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Original Article

Development of Welding Fumes Health Index (WFHI) for Welding Workplace's Safety and Health Assessment

Azian HARIRI [1], Nuur Azreen PAIMAN [1], Abdul Mutalib LEMAN [2], Mohammad Zainal MD. YUSOF [1]

1. *Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia*
2. *Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia*

***Corresponding Author:** Email: azian@uthm.edu.my

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Abstract

Background: This study aimed to develop an index that can rank welding workplace that associate well with possible health risk of welders.

Methods: Welding Fumes Health Index (WFHI) were developed based on data from case studies conducted in Plant 1 and Plant 2. Personal sampling of welding fumes to assess the concentration of metal constituents along with series of lung function tests was conducted. Fifteen metal constituents were investigated in each case study. Index values were derived from aggregation analysis of metal constituent concentration while significant lung functions were recognized through statistical analysis in each plant.

Results: The results showed none of the metal constituent concentration was exceeding the permissible exposure limit (PEL) for all plants. However, statistical analysis showed significant mean differences of lung functions between welders and non-welders. The index was then applied to one of the welding industry (Plant 3) for verification purpose. The developed index showed its promising ability to rank welding workplace, according to the multiple constituent concentrations of welding fumes that associates well with lung functions of the investigated welders.

Conclusion: There was possibility that some of the metal constituents were below the detection limit leading to '0' value of sub index, thus the multiplicative form of aggregation model was not suitable for analysis. On the other hand, maximum or minimum operator forms suffer from compensation issues and were not considered in this study.

Keywords: Welding fumes, Index, Aggregation analysis, Malaysia

Introduction

Hundreds of millions of people throughout the world are working under circumstances that foster ill health or unsafe. It is estimated that yearly over two million people worldwide die of occupational injuries and work-related diseases. In fact, more people die from diseases caused by work than are killed in industrial accidents (1). According to American Welding Society (AWS) and Edison Welding Institution (EWI) (2), welding will continue to be the preferred method of joining for world class product until 2020. Although there is a wide breadth of hazards that exist in welding operations, only 2% of Occupational Safety and Health Association (OSHA) general industry citations addressing on this matter (3).

Previous researches had highlighted the challenges for developing countries in strategies for risk assessment and control in welding industries. Transfer of technologies of welding from developed countries to developing countries which do not have similar infrastructures in terms of health and safety may be disastrous. Uncritical adoption of new welding technologies by developing countries potentiates future health problems (4, 5). To this date, there is still very limited study that discussed the relationship between welding emissions with health risk of welder in automotive industry especially in Malaysia (6).

Currently the welding fumes exposure risk assessments were largely focused on single welding fumes constituents approach because the regulatory standard for compliance only caters for a single constituent. However, in reality, welders are simultaneously exposed to multiple welding fumes constituent at once. Assessment of the hazards of multiple simultaneous exposures only had been done in limited study (7). According to Dominici et al. (8), the shift from a single pollutant to multiple pollutant assessment was desirable by the scientific community and policy makers.

Welding hazard risk assessment had been conducted by several researches. Karkoszka and Sokovic (9), developed the integrated risk estimation in welding process using qualitative method of assigning probability of occurrence, significance and risk involve in aspect of occupational and safety. Yeo and Neo (10), on the other hand introduce the health hazard scoring system to quantify the environmental impact of the different welding process before choosing the most environmentally friendly welding processes. However, these models did not consider the quantitative data on welding fumes exposure and the developed tools had not been verified with actual data. On the other hand, Leman et al. (11) had developed an Environmental Quality Index (EQI) for industrial ventilation and occupational safety and health evaluation of welding processes in manufacturing plants. Although the index has been developed based on actual data on welding exposure, there were no analysis had been done on the selection of the aggregation model used in this study. Thus, there was still gap in developing a suitable risk assessment method relating to welding fume exposure to possible health risk of welder in quantitative manners.

Research needs had been highlighted to pursue a means of indexing exposure by job type or process by taking into account the intensity of the welding job and work practiced (12). However, welders are not a homogeneous group, the potential adverse effect of welding fume exposures are oftentimes difficult to evaluate. Differences exist in welder populations, such as industrial setting, types of ventilation, type of welding processes and materials used (13). Indexing exposure by job type or process is almost impossible to implement. However, indexing exposure according to the location would be benefited as ranking tools between different locations on the same scale. Welding risk assessment would be simpler if a single metric could embody all of the information in the measurement (14). Hence, this study aims to develop an index that can rank welding workplace that associate well with possible health risk of welders.

Materials and Methods

Study Population

The investigation was conducted in two automotive related industrial plants working on spot gun, spot weld and robotic metal inert gas (MIG) weld. Plant 1 consists of 53 male welders while Plant 2 consists of 44 male welders. Plant 1 had the average 12 hour working shifts while Plant 2 has 14 hours average working shifts. Fifty three non-welder male workers that did not have continuous exposure to welding fumes were selected from similar workplaces as control. They were primarily of technicians, engineers and administrators. Another 30 male welders from Plant 3 that work for average 8 hours at automotive assembly industries were investigated for index verification purposed. These welders work on spot gun and spot gun with adhesive welding processes. All welders worked without the benefit of fume ventilation or proper respiratory protective devices.

Lung Function

Lung Function Test (LFT) were performed on handheld spirometer (Micro Medical DL, UK) connected to spirometer software (Care Fusion, San Diego) on a notebook computer. Spirometer was calibrated daily with a 3L calibration syringe. Interviews were conducted before conducting maneuvers to record demographic data, smoking habit and working experience. The maneuver was explained with the help of short video clip demonstration. Maneuvers were performed in standing positions. Tests were conducted according to forced vital capacity procedure of the American Thoracic Society recommends (15). Measured parameters were forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1) and peak expiratory flow (PEF) were all expressed as a percentage of the predicted value and FEV1/FVC ratio. The predicted set used in this study was taken from Pneumobile Project, Indonesia (16). Interpretation and derivation of the value of normal, obstruction and restriction lung function result were done according to the American Thoracic Society (ATS) (15).

Welding Fumes Personal Sampling

Personal samplings of welding fumes were conducted in Plant 1, Plant 2 and Plant 3 during March to June 2013. Sampling heads were located within the breathing zone of the welders. Personal sampling method was based on British Standard guidelines BS EN 689:1996 which stated at least one employee in ten of properly selected homogeneous group performing similar tasks must be sampled (17). The filters media (mixed cellulose ester 0.8 µm pore sizes) was used with sampling pump set to 2 L/min flow rate. Personal sampling of welding fumes was done with the objective to get exposure on maximum risk workers. Thus, in situation where more than one samples were obtained, the results with the highest concentration in most of the constituents were selected. In Malaysia, Under the Occupational Safety and Health Act 1994, Use and Standards of Exposure of Chemical Hazardous to Health regulation (USECHH) (18), chemical classified hazardous to health with its permissible emission limits (PEL) were listed and need to be comply by the employer. The collected samples were sent to the accredited laboratory for analysis. The analysis in certified laboratory was done based on American Society for Testing and Materials (ASTM) D7439-08 method by using inductively coupled plasma mass spectrometry (ICP-MS)(Agilent 7700) with microwave digestion (nitric acid and hydrochloric acid). At least one field blanks were submitted together with batch of samples for each investigated plants to the accredited laboratory for analysis. Duration of sampling was calculated and the concentrations of exposure were calculated in time weighted average 8 hours (TWA 8).

Welding Fumes Health Index Development

From a regulatory compliance perspective, threshold levels of controlled parameters are established in the context of possible adverse impacts to human health. It will be useful to relate the index to some acceptance parameters that are measurable. Development of environmental index involves following four basic steps as shown in Fig. 1 (19-21).

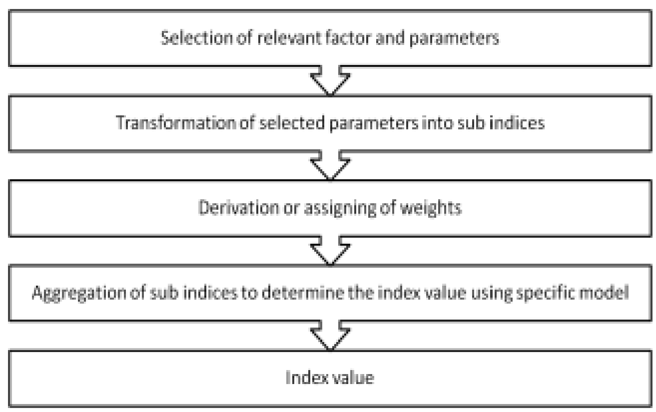

Fig. 1: Basic steps in development of environmental index (19)

Each of these steps was explained in the next subsection.

a. Selection of Relevant Factors and Parameters

In this study, the analyses of welding fumes were conducted by ICP-MS. Currently there are only two standard method for determination of constituents in airborne particulate matters by using ICP-MS, which is ASTM D7439-08 (22) and British Standard (BS) International Standardization Organization (ISO) BS ISO 30011:2010 (23). ICP-MS has the advantage to analyze up to 25 multi constituents in a single sample. From these 25 constituents, only 15 constituents (aluminum, antimony, arsenic, beryllium, cadmium, chromium, cobalt, copper, ferum, lead, manganese, molybdenum, nickel, silver and tin) were shortlisted according to the constituents commonly associated with welding, cutting and brazing (24,25).

b. Transformation of Selected Parameters Into Sub-Index

The development of dose-effect information was often regarded as highly simplistic and not readily accepted by researches in epidemiology field. It is often not possible to identify the dose-effect information that applies to individual pollutant and properly covers all segments of the population. The dose-effect function must contend with the complexity of controlling extraneous factor that gave impact on the observed effect (26). This scenario resulted in limited dose-effect information for pollutants available in the literatures. However, in risk assessment, the ideas on combining dose and health risk (dose-risk) were widely implemented (10,27,28). The dose and risk effect in this study follow the dose-risk model for inhalable toxicity by (10,27,28) as shown in Eq. 1.

$$Sub\ index\ value = doses\ rating \times \sum health\ risk\ rating$$

(Eq. 1)

i. Doses rating

The 15 metal constituents (aluminum, antimony, arsenic, beryllium, cadmium, chromium, cobalt, copper, ferum, lead, manganese, molybdenum, nickel, silver and tin) were selected as parameters of sub - indexes. The doses rating values were derived from a segmented linear function or also known as staircase step function as shown in Fig.2 (26,29,30). Fig. 2 shows the relation between pollution concentration and doses rating values. By taking the PEL as a reference line, the concentration of welding fumes below 5% of the reference line is considered as the moderately serious dose with a rating value of 2. The concentration of welding fumes exceeding the reference line is considered as the lethal dose with a rating value of 3. Mild effect dose with rating value 1 is considered as 5% concentration of welding fumes below the reference line to limit of detection of value. For concentration below the limit of detection, given rating is 0.

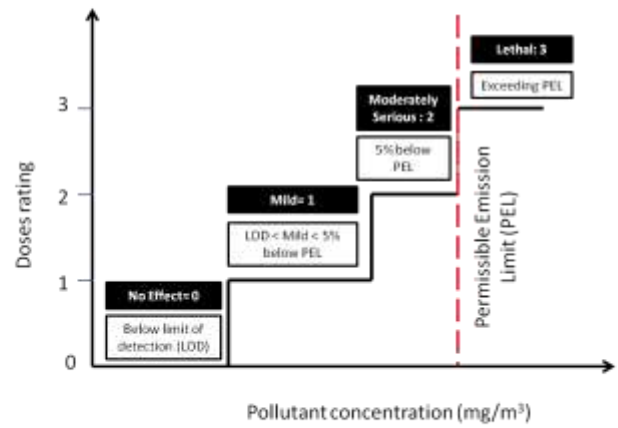

Fig. 2: Relation between doses rating and pollution concentration

ii. Health risk ratings

Four health risks were considered in this study according to National Institute for Occupational Safety and Health (NIOSH) Pocket Guide to Chemical Hazard (24); sensitizer, respiratory toxins, target organ toxins and carcinogen. Table 1 shows the how the health risk rating were categorized.

The health risk ratings according to each investigated constituents were tabulated in Table 2. Arsenic and cadmium had the highest rating score of 9 while Aluminum, Silver and Tin had the lowest total rating score of 1. The health risk information was extracted from NIOSH Pocket Guide to Chemical Hazard (24) for the investigated 15 welding fumes constituents.

c. Derivation of Weight

The weight of each metal constituent was derived according to their PEL. Metal constituents with lower PEL has higher weight as shown in Table 3. As for manganese metal constituents, the PEL is according to the ceiling value. The weight was selected so that their sum is unity.

d. Aggregation Model

The aggregation process is the crucial part in calculation of environmental index. They affect the quality of results in many ways because aggregation process is where most of the simplifying process (reduction of information) takes place (26,31).

Table 1: Criteria for health risk rating

Health Risk Rating	Sensitizer	Respiratory Toxins	Target Organ Toxins	Carcinogen
0 (no effect)	no observed health risk	no observed health risk	no observed health risk	no observed health risk
1 (mild)	one sensitizer health risk	nose, nasal cavities	one target organ health risk	IARC 3,4 TLV A4,A5
2 (moderately serious)	two sensitizer health risks	pharynx, larynx, trachea	two target organs health risks	IARC 2A,2B TLV A2,A3
3 (Lethal)	more than two sensitizer health risks	lower respiratory tracts: lung, bronchioles, alveoli	more than two target organs health risks	IARC 1 TLV A1

Table 2: Health risk rating by constituents

Metal Constituents	Sensitizer	Respiratory Toxins	Target Organ Toxins	Carcinogen	Total Health Risk Ratings
Aluminum (Al)	0	1	1	0	2
Antimony (Sb)	0	2	1	0	3
Arsenic (As)	0	3	3	3	9
Beryllium (Be)	0	3	0	3	6
Cadmium (Cd)	0	3	3	3	9
Chromium (Cr)	0	2	0	1	3
Cobalt (Co)	1	3	0	2	6
Copper (Cu)	0	2	2	0	4
Iron (Fe)	0	3	0	0	3
Lead (Pb)	0	1	3	2	6
Manganese (Mn)	0	3	3	0	6
Molybdenum (Mo)	0	2	2	2	6
Nickel (Ni)	2	3	0	2	7
Silver (Ag)	0	1	0	0	1
Tin (Sn)	0	1	0	0	1

Aggregation model consist of; additive form, multiplicative form and maximum or minimum operator form as shown in Table 4. In this study, 15 welding fumes constituents were considered as sub-indices. There was possibility that some of the constituents were below the detection limit leading to '0' value of sub index, thus a multiplicative form of aggregation model was not suitable for analysis in this study. Maximum and minimum operators were also excluded from this study because these types of operators are biased towards extreme (minimum or maximum) sub index values. Most of the air pollution indices reported in literatures use the additive form aggregation model and developed in the increasing scale form (higher index portray the severe condition) (32-34). Following this, only additive forms of aggregation model were selected for analysis in this study.

i. Penalty Function of Aggregation Models

Combination of sub index by using aggregation models commonly arise issues such as ambiguity, eclipsing, compensation, and rigidity. These issues were explained in Table 5. In order to compare the aggregation models quantitatively, Sadiq et. al (19) had proposed the usage of penalty functions in order to select the most appropriate aggregation models in a specific condition as shown in Table 5. It was highlighted by (19) that in the search of better aggregation model, a trade-off exists between properties; a model may perform very well against one property, but perform poorly against another. Therefore, in a selection of a model producing either ambiguous or eclipsed results, the index developer must consider to what degree the ambiguous or eclipsed result is acceptable. Thus, the penalty function analysis must be done to compare and select the most suitable aggregation model for the developed index based on data collected in the case studies conducted. Penalties are derived from the penalty function such that they are continuous over an interval [0,1], where '0' refers to 'no penalty' (ideal condition) and '1' refers to 'maximum penalty'.

Once the four penalty functions were calculated, a representative value of a cumulative penalty (Pc) is derived to compare different model. The value of cumulative penalty that increase by an increase of α is suitable for the development of an index that considered compensation and rigidity as important characteristic. On the other hand, the value of a cumulative penalty that decrease by an increase of α is suitable for the development of an index that considered ambiguous and eclipsing as important characteristic.

Table 3: Weight according to constituents

No.	Constituents	USECCH PEL (mg/m³)	Weight
1	Aluminum (Al)	5.0 (resp.) 15.0 (total)	0.025
2	Antimony (Sb)	0.5	0.050
3	Arsenic (As)	0.010	0.100
4	Beryllium (Be)	0.002 C 0.005	0.190
5	Cadmium (Cd)	0.005	0.190
6	Chromium (Cr)	0.5	0.050
7	Cobalt (Co)	0.1	0.050
8	Copper (Cu)	1.0	0.025
9	Iron (Fe)	10	0.020
10	Lead (Pb)	0.05	0.100
11	Manganese (Mn)	C5	0.025
12	Molybdenum (Mo)	5.0 (soluble) 15 (total insoluble)	0.025
13	Nickel (Ni)	1.0	0.025
14	Silver (Ag)	0.01	0.100
15	Tin (Sn)	2.0	0.025
Total			1.000

Table 4: List of aggregation model

No.	Aggregation model	Formulation	Used by
Additive form			
1	Unweighted linear sum	$I_{ls}=\sum_{i=1}^{N} S_i$	(11,32)
2	Root sum power addition	$I_{rspa}=\left(\sum_{i=1}^{N} {S_i}^4\right)^{1/4}$ Where $p \geq 1$	(35)
3	Weighted root sum power	$I_{wrsp}=\left(\sum_{i=1}^{N} w_i {S_i}^{10}\right)^{1/10}$ Where $p \geq 1$	(31)
4	Arithmetic mean	$I_{am}=\frac{1}{N}\sum_{i=1}^{N} S_i$	(36-39)
5	Weighted arithmetic mean	$I_{wam}=\sum_{i=1}^{N} w_i S_i$	(40-42)
6	Square root harmonic mean	$I_{srhm}=\left(\frac{1}{N}\sum_{i=1}^{N} {S_i}^2\right)^{0.5}$	(26)
7	Weighted root sum square	$I_{wrss}=\left(\sum_{i=1}^{N} w_i S_i\right)^{1/2}$	(19)
8	Root mean square addition	$I_{rmsa}=\left(\sum_{i=1}^{N} \frac{1}{N} {S_i}^2\right)^{0.5}$ Where $p \geq 1$	(33)
Multiplicative form			
1	Weighted product	$I_{wp}=\prod_{i=1}^{N} S_i$	(19)
2	Geometric mean	$I_{gm}=\left(\prod_{i=1}^{N} S_i\right)^{1/N}$	(43)
Maximum or minimum operator form			
1	Maximum operator	$I_{max} = \max\{S_1, S_2, S_3 \ldots, S_N\}$	(26,44)
2	Minimum operator	$I_{min} = \min\{S_1, S_2, S_3 \ldots, S_N\}$	(26)

Where:
$I = Index$
N: *number of sub − indices*
$S_1 \ldots S_N$ = *sub − indices value*
$w_1 \ldots w_N$: *weight of each sub − indices, where* $\sum_{i=1}^{N} w_i = 1$

Table 5: Aggregation model's issues and penalty function adapted from Sadiq et. al. (19)

Issues	Characteristic	Remark	Penalty function
Ambiguity	Over estimation problem. The index value exceeds the critical level (unacceptable value) without any of the sub indices exceeding the critical level	Ambiguity and eclipsing are mutually exclusive properties, an aggregation model is either ambiguous or eclipsed	$P_1 = \left(1 - \frac{I}{I^{Min}}\right); 0 < I < I^{Min}$ $P_1 = 0; I > I^{Min}$
Eclipsing	Underestimation problem. Index value does not exceed the critical level (unacceptable value) despite one or more of the sub index exceeding the critical value		$P_2 = 0;\ I^{Min} > 1$ $P_2 = \left(\frac{I - I^{Min}}{I^{Max} - I^{Min}}\right);$ $I^{Min} < I < I^{Max}$ $P_2 = 1;\ I > I^{Max}$
Compensation	Index values biased toward extremes (highest or lowest sub index value)	-	$P_3 = 1 - \left(\frac{I - I^{Min}}{I^{AM} - I^{Min}}\right); I^{Min} \leq I < I^{AM}$ $P_3 = \left(\frac{I - I^{AM}}{I^{Max} - I^{AM}}\right); I^{AM} < I < I^{Max}$ $P_3 = n/a;\ Otherwise$
Rigidity	Index value reduces despite of new sub index added in the aggregation model	-	$P_4 = \left\lvert\frac{\Delta I}{\Delta N}\right\rvert \times 10$ $P_4 \epsilon [0,1]$ $P_4 = n/a;\ P_4 > 1$
Cumulative Penalty			$(P_1 + P_2) \cdot \alpha + 0.5(P_3 + P_4) \cdot (1 - \alpha);\ (\alpha)\epsilon[0,1]$

Where
P_1: *penalty values for ambiguity*
P_2: *penalty values for eclipsing*
P_3: *penalty values for compensation*
P_4: *penalty values for rigidity*
I: *index value*
I^{Max} = *maximum index value*
I^{Min} = *minimum index value*
I^{AM} = *mean index value*
α = *weighing factor*
$\frac{\Delta I}{\Delta N}$ = *change in index value with respect to the change in number of subindices*

Statistical Analysis

Statistical analysis was conducted by SPSS software version 18 (SPSS Inc., Chicago). Analysis of variance (ANOVA) and multivariate analysis of variance (MANOVA) was used to compare mean lung function parameters between welders and control groups. Pearson correlation analysis was done to get association between working duration, smoking duration and type of welding with lung function. Further analysis using multiple regression analysis was done to confirm the predictors of the lung functions increased/decreased value. The level of significance was taken as P <0.05.

Results

i. Lung Function

Lung function data (mean ± standard deviation (SD)) of welders on each plant and control groups was shown in Table 6. Apparently lung function results showed that the mean of all lung function parameters of Plant 1 and Plant 2 were lower than the control group. The multivariate MANOVA analysis reveals there was a significant mean difference of lung function values between groups F (10,282) =6. 53, P <. 01. Further separate univariate ANOVAs on the outcome variable reveals welders on each plant had significant difference of the mean value of FEV1/FVC, F (2,146) =3. 84, P <. 05 and PEF, F (2,146) =18. 49, P <. 01 compared to control group.

Index verification was done by conducting a lung function and welding fumes investigation in an automotive assembly plant (refer as Plant 3 afterwards).

Lung function data (mean ± SD) of welders on each plant and control groups was also shown in Table 6. Apparently lung function results showed that the mean of all lung function parameters of

Plant 1, Plant 2 and Plant 3 were lower than the control group. The multivariate MANOVA analysis reveals there was a significant mean difference of lung function values between groups F (12,512) =3. 84, *P* <. 01. Further separate univariate ANOVAs on the outcome variable reveals welders on each plant had significant difference of the mean value of FEV1/FVC, F (3,175) =2. 70, *P* <. 05 and PEF, F (3,175) =12. 70, *P* <. 01 compared to control group.

ii. Personal Sampling

Table 7 shows the results of welding fumes personal sampling collected in Plant 1 and Plant 2 according to welding job type. There were no metal constituents that exceeding the USECCH PEL for all plants. Iron was the highest constituent concentration in all plants with 0.602 (mg/m³) detected in spot gun welding job process in Plant 2.

Several constituents such as antimony, beryllium, cadmium, cobalt, molybdenum, nickel and tin were detected below the limit of detection in all plants. The results of the field blanks did not show any contaminants or unusual concentration of metal constituents detected during sampling or handling of samples.

Table 6: Mean values for control, Plant 1, Plant 2 and Plant 3

Criteria	Control n=52 (mean±SD)	Plant 1 n=53 (mean±SD)	Plant 2 n=44 (mean±SD)	Plant 3 n=30 (mean±SD)
Age	34.56±7.65	30.62±5.96	28.84±5.55	29.73±9.04
FVC (% pred)	88.33 ±12.19	84.09±15.79	87.86±13.20	87.20 ±12.90
FEV_1 (% pred)	94.58±12.40	88.51±15.30	91.14±12.99	90.83±11.48
FEV_1/FVC	107.94±6.38	105.91±9.89	103.61±5.55	104.87±7.82
PEF (% pred)	84.67±11.93	68.58±16.07	71.68±14.50	79.53±15.64

Table 7: Welding Fumes Personal Sampling

Constituents		Spot gun (mg/m³)		Spot weld (mg/m³)		Robotic (MIG) weld (mg/m³)		USECCH PEL (mg/m³)
		Plant 1	Plant 2	Plant 1	Plant 2	Plant 1	Plant 2	
Aluminum	Al	0.021	0.038	0.014	0.021	0.021	0.028	5.0 (resp.) 15.0 (total)
Antimony	Sb	< 0.001	n/d	< 0.001	n/d	< 0.001	n/d	0.5
Arsenic	As	0.003	0.009	0.003	0.008	0.003	0.009	0.010
Beryllium	Be	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	n/d	0.002 C 0.005
Cadmium	Cd	< 0.001	n/d	< 0.001	< 0.001	< 0.001	n/d	0.005
Chromium	Cr	0.009	0.028	0.007	0.028	0.007	0.034	0.5
Cobalt	Co	< 0.001	n/d	n/d	n/d	< 0.001	n/d	0.1
Copper	Cu	0.003	0.003	0.002	0.002	< 0.001	0.005	1.0
Iron	Fe	0.019	0.602	0.008	0.053	0.362	0.265	10
Lead	Pb	0.001	0.001	0.001	0.001	0.002	0.001	0.05
Manganese	Mn	0.009	0.012	0.012	< 0.001	0.082	0.031	C5
Molyb-denum	Mo	< 0.001	n/d	< 0.001	n/d	< 0.001	n/d	5.0 (soluble) 15 (total insoluble)
Nickel	Ni	n/d	n/d	n/d	n/d	n/d	n/d	1.0
Silver	Ag	< 0.001	n/d	< 0.001	n/d	0.001	< 0.001	0.01
Tin	Sn	< 0.001	n/d	n/d	n/d	< 0.001	< 0.001	2.0

<: less than, n/d: not detected

Table 8 shows welding fume concentration for Plant 3. Iron constituents had the highest concentration with 0.633 mg/m³. However, none of the constituents were exceeding the PEL.

Table 8: Welding fume concentration for Plant 3

Constituents		**Plant 3** (mg/m³)	
		Spot gun	**Spot gun + adhesive**
Aluminum	Al	0.018	0.02
Antimony	Sb	< 0.001	< 0.001
Arsenic	As	0.002	0.003
Beryllium	Be	< 0.001	< 0.001
Cadmium	Cd	< 0.001	< 0.001
Chromium	Cr	0.009	0.011
Cobalt	Co	< 0.001	< 0.001
Copper	Cu	0.003	0.002
Iron	Fe	0.633	0.027
Lead	Pb	< 0.001	0.001
Manganese	Mn	0.006	n/d
Molybdenum	Mo	< 0.001	< 0.001
Nickel	Ni	n/d	n/d
Silver	Ag	0.001	n/d
Tin	Sn	n/d	n/d

Discussions

Table 9 shows the correlation between lung functions of welders in each plant with working years, smoking years and type of welding. Pearson correlation reveals there was a significant relationship in each plant as follows;

Plant 1: significant relationship between FVC and the number of working years (r=-. 40, *P* (two tailed) <. 001) and significant relationship between FEV1 and the number of working years (r=-. 40, *P* (two tailed) <. 001). Further analysis by multiple regressions (backward stepwise method) confirmed number of working years was the significant predictor to the decreased value of FVC. However, the number of smoking years and type of welding was not the significant predictors of decreased values of FVC. Number of working years was also the significant predictor to the decreased value of FEV1. However, the number of smoking years and type of welding was not the significant predictors of decreased values FEV1.

Plant 2: significant relationship between FEV1/FVC and number of working years (r=. 31, *P* (two tailed) <. 05). Further analysis by multiple regressions (backward stepwise method) confirmed number of working years was also the significant predictor to the increase values of FEV1/FVC. However, the number of smoking years and type of welding was not the significant predictors of the increase values of FEV1/FVC.

Plant 3: Significant relationship between FEV1/FVC and number of smoking years (r=. 58, *P* (two tailed) <. 001). Further analysis by multiple regressions (backward stepwise method) confirmed number of smoking years was the significant predictor to the increase values of FEV1/FVC. However, working duration and type of welding were not the significant predictors of FEV1/FVC. Apparently high values FEV1/FVC relates to a restrictive disorder which contradicts with smoking effects which was the low values of FEV1/FVC (obstruction disorder). The welding fume exposures often associate with restrictive disorders (45-47) while smoking is associated with obstruction disorder (48,49). There were also synergistic relations between the effects of smoking and welding exposure causing lung impairment reported by (50-52). To clarify these issues, analysis between smoker and nonsmoker welder were being carried out. Thus, multiple regression analysis (backward stepwise method) was conducted again for FEV1/FVC value as dependent variables, smoking status (smoker and nonsmoker) and working group (less and more than 5 years working experience) and as predictors. The working group was the significant predictor of increased of FEV1/FVC. These results showed a synergistic relationship between the effects of number of smoking years and welding exposure for more and less than 5 years working experience causing restrictive disorder in Plant 3.

Table 10 shows the mean values of FVC, FEV1, FEV1/FVC and PEF in Plant 1, 2 and 3. Plant 3 pulmonary function values were adjusted with smoking years.

The mean number of cigarette smoke by welder was 3, 4 and 7 for Plant 1, 2 and 3 respectively. It is clear that welders in Plant 3 smoke in average 2 times higher (number of cigarette) than plant 1 and 2.

Table 9: Pearson correlation between lung functions of welders in each plant with working years, smoking years and type of welding

Plant 1				
	FVC	**FEV1**	**FEV1/FVC**	**PEF**
Number of working years	-.404**	-.399**	.131	-.024
Number of smoking years	.015	-.056	-.056	-.132
Type of welding	.056	.200	.149	.092
Plant 2				
	FVC	FEV1	FEV1/FVC	PEF
Number of working years	.021	.146	.306*	.016
Number of smoking years	.093	.072	-.037	-.202
Type of welding	.114	.077	-.098	.101
Plant 3				
	FVC	FEV1	FEV1/FVC	PEF
Number of working years	-.193	-.023	.352	-.180
Number of smoking years	-.294	-.051	.579**	-.125
Type of welding	-.108	-.330	-.247	-.073

*P<. 05, **P<0.01

Only smokers with below than 10 years smoking duration were selected for Plant 3. This exclusion decreased the average number of cigarette smoke for Plant 3 from 7 to 5. For smoking years were not the significant predictors for Plant 1 and 2, no adjustment towards smoking years were made from these plants. Data tabulated in Table 8 were used for comparison between index value and percentage of predicted pulmonary function's value at the end of this section.

Aggregation Model Analysis

Table 11 shows the mean penalty functions for nine aggregation model (explained in Table 4) based on welding fume concentration in plant 1 and 2.

Table 10: Mean values for the control, Plant 3 (adjusting for smoker*), Plant 1 and Plant 2

Criteria	**Control n=52 (mean±SD)**	**Plant 3 n=23* (mean±SD)**	**Plant 1 n=53 (mean±SD)**	**Plant 2 n=44 (mean±SD)**
Age	34.56±7.65	28.00±9.17	30.62±5.96	28.84±5.55
FVC (% pred)	88.33 ±12.19	89.65 ±13.23	84.09±15.79	87.86±13.20
FEV_1 (% pred)	94.58±12.40	91.96±11.27	88.51±15.30	91.14±12.99
FEV_1/FVC	107.94±6.38	102.96±6.65	105.91±9.89	103.61±5.55
PEF (% pred)	84.67±11.93	80.565±12.55	68.58±16.07	71.68±14.50

Table 11: Mean penalty functions values for aggregation models

Penalty Functions	***Ils***	***Irspa***	***Iwrsp***	***Iam***	***Iwam***	***Isrhm***	***Iwrss***	***Irmsa***
P1	0	0	0	0	0	0	0	0
P2	1	1	0.80	0.23	0.22	1	0.16	0.39
P3	n/a	n/a	0.74	n/a	0.06	n/a	0.33	0.20
P4	n/a	0.83	0.27	0.77	0.84	n/a	0.68	0.63

Cumulative Penalties Pc for nine aggregation models were calculated and tabulated in Table 12. In the development of WFHI, ambiguity and eclipsing were considered more important because the index should not suffer from overestimation or underestimation of health risk related to welding fumes exposure. The values of the aggregation model of *Iam*, *Iwam*, *Iwrss* and *Irmsa* decreased by an increase of α thus suitable for index that considered ambiguity and eclipsing were more important (19). From this four shortlisted aggregation models, *Iwam and Iwrss* were selected because the smallest penalty function values.

Table 12: Cumulative penalty values for aggregation models

alpha	*Ils*	*Irspa*	*Iwrsp*	*Iam*	*Iwam*	*Isrhm*	*Iwrss*	*Irmsa*
0	0.00	0.42	0.50	0.39	0.45	0.00	0.50	0.42
0.1	0.10	0.47	0.53	0.37	0.43	0.10	0.47	0.41
0.2	0.20	0.53	0.56	0.36	0.40	0.20	0.43	0.41
0.3	0.30	0.60	0.59	0.34	0.38	0.30	0.40	0.41
0.4	0.40	0.65	0.62	0.32	0.36	0.40	0.36	0.40
0.5	0.50	0.71	0.65	0.31	0.34	0.50	0.33	0.40
0.6	0.60	0.77	0.68	0.29	0.31	0.60	0.30	0.40
0.7	0.70	0.83	0.71	0.28	0.29	0.70	0.26	0.40
0.8	0.80	0.88	0.74	0.26	0.27	0.80	0.23	0.39
0.9	0.90	0.94	0.77	0.25	0.24	0.90	0.19	0.39

Table 13 shows the mean value of P_1, P_2, P_3 and P_4 for *Iwam and Iwrss* aggregation models. These two models were compared on the triangular area basis as shown in Fig. 3, where the larger area would present poor performance, and vice versa (19). These figures are plotted on a four quadrant point which represents the penalties of four characteristic properties (ambiguity, eclipsing, compensation, rigidity) as shown in Fig. 3.

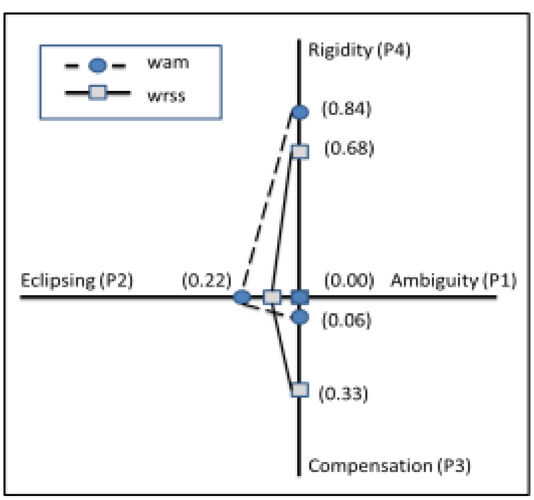

Fig. 3: Comparison of *Iwam* and *Iwrss* mean penalty values

Table 13: Penalty function's value for *Iwam and Iwrss* aggregation model

	Iwam	*Iwrss*
P1	0.00	0.00
P2	0.22	0.16
P3	0.06	0.33
P4	0.84	0.68

Table 14: Index value for Plant 1 and Plant 2 with *Iwrss* aggregation model

	Iwrss
Plant 1	
Spot Gun	1.42
Spot Weld	1.42
Robotic (MIG)	1.42
Mean	1.42
Plant 2	
Spot Gun	1.42
Spot Weld	1.36
Robotic (MIG)	1.42
Mean	1.40
Plant 3	
Spot Gun	1.23
Spot + sealant	1.36
Mean	1.30

From the four quadrant analysis, *Iwrss* had the smallest triangle area. Thus, *Iwrss* were selected as the aggregation function for WFHI. Table 14 shows the index value for plant 1, 2 and 3 by implementing *Iwrss* on each welding job type.

Index Verification

Figure 4 shows the relation between pulmonary functions with mean index value of each plant. WFHI were formulated by using data from Plant 1 and 2. WFHI were applied to Plant 3 for verification purpose. The results of the study showed mean index value was directly proportional to percentage predicted of welder's lung functions in all the investigated plants. Plant 1 has the highest index value which also has the lowest values of FVC, FEV1 and PEF. However, the values of, FEV1/FVC were the highest in Plant 1. Plant 3 has the lowest index value which also has the highest values of FVC, FEV1 and PEF. However, the values of, FEV1/FVC were the lowest in Plant 3 which in the agreement with restrictive disorder commonly exist in welders. The pulmonary functions of the investigated welders cannot be compared directly with previous study from other researcher mainly due to the predicted set used were differs from one study to another. There were also differences existed in welding fumes analysis method, digestion and constituents being investigated which had limited the comparison to be made between this study and previous study by other researcher.

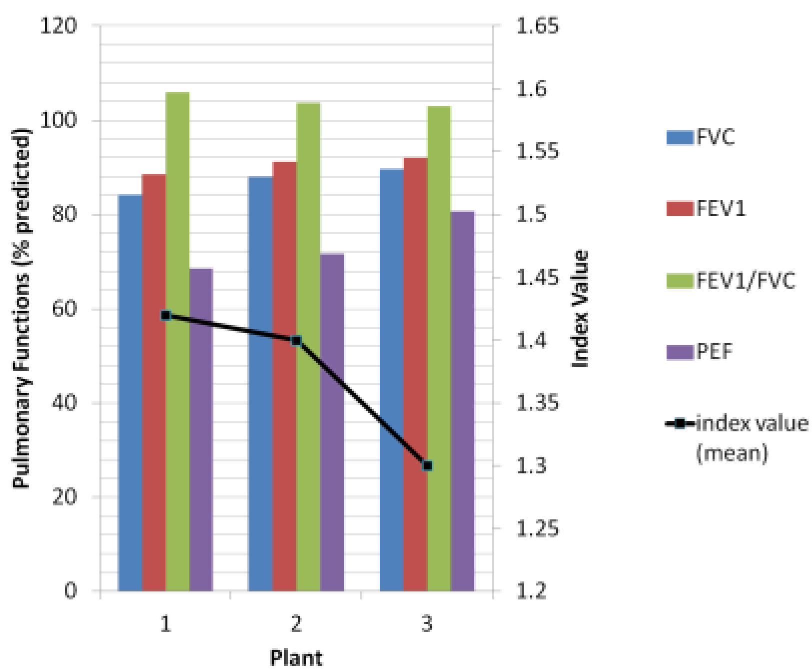

Fig. 4: Relation between percentages predicted of lung function and index value for Plant 1, 2 and 3

Conclusion

The conclusions of this work are as follows

a) There was possibility that some of the metal constituents were below the detection limit leading to '0' value of sub index, thus the multiplicative form of aggregation model was not suitable for analysis in this study. On the other hand, maximum or minimum operator forms suffer from compensation issues and were not considered in this study.

b) It is important that the developed index should not suffer from overestimation (ambiguity) or underestimation (eclipsing) of health risk related to welding fumes exposure. Thus, four aggregation models (*Iam*, *Iwam*, *Iwrss* and *Irmsa*) were shortlisted according to the cumulative penalty value calculated.

c) The penalty function analysis (P1, P2, P3 and P4) calculated from metal fume concentration in Plant 1 and 2, suggest that *Iwrss* had the minimal penalty function values and the best performance in describing WFHI.

d) Results from 3 case studies successfully relate mean index value with welder's lung functions in each investigated plant.

Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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