therefore, to consider only legislation, current practices and major past fire incidents in the development of fire risk factors. Gwynne et al. (1999) considered that legislation and fire codes are not sensitive to human behavior and real fire situations<sup>[18]</sup>. Thus, evacuation models should be considered in the development of fire risk factors. However, evacuation models are often applied by fire engineers to check that adequate time is provided for evacuation of the occupants<sup>[19]</sup>. Such models are seldom used for assessing fire risk levels on construction sites. Hence, only that part of those evacuation models which is related to human behavior under an evacuation situation is considered. In fact, evacuation models are usually used together with fire models to establish the risk of occupants in fire. Thus, evacuation models are useful to develop the fire risk factor of "Means of Escape" together with its relevant fire risk sub-factors, such as "Adequate Number of Exits", "Free from Obstruction", and "Reasonable Travel Distance".

Lo (1999) suggested that major fire risk factors could be identified in the fire codes and regulations<sup>[11]</sup>. Based on this method, the following legislation was analyzed to identify an initial checklist of fire risk factors and subfactors.

The Hong Kong Labor Department<sup>[20][21][22]</sup> issued the following documents:

1.The Construction Sites (Safety) Regulations<sup>[20]</sup>

2.A Guide to the Factories and Industrial Undertakings (Fire Precautions in Registrable Workplaces)<sup>[21]</sup>

3.A Guide to the Factories and Industrial Undertakings (Safety Supervisor)<sup>[22]</sup>

The Hong Kong Buildings Department<sup>[23][24][25]</sup> issued the following documents:

1.Code of Practice for Means of Access for Firefighting and  $Rescue^{[23]}$ 

2.Code of Practice for Fire Resisting Construction<sup>[24]</sup>

3.Code of Practice for Provision of Means of Escape in Case of  $Fire^{[25]}$ 

The Hong Kong Fire Services Department<sup>[26][27]</sup> issued the following documents:

1.Code of Practice for Minimum Fire Services Installation and Equipment<sup>[26]</sup>

2.Fire Safety (Building) Ordinance<sup>[27]</sup>

In addition, the Hong Kong Fire Services Department<sup>[28]</sup> provided some additional notices regarding some high-risk areas.

1.Fire Protection Notice No. 9 – Electrical Safety<sup>[28]</sup>

2.Fire Protection Notice No.13 – Fire Protection at Construction Site<sup>[29]</sup>

It should be noted that the Fire Protection Notice No.13 – Fire Protection at Construction Site issued by the Hong Kong Fire Services Department is in line with the EU Council Directive 92/57/EEC (of 24th June 1992) on the implementation of minimum safety and health requirements at temporary or mobile construction sites regarding emergency routes and exits, fire detection and fire-fighting<sup>[5]</sup>. Yam (2008) stated that legislation and current practice can provide a basic framework for fire protection on construction sites while major past fire incidents reflect the insufficiencies in existing practice and evacuation criteria<sup>[30]</sup>.

After conducting a comprehensive literature review of the fire risk assessment systems, evacuation models; local legislations, current practices and major past fire incidents on construction sites, an initial checklist of fire risk factors and sub-factors is developed (Table 2), which is reported in the subsequent section.

## 2.2. Structured Face-to-Face Interviews with Experienced Site Professionals

A panel of experts was invited for structured face-toface interviews to help complement and refine the initial checklist of fire risk factors obtained from the literature review. The list of fire risk factors and sub-factors is formulated by comparing opinions of each expert. The structured interview, in which the interviewer asks predetermined questions with the same wording and order, is adopted because it provides uniform information<sup>[31]</sup>. Questions in the interview are based on the identified initial checklist of fire risk factors and sub-factors legislation, current practices, major past accidents and evacuation issues with respect to fire safety in construction sites in Hong Kong. Finally, experts are also asked to identify fire risk factors and sub-factors that are not covered by the questions to ensure that a wide range of factors and sub-factors could be identified. Very importantly, each expert is asked for the extent their jobs relate to site fire safety at the beginning of the interview to ensure that they have adequate knowledge and experience. The interviewees included one fire safety engineer, one safety manager, one senior project manager (civil engineer), one senior structural engineer (who was involved in the drafting of the requirement of the site safety supervision plan issued by the Hong Kong Buildings Department), and two senior project building engineers. All the six interviewees had ten to twenty-five years of experience of construction site management and/or safety and they held vital roles in construction site management being responsible for monitoring the daily operations of construction sites and taking care of construction site safety (including construction site fire safety). They are believed to have adequate related knowledge and experience in assessing construction site fire risk and are well able to identify fire risk factors towards a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites in Hong Kong. It should be noted that the use of expert judgment or expert elicitation has also been adopted for other fire risk engineering or infrastructure risk analysis related research studies<sup>[32][33]</sup> <sup>[34][35][36][37]</sup>. As shown in Appendix 1, there were a total of twelve interview questions based on the initial checklist of fire risk factors developed from the desk research. The interview questions were divided into four parts: (1) background information; (2) views on the general construction sites situation; (3) views on evacuation issues; and (4) further supplementary information.

Having conducted the structured face-to-face interviews, content analysis was adopted to identify the fire risk factors and sub-factors. Weber (1990) took a view that content analysis is able to assist in classifying textual material, so that more relevant and manageable bits of data can be grouped<sup>[38]</sup>. Fellows and Liu (2008) stated that the usage of content analysis is mainly to determine the main facets of a data set, by simply counting the number of occurrence of an activity or a topic<sup>[39]</sup>. The first step to conduct content analysis is to identify the materials to be analyzed. The second step is to decide the form of content analysis to be adopted, either qualitative or quantitative. The option depends on the nature of the research study. The choice of categories will also be dependent on the issues to be addressed in the study if they are known. The emphasis of qualitative content analysis is to determine the meaning of data (i.e. grouping data into categories) while the emphasis of quantitative content analysis is to extend the approach of the qualitative form to generate numerical values of the grouped data (frequency, ratings, ranking, etc.) which may be subject to statistical analyses<sup>[39]</sup>. During the process of content analysis in this study, the key points and main ideas of each interview verbatim transcript were first marked down. Then, similar main points were assembled and different fire risk factors and sub-factors were finally crystallized from the analyzed interview transcripts. Transcriptions of the interviews were returned to all interviewees for vetting and approval before further analysis. After the analysis of the results of the interviews, the final checklist of 11 fire risk factors and 48 sub-factors was developed (reported below), which then formed the basis for development of a subsequent questionnaire survey form.

#### 2.3 Questionnaire Survey

This questionnaire survey form was developed based on the final checklist of fire risk factors developed from the results of the literature review and the structured interviews. The results of the survey were used to develop appropriate weightings for different fire risk factors and sub-factors. There were two major sections in the questionnaire, encompassing: (1) general conditions on construction sites; and (2) evacuation efficiency during fire on construction sites. These two parts were to be answered by survey respondents with interval grading so that the data analysis method, Reliability Interval Method (RIM), could be facilitated. The study population included all industrial practitioners who have acquired direct hands-on working experience at construction sites in general and site fire risk assessment in particular. The simple random sampling method was adopted in this study. A total of 111 blank questionnaires were dispatched

by hand on the spot to those industrial practitioners who attended a continuing professional development (CPD) seminar on construction management in Hong Kong, and 46 completed questionnaires were returned, representing a very satisfactory response rate of 41.44%. In fact, the response rate is not considered to be low because a typical response rate of questionnaire survey in construction management in Hong Kong is around 30% to 50%<sup>[47]</sup>. The professional affiliation for the 46 survey respondents included 1 architect, 25 building engineers, 10 building services engineers, 3 fire engineers, 1 planning engineer, 4 safety engineers, and 2 structural engineers. Most of them worked for main contractors and some of them worked for client organizations, design consultants and trade subcontractors. They held important roles in construction site management, being responsible for monitoring the daily operations of construction sites and taking care of site safety (including site fire safety). Therefore, it is believed that they possessed adequate knowledge and experience to deal with site fire safety. In order to assess the weighting to be applied to each factor, a proper weighting assessment method is required, taking into account a good practice of using interval grading in fire study<sup>[29][30]</sup>. The following section presents two possible weighting assessment methods which can be used to develop the weightings for the factors and sub-factors.

#### 2.4 Weighting Assessment Methods

It is important to choose the appropriate weighting assessment method since this directly affects the accuracy of the fire risk assessment<sup>[11]</sup>. Two weighting assessment methods were considered in this study. They are: (1) the Analytical Hierarchy Process (AHP) and (2) the Reliability Interval Method (RIM).

#### 2.5 Analytical Hierarchy Process (AHP)

The AHP is a theory of measurement using pairwise comparisons. It relies on the judgments of experts to derive priority scales. These scales measure the intangibles in relative terms and comparisons are made using a scale of absolute judgments that represents the extent to which one element dominates another with respect to a given attribute<sup>[40]</sup>. Saaty (1980) stated that AHP is widely used in prediction, prioritization, and probability judgments<sup>[41]</sup>. A hierarchy is constructed by analyzing real-life problems and investigating mutual dependence of the different criteria. A pair-wise comparison is incorporated in order to determine relative importance. The relationships are presented in matrix form. In our case, the impact of a fire risk factor on the fire risk is greater if the weighting is higher. Shields and Silcock (1986) felt that AHP was generally good at prioritizing the effect of uncertainty, but they experienced difficulties in conducting pair-wise comparisons when more than five criteria were under consideration at any one time<sup>[42]</sup>. Yiu et al. (2005) reported that there are two limitations of AHP<sup>[43]</sup>. Firstly, it is difficult to avoid inconsistency between pair-wise comparisons even if evaluators have comprehensive explanations of the factors and sub-factors. Secondly, evaluators may find it difficult to determine an exact weighting for some factors because they are vague in nature. In other words, fuzziness is difficult to incorporate with the use of AHP and evaluators may be unable to provide appropriate weightings when they find it difficult to weigh these vague criteria. These limitations make AHP difficult to apply to fire risk assessment.

#### 2.6 Reliability Interval Method (RIM)

With reference to Moore's (1979) research work<sup>[44]</sup>, Lo et al. (2001) developed RIM to assess fire risk for highrise buildings<sup>[32]</sup>. RIM allows the expert to assign a grade range instead of a fixed integer score enabling flexibility in reflecting a fuzzy range of importance for each criterion as perceived by the expert<sup>[33][43]</sup>. RIM is different from another common weighting assessment method, i.e. direct point allocation (DIRECT)<sup>[43]</sup>. In the DIRECT method, the decision maker allocates numbers to describe the factor weights directly and then the factor weightings are obtained by normalization. However, it is questionable whether this is reliable since a fuzzy allocation of weightings is not allowed<sup>[43]</sup>. On the contrary, RIM is particularly useful in handling imprecise information. It requires evaluators to weigh a factor using a fuzzy range of numbers. For instance, evaluators can weigh a factor as a range of 2 to 4,  $^{[2, 4]}$ , instead of an exact value of  $^{[3]}$ . The influence of a fire risk factor on fire safety is greater if the weighting is higher. As pair-wise comparisons are not needed in this assessment method, the problem of inconsistency arising from pair-wise comparison is eliminated. This method can also determine the degree of reliability based on center variance (CV) and interval variance (IV). According to Lo et al. (2005), the degree of reliability is the proportion of the ranges weighted by the evaluators which falls within the average range<sup>[33]</sup>. CV and IV indicate the consistency of opinions amongst survey respondents. When the values of CV and IV are small, it implies that the opinions of the survey respondents are consistent with one another as a whole. Yiu et al. (2005) used RIM to develop weightings for different decision criteria and their sub-criteria in evaluating cost estimator's performance<sup>[43]</sup></sup>. Lo et al. (2005) stated that this method is particularly practical when the number of factors and subfactors are large because the use of pair-wise comparisons

in AHP may lead to a lengthy questionnaire<sup>[43]</sup>. Based on the above discussion, RIM was chosen for this research as the most appropriate weighting assessment method for determining the weightings of each fire risk factor and sub-factor as they relate to the fire risk assessment of a construction site.

The mathematical principle of RIM is as follows<sup>[32][33]</sup><sup>[43]</sup>.



In Figure 4, let the  $i^{th}$  expert grades the  $j^{th}$  factor as belonging to the interval value  $[l_{ij}, r_{ij}]$ , where  $0 \le l_{ij} \le r_{ij} \le N$ , i = 1, 2, ..., M, j = 1, 2, ..., J.

Two assumptions are made for the development of RIM:

(1)The probability distribution function within the interval  $[l_{ii}, r_{ij}]$  is linear;

(2)Equal weighting is given to the opinions of the different experts.

Hence, the interval grade for the  $j^{th}$  factor is defined as:

$$[a_{j}, b_{j}] = \frac{1}{M} \sum_{i=1}^{M} [l_{ij}, r_{ij}]$$
(1)

and the grade eigenvalue of the  $j^{th}$  factor is defined as:

$$\zeta_{j} = \frac{1}{2} (a_{j} + b_{j}) = \frac{1}{M} \sum_{i=1}^{M} \frac{l_{ij} + r_{ij}}{2}$$
(2)

Then, by normalization, the weighting of the  $j^{th}$  factor  $(\eta_i)$  is obtained:

$$\eta_j = \frac{\zeta_j}{\sum_{i=1}^J \zeta_i} \tag{3}$$

The weighting of the  $j^{th}$  factor (that is  $\eta j$ ) equals the grade eigenvalue (that is  $\zeta j$ ) of the  $j^{th}$  factor divided by the sum of grade eigenvalues of J factors.

To allow statistical analysis of the results, RIM provides three parameters with the fuzzy assessment of weightings, namely, reliability, center variance (CV) and interval variance (IV).

For the definition of reliability, two parameters are in-

troduced:

$$\delta_{\zeta_j} = \left\{ x \| x - \zeta_j \right\} \le 0.5 \right\} \tag{4}$$

$$I_{j} = \left\{ i \left[ l_{ij}, r_{ij} \right] \cap \delta_{ij} \neq \phi \right\}$$
<sup>(5)</sup>

 $\delta_{\zeta_j}$  corresponds to a range where *x* has a value such that  $|x - \zeta_j| \le 0.5$ , which means that  $-0.5 \le x - \zeta_j \le 0.5$ . Therefore, the range  $\delta_{\zeta_j}$  is  $[\zeta_j - 0.5, \zeta_j + 0.5]$ .

 $I_j$  corresponds to a set that i has a value such that  $[l_{ij}, r_{ij}]$ and  $\delta_{\zeta_j}$  contain elements in common (under the situation that they have elements in common, denoted:  $\neq$ f), which is the intersection of the two sets as shown in Fig. 5.



**Figure 5.** Intersection of  $[l_{ii}, r_{ii}]$  and  $\delta_{\zeta_i}$ 

So, the reliability of the j<sup>th</sup> factor attaining  $\eta_j$  grade is  $|I_j|/M$ , where  $|I_j|$  is the number of set  $I_j$ . As mentioned above, the reliability illustrates the proportion of the ranges weighted by the experts that falls within the average range.

Center variance  $(CV_j)$  and interval variance  $(IV_j)$  for the j<sup>th</sup> factor are defined as:

$$CV_{j} = \frac{1}{M} \sum_{i=1}^{M} \left( \zeta_{j} - \frac{l_{ij} + r_{ij}}{2} \right)^{2}$$
(6)

$$IV_{j} = \frac{1}{M} \sum_{i=1}^{M} \left( \max\{ |\zeta_{i} - l_{ij}|, |\zeta_{i} - r_{ij}| \} \right)^{2}$$
(7)

The value of CV reflects the difference between the grade eigenvalue ( $\zeta_j$ ) and the average of interval grades ( $l_{ij}$  and  $r_{ij}$ ) for a particular factor.

The value of IV reflects the difference between the grade eigenvalue ( $\zeta_i$ ) and the interval value  $l_{ij}$  or  $r_{ij}$  (which has a larger difference with the grade eigenvalue).

As mentioned, consistency of opinions among experts can be reflected with the use of these two variances. The smaller the values of center variance (CV) and interval variance (IV) are, the more consistent are the opinions of the respondents.<sup>[32][33][43]</sup>

#### 3. Research Findings and Discussion

Based on the comprehensive literature review of fire risk assessment systems, evacuation models, local legislation, current practices and the major past fire accidents in construction sites, an initial checklist of 10 fire risk factors and 52 fire risk sub-factors was developed (Table 2). It should be noted that only the 10 fire risk factors identified in the initial checklist were used to set questions for the subsequent interviews with experienced site experts. The panel of experts was expected to identify the fire risk sub-factors during the interviews without any prior knowledge of the results of the desk research conducted in the study. By doing so, the consistency of the fire risk factors and sub-factors identified by the desk research can be compared with the fire risk factors and sub-factors proposed by the site experts during the interviews.

#### Table 2. An Initial Checklist of Fire Risk Factors and Sub-factors<sup>[4]</sup>

Ultimate Goal: Developing a Fire Risk Assessment System for Building Construction Sites		
Fire Risk Factors	Fire Risk Sub-factors	
Law Enforcement and On site	Enforcement of smoking prohibition	
Supervision	Gas welding and flame cutting works done by competent workers	
	Emergency vehicle access	
	Free from obstruction	
Means of Access for Firefighting	Provision of firefighting and rescue staircase	
and Rescue Purpose	Smoke vent	
	Substantial staircases erected	
	Ventilated lobby	
	Adequate emergency lighting	
	Adequate width of means of escape	
	Adequate number of exits	
Means of Escape in Case of Fire	Free from obstruction	
	Provision of exit signs	
	Reasonable travel distance	
	Under good condition	
	Clearance of rubbish	
	Flammable liquids in spraying area stored in metal con- tainer with self-closing lid	
	Flammable liquids stored in closed containers that kept in cupboard or bin	
Storage of Combustible Materials and Dangerous Goods	Provision of water type fire extinguisher near doorway of dangerous goods store	
	Reasonable quantity of flammable liquids in spraying area	
	Removal or disposal of combustible materials after use	
	Smoking prohibition	
	The use of dangerous goods store	

	Overheating of excavator
	Overheating of generator
Electricity Management	Overheating of roller
	Properly insulate and protect electric wiring
	Use of earth leakage circuit breakers
Characteristics of Construction	Fire resistance period of elements of construction
Site	Size of compartment
	Audio/visual advisory systems
	Fire alarm
	Fire blankets
	Fire hydrant riser
	Fixed fire pump with electricity supply
Fire Services Equipment and	Hose reel
Installations	Periodical Inspection
	Portable fire extinguishers at each floor and site office
	Portable fire extinguishers at open flame workplace
	Provision in area of spraying flammable liquids
	Sprinkler system
	Under good condition
	Evacuation training for on-site staff
Safety Procedures for Evacuation	Location of emergency signage
	Configuration knowledge of occupants
	Low hazards of heat
Site Environment during Fire	Low hazards of irritant gases
Site Environment during Fite	Low hazards of smoke
	Low hazards of toxic gases
	Achievable travel rate
Safety Behaviors of On-Site Staff	Peer relationship of individuals
	Willingness of on-site staff for evacuation in fire situation

After developing the initial checklist of fire risk factors and sub-factors, five structured face-to-face interviews with experienced site experts were conducted to verify and validate the comprehensiveness of the initial checklist. Then, the opinions of the panel of experts were consolidated and a total of 11 fire risk factors and 48 fire risk sub-factors were identified (Table 3). It should be highlighted that most of the fire risk factors and sub-factors identified during the interviews were in line with those fire risk factors and sub-factors identified by the desk research. Therefore, it was deemed valid and logical to use these 11 fire risk factors and 48 fire risk sub-factors in the development of the next questionnaire survey form.

**Table 3.** Average Interval Grades for the Final Check-list of 11 Fire Risk Factors and 48 Fire Risk Sub-factorsDeveloped from Structured Face-to-Face Interviews withExperienced Site Professionals

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	Goal: Fire Safety of Construction Sites					
	Fire Risk Factors and Sub-factors	Average Interval Grades				
1	Law Enforcement and On-site Supervision	[ 2.978, 4.402]				
1.1	Enforcement of smoking prohibition	[ 3.228, 4.370]				
1.2	Gas welding and flame cutting work done by competent workers	[ 2.815, 4.141]				
1.3	Supervision by site supervisors or foremen	[ 2.793, 4.228]				
1.4	System of rewards and punishment	[ 2.359, 3.663]				
1.5	Use of hot work procedures	[ 2.891, 4.207]				

2	Manna of Alexandra Dimetic between and Deserve Deserves	r 2,001 4,2041
21	Neans of Access for Firengating and Rescue Furpose	I 2.891, 4.304 I 2.000 4.3901
2.1		I 2.457 2.9501
2.2	Emergency venicle access	2.457, 5.659
2.3	Provision of intergrating & rescue staticase	2.857, 4.504
3	Means of Escape in Case of Fire	3.185, 4.554
3.1	Adequate emergency lighting	[ <u>3.261</u> , <u>4.543</u> ]
3.2	Adequate width of means of escape	[ 2.511, 3.848]
3.3	Free from obstruction	[ 2.978, 4.326]
3.4	Provision of exit signs	[ 2.533, 3.935]
3.5	Under good condition	[ 2.565, 3.946]
4	Storage of Flammable Liquids and Dangerous Goods	[ 2.880, 4.391]
4.1	Cleared of rubbish	[ 2.859, 4.163]
4.2	Flammable liquids in spraving area stored in metal container with self-closing lid	[ 2.750, 3.957]
4.3	Flammable liquids stored in closed containers that kept in cupboard or bin	[ 2.543, 3.804]
4.4	Reasonable quantity of flammable liquids in spraying area	[ 2.554, 3.761]
4.5	Removal or disposal of combustible materials after use	[ 2.815, 4.152]
4.6	Smoking prohibition	[ 3.185, 4.554]
4.7	The use of Dangerous Goods Store	[ 2.598, 3.978]
5	Electricity Management	[ 3.011, 4.380]
5.1	Enough supply of electricity	2.478. 3.6851
5.2	Properly insulate and protect electricity wiring	[ 2.717. 4.087]
5.3	Use of earth leakage circuit breakers	[ 2.946. 4.446]
6	Fire Services Foundment and Installations	[ 3 217 4 609]
61	Fire starm	[ 2.543 3.013]
6.2	Fire blankets	[ 1.967 3.500]
6.2	The output of the second s	1 2 479 2 0571
6.4	File invitant list	1 2.652 4.0971
6.5	Late real	[ 2.652, 4.057]
6.6	Periodical Inspection	[ 2.663 4.000]
67	Dortshie fire extinguishers at each floor and site office	[ 3.054 4.500]
6.8	Dortable fire extinguisher at onen flame worknisse	[ 2.957 4.402]
6.0	Provision in srea of spraving flammable biologice	[ 2.76] 4.207]
610	Index and condition	[ 2,707 4,087]
-	Attisted of Main Contractor towards Fire Safety	1 2.042 4.6531
71	Attrade of Main Contractor towards File Safety	1 2.067 4.052
7.2	High level of comments of weakshifts of starting five	1 2.907, 4.407 1 2.720 4.1051
7.2	Received to concerns or processing of starting the	2.726, 4.165
/.5	Reasonable outget spent on site fire safety	2.032, 4.033
8	Characteristics of Construction Site	2.554, 3.859
8.1	Choices of less computatione materials	2.2/2, 3.5/0
8.2	Good level of ventilation	2.228, 3.003
8.3	Types of works that induce numbers of fire sources (e.g. welding works, open flame)	2.130, 3.511
9	Safety Procedures for Evacuation	[ 2.848, 4.337]
9.1	Designated staff (e.g. wardens) help evacuation in fire situation	[ 2.576, 3.848]
9.2	Evacuation training for on-site staff	[ 2.587, 3.870]
9.3	Location of emergency signage	[ 2.478, 3.815]
9.4	Planned evacuation route	[ 2.870, 4.402]
10	Site Environment during Fire	[ 2.402, 3.837]
10.1	Low hazards of smoke	[ 2.522, 3.793]
10.2	Low hazards of irritant gases	[ 2.196, 3.478]
10.3	Low hazards of toxic gases	[ 2.272, 3.609]
11	Safety Behaviors of On-Site Staff	[ 2.728, 4.207]
11.1	Peer relationship of individuals	2.435, 3.859]
11.2	Willingness of on-site staff for evacuation in fire situation	[ 2.152, 3.663]
	-	

Table 3 shows the results of the average interval grades for each fire risk factor and sub-factor obtained from the 46 completed and valid questionnaires. A "valid" questionnaire here refers to a questionnaire that is wholly completed. In fact, there were five questionnaires that were only partly completed and they were regarded as "invalid" questionnaires and therefore, they were excluded from the data analysis. Table 4 shows the survey results of the respondents' weightings of each fire risk factor and sub-factor. Since RIM has only been recently applied to fire related safety, the following principles should be noted. Lo et al. (2001) stated that when the weightings of two factors are nearly the same, the one with the higher reliability and vice versa is more reliable<sup>[32]</sup>. They also stated that a low value of variance indicates that a higher level of consistency exists amongst respondents, and vice versa. Yiu et al. (2005) conducted questionnaires on performance evaluation for cost estimators and suggested that when adopting the RIM, a level of 65% reliability could be regarded as reasonably good<sup>[43]</sup>. The authors also took the view that only minor inconsistencies in opinions exist amongst clients if the values of average center and interval variances are lower than 0.65 and 2.10 respectively. Accordingly, cut-off values of 0.65, 0.65 and 2.20 for reliability, center variance (CV) and interval variance (IV) respectively were used in establishing the fire risk assessment framework. It should be noted that the cut-off value of 2.10 for IV was too strict so a slightly modified value 2.20 was chosen. Any fire risk factor or sub-factor beyond these values was deemed worth eliminating. In total, 9 fire risk factors and 20 fire risk sub-factors met those requirements and they were selected for the development of the fire risk assessment framework of this study (Table 5).

Table 4.	Results	of Reliability	Interval	Method	(RIM)	)
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Fire Risk Factors and Sub-factors		First level weighting	Second level weighting	Reliability	Center variance	Interval vari- ance
1	Law Enforcement and On-site Supervision			0.93478	0.63909	1.97817
1.1	Enforcement of smoking prohibition		0.02374	0.89130	0.64571	1.83580
1.2	Gas welding and flame cutting work done by competent workers		0.02174	0.65217	0.78485	2.27009
1.3	Supervision by site supervisors or foremen		0.02194	0.80435	0.66564	2.20711
1.4	System of rewards and punishment		0.01882	0.82609	0.68195	2.03462
1.5	Use of hot work procedures		0.02218	0.89130	0.60494	2.04977
2	Means of Access for Firefighting and Rescue Purpose	0.09077		0.95652	0.25402	1.39473
2.1	Free from obstruction		0.02307	0.86957	0.75050	2.50133
2.2	Emergency vehicle access		0.01974	0.80435	0.68304	2.17016
2.3	Provision of firefighting & rescue staircase		0.02232	0.93478	0.47191	1.99637
3	Means of Escape in Case of Fire	0.09763		1.00000	0.21940	1.31971
3.1	Adequate emergency lighting		0.02439	0.95652	0.46869	1.77942
3.2	Adequate width of means of escape		0.01987	0.93478	0.55615	2.04741
3.3	Free from obstruction		0.02283	0.84783	0.75402	2.25780
3.4	Provision of exit signs		0.02021	0.86957	0.60707	2.23172
3.5	Under good condition		0.02035	0.86957	0.63992	2.21565
4	Storage of Flammable Liquids and Dangerous Goods	0.09173		0.84783	0.33888	1.68824
4.1	Cleared of rubbish		0.02194	0.86957	0.65749	1.99634
4.2	Flammable liquids in spraying area stored in metal container with self-closing lid		0.02096	0.89130	0.35483	1.39441
4.3	Flammable liquids stored in closed containers that kept in cupboard or bin		0.01984	0.69565	0.87465	2.37902
4.4	Reasonable quantity of flammable liquids in spraying area		0.01974	0.89130	0.43576	1.49341
4.5	Removal or disposal of combustible materials after use		0.02177	0.78261	0.44403	1.65374
4.6	Smoking prohibition		0.02419	0.86957	0.66233	2.33648
4.7	The use of Dangerous Goods Store		0.02055	0.67391	1.10317	2.59325
5	Electricity Management	0.09324		0.89130	0.54868	1.89036
5.1	Enough supply of electricity		0.01926	0.73913	1.18221	2.57978
5.2	Properly insulate and protect electricity wiring		0.02127	0.82609	0.67250	2.17781
5.3	Use of earth leakage circuit breakers		0.02310	0.86957	0.61933	2.15430
6	Fire Services Equipment and Installations	0.09872		0.93478	0.37287	1.60539
6.1	Fire alarm		0.02018	0.97826	0.46692	1.85456
6.2	Fire blankets		0.01709	0.82609	0.72935	2.41768
6.3	Fire hydrant riser		0.02011	0.89130	0.48807	1.92888
6.4	Fixed fire pump with electricity supply		0.02106	0.76087	0.65147	2.25118
6.5	Hose reel		0.02093	0.80435	0.68065	2.17557
6.6	Periodical Inspection		0.02082	0.82609	0.58982	1.92831
6.7	Portable fire extinguishers at each floor and site office		0.02361	0.84783	0.65823	2.20100
6.8	Portable fire extinguisher at open flame workplace		0.02300	0.80435	0.74365	2.47758
6.9	Provision in area of spraying flammable liquids		0.02177	0.84783	0.43044	1.69722
6.10	Under good condition		0.02123	0.78261	0.55591	1.96778
7	Attitude of Main Contractor towards Fire Safety	0.09708		1.00000	0.21326	1.53592
7.1	High level of commitment to fire safety system		0.02324	0.91304	0.29785	1.54608
7.2	High level of concerns of probability of starting fire		0.02160	0.78261	0.64213	2.17628
7.3	Reasonable budget spent on site fire safety		0.02089	0.78261	0.49826	1.80213
8	Characteristics of Construction Site	0.08090		0.84783	0.66659	2.04360
8.1	Choices of less combustible materials		0.01828	0.78261	0.73334	2.19624
8.2	Good level of ventilation		0.01841	0.84783	0.73346	2.31534
8.3	Types of works that induce numbers of fire sources (e.g. welding works, open flame)		0.01763	0.86957	0.73278	2.20135
9	Safety Procedures for Evacuation	0.09063		0.95652	0.35152	1.69958
9.1	Designated staff (e.g. wardens) help evacuation in fire situation		0.02008	0.89130	0.41839	1.47120
9.2	Evacuation training for on-site staff		0.02018	0.78261	0.65170	1.99634
9.3	Location of emergency signage		0.01967	0.78261	0.83037	2.47498
9.4	Planned evacuation route		0.02273	0.89130	0.48562	1.93859
10	Site Environment during Fire	0.07871		0.84783	0.84440	2.37914
10.1	Low hazards of smoke		0.01974	0.76087	0.96293	2.35565
10.2	Low hazards of irritant gases		0.01773	0.80435	0.78592	2.09983
10.3	Low hazards of toxic gases		0.01838	0.78261	0.94072	2.39393
11	Safety Behaviors of On-Site Staff	0.08748		0.80435	0.52339	1.94293

	Tuble 5. Science in the Risk i detoris and Sub-inetoris	unter combit	aering the v	urues or reen	aonny, e i	und I v
Fire Risk Factors and Sub-factors (Cont'd)		First level weight- ing	Second level weighting	Reliability	Center variance	Interval variance
6	Fire Services Equipment and Installations	0.09872		0.93478	0.37287	1.60539
6.1	Fire alarm		0.02018	0.97826	0.46692	1.85456
6.3	Fire hydrant riser		0.02011	0.89130	0.48807	1.92888
6.6	Periodical Inspection		0.02082	0.82609	0.58982	1.92831
6.9	Provision in area of spraying flammable liquids		0.02177	0.84783	0.43044	1.69722
6.10	Under good condition		0.02123	0.78261	0.55591	1.96778
3	Means of Escape in Case of Fire	0.09763		1.00000	0.21940	1.31971
3.1	Adequate emergency lighting		0.02439	0.95652	0.46869	1.77942
3.2	Adequate width of means of escape		0.01987	0.93478	0.55615	2.04741
7	Attitude of Main Contractor towards Fire Safety	0.09708		1.00000	0.21326	1.53592
7.1	High level of commitment to fire safety system		0.02324	0.91304	0.29785	1.54608
7.2	High level of concern for main contractor about the probability of fire occurrence		0.02160	0.78261	0.64213	2.17628
7.3	Reasonable budget spent on site fire safety		0.02089	0.78261	0.49826	1.80213
5	Electricity Management	0.09324		0.89130	0.54868	1.89036
5.1	Use of earth leakage circuit breakers		0.02310	0.86957	0.61933	2.15430
1	Law Enforcement and On-site Supervision	0.09310		0.93478	0.63909	1.97817
1.1	Enforcement of smoking prohibition		0.02374	0.89130	0.64571	1.83580
1.5	Use of hot work procedures		0.02218	0.89130	0.60494	2.04977
4	Storage of Flammable Liquids and Dangerous Goods	0.09173		0.84783	0.33888	1.68824
4.2	Flammable liquids in spraying area stored in metal container with self-closing lid		0.02096	0.89130	0.35483	1.39441
4.4	Reasonable quantity of flammable liquids in spraying area		0.01974	0.89130	0.43576	1.49341
4.5	Removal or disposal of combustible materials after use		0.02177	0.78261	0.44403	1.65374
2	Means of Access for Firefighting and Rescue Purpose	0.09077		0.95652	0.25402	1.39473
2.3	Provision of firefighting & rescue staircase		0.02232	0.93478	0.47191	1.99637
9	Safety Procedures for Evacuation	0.09063		0.95652	0.35152	1.69958
9.1	Designated staff (e.g. wardens) help evacuation in fire situation		0.02008	0.89130	0.41839	1.47120
9.4	Planned evacuation route		0.02273	0.89130	0.48562	1.93859
11	Safety Behaviours of On-Site Staff	0.08748		0.80435	0.52339	1.94293
11.1	Peer relationship of individuals		0.01967	0.84783	0.63472	2.09006

Table 5. Selected Fire	e Risk Factors and	d Sub-factors after	Considering the	Values of Reliability.	CV and IV

Figure 6 shows the results of rankings and weightings of the 9 selected fire risk factors in descending order. The results show that "Fire Services Equipment and Installations" is the most important fire risk factor. Referring to Table 4, its reliability nearly reaches 94%, which is very satisfactory. The center variance (CV) and interval variance (IV) of this fire risk factor are small (0.37287 and 1.60539 respectively) and this implies that the opinions of the survey respondents are consistent. Due to the high reliability and small variances, it is appropriate to rank this fire risk factor as the most important one. The second and the third most important fire risk factors are "Means of Escape in Case of Fire" and "Attitude of Main Contractor towards Fire Safety", with weightings of 0.09763 and 0.09708 respectively. These two factors both achieved a reliability of 100% and their CV (0.21940 and 0.21326, respectively) and IV (1.31971 and 1.53592, respectively) are also small, which show that the opinions of survey respondents are consistent. It should be noted that the fire risk factor "Attitude of Main Contractor towards Fire Safety" was formulated through structured interviews. The high ranking of this fire risk factor reflects the fact that respondents believe that to only consider fire services equipment and installations is not enough to achieve a good site fire safety level. Attention needs to be paid to human factors as well.



Figure 6. Fire Risk Factors' Weightings

Figure 7 indicates the rankings and weightings of the 20 selected fire risk sub-factors in descending order. The results show that "Adequate Emergency Lighting" is the most important fire risk sub-factor, with a weighting of 0.02439. Referring to Table 4, its reliability nearly reaches 96%, which is a very satisfactory result. The center variance (CV) and interval variance (IV) of this fire risk sub-factor are small (0.46869 and 1.77942, respectively) implying that the opinions of respondents are consistent. With the high reliability and small variances, it is appropriate to rank this fire risk sub-factor as the most important. In addition, its high ranking is in line with the high ranking of its corresponding fire risk factor. The second and the third most important fire risk sub-factors are "Enforcement of Smoking Prohibition" and "High Level of Commitment to Fire Safety System", with weightings of 0.02374 and 0.02324, respectively. These two fire risk sub-factors both achieved a reliability of 89.13% and 91.30% and their CV (0.64571 and 0.29785, respectively) and IV (1.83580 and 1.54608, respectively) are also small, which show that the opinions of survey respondents are quite consistent. It should be noted that these are main-contractor related fire risk subfactors, indicating that main contractors play a vital role in securing construction site fire safety. In other words, it is important for main contractors to monitor and maintain fire safety standards and practices. This analysis also fits the high ranking of the fire risk factor "Attitude of Main Contractor towards Fire Safety", which was ranked as the third most important factor.



Figure 7. Fire Risk Sub-factors' Weightings

#### 4. Application of the Developed Fire Risk Assessment Framework

The fire risk assessment framework which has been developed allows the assessment of site fire risks and their prioritization so that improvement can be affected as necessary for areas with higher risks. In this section, application of the fire risk assessment framework is illustrated using a hypothetical simplified example.

#### **4.1 Application Procedures**

The following application procedures for the fire risk assessment system represent a departure from the inspection approach for existing buildings as suggested by Lo et al. (2005)<sup>[33]</sup>. First, when the level of fire risk is assessed for a construction site, a checklist of fire risk factors should be established. Second, a site inspection should be carried out and information collected relating to the checklist factors. Finally, a fire risk assessment can be conducted and improvement work prioritized, and scheduled.

#### 4.2 A Hypothetical Simplified Example of Applying the Proposed Fire Risk Assessment Framework for a Building Construction Site

To ensure a better understanding of the use of the checklist of fire risk factors and sub-factors, a hypothetical simplified example is presented here, which is based on the 3 selected fire risk factors: (1) "Means of Escape in Case of Fire"; (2) "Electricity Management"; and (3) "Attitude of Main Contractor towards Fire Safety". Their corresponding fire risk sub-factors are also included in the checklist in order to assess the fire risk level (construction site A).

Table 6 shows the weightings of these fire risk factors and sub-factors, obtained from Table 4. Rating means the "score" obtained from the assessed construction site (that is construction site A) during site inspection. The rating system in this instance is based on a 5-point Likert scale, in which 1 represents "very unsatisfactory", 2 represents "unsatisfactory", 3 represents "neutral", 4 represents "satisfactory", and 5 represents "very satisfactory".

After multiplying the weighting and rating for each fire risk sub-factor, the overall grading for the construction site can be calculated as follows:

The overall grading for the construction site, R:

$$R = \sum_{i=1}^{m} (Weighting)_i x (Rating)_i$$
(8)

where R = overall grading for the construction site m = total number of fire risk sub-factors

**Table 6.** A Hypothetical Simplified Example of Application of the Developed Fire Risk Assessment Framework

	Weight- ings	Rating for the Con- struction Site A	Weights x Rating	Overall Grading
		1 – very unsatisfactory		
Fire Risk Factors and Sub-factors		2 – unsatisfactory		
		3 – neutral		
		4 - satisfactory		
		5 – very satisfactory		
Means of Escape in Case of Fire	0.0976	4	0.3904	0.3904
Adequate emergency lighting	0.0244	5	0.1220	
Adequate width of means of escape	0.0199	3	0.0597	
Free from obstruction	0.0228	4.5	0.1026	0.4669
Provision of exit signs	0.0202	5	0.1010	
Under good condition	0.0204	4	0.0816	
Electricity Management	0.0932	2	0.1864	0.1864
Enough supply of electricity	0.0193	1	0.0193	
Properly insulate and protect electricity wiring	0.0213	2.5	0.0533	0.1188
Use of earth leakage circuit breakers	0.0231	2	0.0462	
Attitude of Main Contractor towards Fire Safety	0.0971	3	0.2913	0.2913
High level of commitment to fire safety system	0.0232	5	0.1160	
High level of concerns of probability of starting fire	0.0216	4	0.0864	0.2233
Reasonable budget spent on site fire safety	0.0209	1	0.0209	

The calculation regarding the total number of 11 fire risk sub-factors is as follows:

 $R = R_{Means of Escape in Case of Fire} + R_{Electricity Management} + R_{Attilude of Main Contractor towards Fire Safety}$ = (0.0244 x 5 + 0.0199 x 3 + 0.0228 x 4.5 + 0.0202 x 5 + 0.0204 x 4) + (0.0193 x 1 + 0.0213 x 2.5 + 0.0231 x 2) + (0.0232 x 5 + 0.0216 x 4 + 0.0209 x 1) = 0.4669 + 0.1188 + 0.2233 = 0.809

The overall grading for the construction site, "R", could be used as an indicator for internal benchmarking (i.e. to compare the fire risk levels between the construction sites of a specific construction company). It should be noted that when the overall grading is high, the level of fire risk is low, and vice versa. Based on the above example, when comparing the overall grading of the 3 fire risk factors, it was found that "Electricity Management" should be set as the first priority when conducting improvement work because its overall grading is the lowest (0.1188) in relation to the other two factors. Hence, the proposed fire risk assessment framework can help prioritize improvement work.

#### 5. Significance and Limitations of the Research Study

The developed fire risk assessment framework should be very useful and relevant to those construction personnel responsible for assessing fire risk levels on construction sites and prioritizing improvement work. These construction personnel are not necessarily the safety committee members of the main contractor. They could be project managers, safety managers, building engineers, and building services engineers. The research validity is limited by the number of interviewees. If more respondents with a full range of types of site experiences were sought, the validity of the fire risk assessment framework could be further improved. It should be noted that other fire risk factors, such as underground structures, temporary structures on sites, scaffolding, roofing, planning and phasing, are also important for fire risk assessment for construction sites. However, it is observed that they are of less importance in the local context when compared with the 11 fire risk factors identified in this research study (also verified and validated by the six interviewees). However, these fire risk factors may be significant in construction sites of other countries. Therefore, it is suggested that these other fire risk factors could be included for developing similar comprehensive, objective, reliable, and practical fire risk frameworks for construction sites in other countries. Since the fire risk assessment framework developed in this research study is mainly used for generic situation, this study has not considered the "Planning and Phasing" factor into the

framework in order to make the model simpler and easier. By doing so, the industrial practitioners working for client organizations, main contractors, design consultants and trade subcontractors may find the model use-friendly and this could enhance the effectiveness and efficiency of the model.

#### 6. Summary and Conclusion

Major construction site fire risk factors and their subfactors were successfully identified following the use of (1) review of the literature, legislation, current practices, major past accident records and evacuation issues related to fire safety on construction sites; and (2) structured face-to-face interviews with experienced site personnel using questions developed from the desktop research. On the basis of the identified fire risk factors and their subfactors, an empirical questionnaire survey was launched to determine the levels of influence of each fire risk factor and sub-factor. Subsequently, the weighting assessment method, Reliability Interval Method (RIM), was used to develop the weightings for the fire risk factors and subfactors. RIM is considered the most appropriate method because it is suitable for analyzing a large number of fuzzy factors and sub-factors and allows the use of fuzzy ranges in the weighting assessments. In addition, statistical analysis of weightings using RIM, allows the determination of reliability, center variance (CV) and interval variance (IV). The RIM analysis found the reliability of the questionnaire results attained in this study to be reasonably high and the opinions of the survey respondents to be consistent with one another as a whole.

Based on the analytical results, it was found that the top three fire risk factors are: (1) "Fire Services Equipment and Installations", "Means of Escape in Case of Fire" and "Attitude of Main Contractor towards Fire Safety". The high ranking of "Attitude of Main Contractor towards Fire Safety" implies that to solely rely on fire services installations and the provision of equipment are inadequate if a good site fire safety level is to be attained. Attention should also be paid to human factor aspects. The rankings of fire risk sub-factors show that a number of main-contractor related sub-factors ranked highly, reflecting the fact that it is the main contractor who plays the essential role in maintaining site fire safety. This observation also agrees with the high ranking of the fire risk factor "Attitude of Main Contractor towards Fire Safety".

Based on the weighted fire risk factors and sub-factors, the overall fire risk level of an individual construction site can be objectively assessed and given a score. Moreover, the fire risk assessment framework can be used to identify those factors needing attention to enhance site fire safety. The established assessment framework should be useful to those construction personnel responsible for assuring fire safety levels on construction sites and for prioritizing improvement work. It should be stressed that since this is a generic assessment framework, it can be applied to all types of construction sites, including large, medium or small scale.

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#### Appendix 1: Interview Questions Based on the Initial Checklist of Fire Risk Factors Developed From the Desk Research

#### **Part 1: Background Information**

Q1. To what extent does your job deal with fire safety in construction sites?

#### Part 2: Views on General Situation on Construction Sites

Q2. Do you think appropriate restrictions for on-site personnel, such as smoking prohibition, gas welding and flame cutting work carried out by competent

workers, could affect fire safety on site? If yes, could you identify major sub-factors of appropriate restrictions for on-site personnel?

- Q3. Do you think provision of means of access for firefighting and rescue purposes could affect fire safety on sites? If yes, could you identify major sub-factors of provision of means of access for firefighting and rescue purposes?
- Q4. Do you think provision of means of escape could affect fire safety on sites? If yes, could you identify major sub-factors of provision of means of escape?
- Q5. Do you think storage of flammable liquids or dangerous goods could affect fire safety on sites? If yes, could you identify major sub-factors of storage of flammable liquids or dangerous goods?
- Q6. Do you think proper electricity wiring management such as insulating electric wiring properly could affect fire safety on sites? If yes, could you identify major sub-factors of proper electricity wiring management?
- Q7. Do you think appropriate design of construction sites, such as compartment, could affect fire safety on sites? If yes, could you identify major sub-factors of appropriate design characteristics of construction sites?
- Q8. Do you think provision of fire services equipment and installations could affect fire safety on sites? If yes, could you identify major sub-factors of provision of fire services equipment and installations?

#### **Part 3: Views on Evacuation Issue**

- Q9. Do you think procedures implemented within the site, such as provision of staff evacuation training and prior knowledge of location signage, could affect fire safety on sites? If yes, could you identify major sub-factors of the procedural influences?
- Q10.Do you think environment within the site during fire, such as hazards of heat, smoke and toxic and irritant gases, could affect fire safety on sites?
- Q11.Do you think behaviour of site staff, such as initial response to fire alarm and travel rate, could affect fire safety on sites?

#### **Part 4: Further Information**

Q12.Can you suggest any other factors that could affect fire safety on sites? If yes, could you identify major sub-factors of this factor?

## **Author Guidelines**

This document provides some guidelines to authors for submission in order to work towards a seamless submission process. While complete adherence to the following guidelines is not enforced, authors should note that following through with the guidelines will be helpful in expediting the copyediting and proofreading processes, and allow for improved readability during the review process.

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- Program: Microsoft Word (preferred)
- Font: Times New Roman
- Size: 12
- Style: Normal
- Paragraph: Justified
- Required Documents

#### II. Cover Letter

All articles should include a cover letter as a separate document.

The cover letter should include:

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The corresponding author should be identified.

Eg. Department, University, Province/City/State, Postal Code, Country

• A brief description of the novelty and importance of the findings detailed in the paper

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v Conflict of Interest

Examples of conflicts of interest include (but are not limited to):

- Research grants
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- Employment or consultation
- Project sponsors
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- Other financial relationships/support
- Informed Consent

This section confirms that written consent was obtained from all participants prior to the study.

Ethical Approval

Eg. The paper received the ethical approval of XXX Ethics Committee.

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Eg. Name of Trial Registry: Trial Registration Number

#### • Contributorship

The role(s) that each author undertook should be reflected in this section. This section affirms that each credited author has had a significant contribution to the article.

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Supplementary figures, small tables, text etc.

As supplementary data/information is not copyedited/proofread, kindly ensure that the section is free from errors, and is presented clearly.

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A general introduction to the research topic of the paper should be provided, along with a brief summary of its main results and implications. Kindly ensure the abstract is self-contained and remains readable to a wider audience. The abstract should also be kept to a maximum of 200 words.

Authors should also include 5-8 keywords after the abstract, separated by a semi-colon, avoiding the words already used in the title of the article.

Abstract and keywords should be reflected as font size 14.

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The title should not exceed 50 words. Authors are encouraged to keep their titles succinct and relevant.

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Section headings, sub-headings, and sub-subheadings should be differentiated by font size.

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The introduction should highlight the significance of the research conducted, in particular, in relation to current state of research in the field. A clear research objective should be conveyed within a single sentence.

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this section. Alternatively, Results and Discussion can also be combined to a single section.

#### **W**. Discussion

In this section, the results of the experiments conducted can be discussed in detail. Authors should discuss the direct and indirect implications of their findings, and also discuss if the results obtain reflect the current state of research in the field. Applications for the research should be discussed in this section. Suggestions for future research can also be discussed in this section.

#### $\ensuremath{\mathrm{I\!X}}\xspace$ . Conclusion

This section offers closure for the paper. An effective conclusion will need to sum up the principal findings of the papers, and its implications for further research.

#### X. References

References should be included as a separate page from the main manuscript. For parts of the manuscript that have referenced a particular source, a superscript (ie. [x]) should be included next to the referenced text.

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#### XI. Glossary of Publication Type

J = Journal/Magazine

- M = Monograph/Book
- C = (Article) Collection
- D = Dissertation/Thesis
- P = Patent
- S = Standards
- N = Newspapers
- R = Reports

Kindly note that the order of appearance of the referenced source should follow its order of appearance in the main manuscript.

Graphs, Figures, Tables, and Equations

Graphs, figures and tables should be labelled closely below it and aligned to the center. Each data presentation type should be labelled as Graph, Figure, or Table, and its sequence should be in running order, separate from each other. Equations should be aligned to the left, and numbered with in running order with its number in parenthesis (aligned right).

#### XII. Others

Conflicts of interest, acknowledgements, and publication ethics should also be declared in the final version of the manuscript. Instructions have been provided as its counterpart under Cover Letter.



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