THE DEVELOPMENT OF WELDING FUMES HEALTH RISK ASSESSMENT TOOL FOR AUTOMOTIVE COMPONENT RELATED INDUSTRIES

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ABSTRACT

The environmental quality index had been applied and used widely for water and ambient air quality. However, indices for industrial indoor air pollutants are relatively novel and limited. Currently, the welding fume exposure risk assessments are largely focused on a single welding fume constituent approach because the regulatory standard for compliance only caters for a single constituent. However, in reality, welders are simultaneously exposed to multiple welding fume constituents at once. To fulfill this gap, welding fumes health index was developed by assigning doses rating and health risk rating to the multiple constituent of welding fumes and aggregated into index values. In the initial stage of this study, the type of health risks included in the index (sensitizer, respiratory toxins, target organ toxins, and carcinogenicity) and the related technical characteristics were determined by using quality function deployment approach. Personal samplings of welding fumes were conducted in Plant 1 and 2 to assess the concentration of metal constituents during the investigation of case studies along with a series of pulmonary function tests and questionnaire on persistent symptoms. Index values were derived from the aggregation analysis of metal constituent constituents while significant persistent symptoms and pulmonary functions were recognized through statistical analysis. The proposed index was then applied to a selected welding industry for verification purposes (Plant 3). The results of the study showed that the index value was directly proportional with the percentage decrease of the welder's pulmonary functions in all investigated plants and the significant persistent symptoms (Plant 1: mean index value=1.42, FVC=84.09%, FEV_1=88.51%, PEF= 68.58%, significant persistent symptom: sore or dry throat; Plant 2: mean index value=1.40, FVC=87.86%, FEV_1=91.14%, PEF=71.68%, significant persistent symptom: none ;Plant 3: mean index value=1.30, FVC=89.65%, FEV_1=91.96%, PEF= 80.57%, significant persistent symptom: none). The developed welding fumes health index showed its promising ability to rank welding workplace that associates well with persistent symptoms and pulmonary functions of the investigated welders.

ABSTRAK

Indeks kualiti alam sekitar telah diaplikasikan dan digunakan secara meluas untuk kualiti air dan udara ambien. Walau bagaimanapun, pembangunan indeks pencemar udara dalaman industri adalah baru dan terhad. Pada masa ini, penilaian risiko wasap kimpalan fokus kepada wasap kimpalan unsur tunggal kerana pematuhan garis panduan adalah untuk unsur tunggal sahaja. Namun, pada hakikatnya, pengimpal terdedah kepada pelbagai unsur wasap kimpalan sekaligus. Untuk memenuhi jurang ini, indeks kesihatan wasap kimpalan telah dibangunkan dengan memberikan penarafan dos dan risiko kesihatan kepada pelbagai unsur wasap kimpalan dan dijumlahkan menjadi nilai indeks. Pada peringkat permulaan kajian ini, penentuan risiko kesihatan (sensitizer, racun pernafasan, racun organ sasaran dan kekarsinogenan) dan ciri-ciri teknikal yang terkandung dalam indeks ditentukan dengan menggunakan pendekatan *quality function deployment*. Sampel peribadi wasap kimpalan dilakukan di Industri 1 dan 2 bagi mengenalpasti kosentrasi unsur- unsur logam bersama siri ujian fungsi paru-paru dan soal-selidik gejala berterusan. Nilai indeks diperolehi melalui analisis agregat konsentrasi unsur-unsur logam, manakala gejala berterusan dan fungsi paru-paru yang signifikan dikenalpasti melalui analisis statistik. Indeks itu kemudiannya diaplikasikan disalah satu industri kimpalan bagi tujuan pengesahan (Industri 3). Keputusan kajian menunjukkan nilai indeks berkadar terus dengan gejala berterusan yang signifikan dan peratusan penurunan fungsi paru-paru pengimpal (Industri 1: nilai purata indek=1.42, FVC=84.09%, FEV_1= 88.51%, PEF=68.58%, gejala berterusan yang signifikan: tekak sakit atau kering; Industri 2: nilai purata indeke=1.40, FVC=87.86%, FEV_1=91.14%, PEF=71.68%, gejala berterusan yang signifikan: tiada ;Industri 3: nilai purata indek=1.30, FVC= 89.65%, FEV_1=91.96%, PEF=80.57%, gejala berterusan yang signifikan: tiada). Indeks kesihatan wasap kimpalan yang dibangunkan mempunyai potensi yang baik untuk mengkategorikan tempat kerja kimpalan dan mempunyai perkaitan baik dengan gejala berterusan dan fungsi paru-paru pengimpal yang disiasat.

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LIST OF SYMBOLS AND ABBREVIATIONS

α	weighting factor
$\rho_{m,0}$	the mean concentration of metal and metalloid in the blank solutions, in microgram per litre
$\rho_{m,1}$	the mean concentration of metal and metalloid in the sample test solution, in microgram per litre
ρ_m	calculated mass concentration of metal or metalloid in the air filter sample, in milligram per cubic meter, at ambient condition
$\underline{F}$	transport column vector derived from the analytical hierarchy matrix
$\underline{H}$	hazard score derived from the analysis of the data requirements
$\underline{P}$	phase vector derived from the phase matrix
am	arithmetic mean
am	arithmetic mean
C	the concentration of a sample, in milligram per cubic meter
$C(TWA)$	the 8-hours time-weighted average, in milligram per cubic meter
F	dilution factor used
gm	geometric mean
I	index
I^{AM}	mean index value
I^{max}	maximum index value
I^{min}	minimum index value
ls	unweighted linear sum
ls	unweighted linear sum

m	calculated mass concentration of metal or metalloid in the air filter sample, in ppm
max	maximum
min	minimum
N	number of subindices
$P1$	penalty values for ambiguity
$P2$	penalty values for eclipsing
$P3$	penalty values for compensation
$P4$	penalty values for rigidity
Pc	cumulative penalty
$rmsa$	root mean square addition
$rmsa$	root mean square addition
$rspa$	root sum power addition
$rspa$	root sum power addition
$S_1 ... S_N$	subindices value
$srhm$	square root harmonic mean
$srhm$	square root harmonic mean
T	the sampling time for that sample, in hours
V	volume, in litres, of the collected samples
V_0	volume in milimeters, of the blank solutions
V_1	volume, in milimeters, of the sample test solutions
$w_1 ... w_N$	weight of each sub-indices, where $\sum_{i=1}^{N} w_i = 1$
wam	weighted arithmetic mean
wam	weighted arithmetic mean
wp	weighted product
$wrsp$	weighted root sum power
$wrsp$	weighted root sum power
$wrss$	weighted root sum square
$wrss$	weighted root sum square
Abs	skin absorbtion

ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
API	Air Pollution Index
ASTM	American Society of Testing and Materials
ATS	American Thoracic Society
ATS-DLD	American Thoraric Society and The Division of Lung Diseases
AWS	American Welding Society
BS	British Standard
C	carcinogen
CEN	European Committee for Standardisation
CHRA	Chemical Health Risk Assessment
Con	skin and/or eye contact
CPD	Comprehensive Percentage Dissatisfied
DOSH	Department of Occupational Safety and Health
EPA	Environment Protection Agency
EQI	Environment Quality Index
FER	Forced Expired Ratio
FEV1	Forced Expiratory Volume in 1 second
FVC	Forced Vital Capacity
GI	gastrointestinal
h.r.r	health risk rating
HHS	Health Hazard Score
HIRA	Hazard Identification and Ranking
HoQ	House of Quality
IAPI	Indoor Air Pollution Index
IARC	International Agency for Research on Cancer
ICP-MS	inductively coupled plasma mass spectroscopy
IIW	International Institute of Welding
Ing	ingestion
Inh	inhalation

IPSI	Indoor Pollutant Standard Index
ISO	International Standards Organization
IUATLD	International Union against Tuberculosis and Lung Disease
LD	Lethal Dose 50
LEV	local exhaust fan
LFC	Lowest Feasible Concentration
LLN	Lower Limits of Normal
MAI	Malaysian Automotive Institute
MANOVA	Multivariate Analysis of Variance
MIG	metal inert gas
MS	Malaysian Standard
NIOSH	National Institute of Occupational Safety and Health
OELs	Occupational Exposure Limits
OHD	Occupational Health Doctor
OSHA	Occupational Safety and Health Association
PEF	Peak Expiratory Flow
PEL	Permissible Exposure Limit
QEESI	Quick Environmental Exposure and Sensitivity Inventory
REL	Recommended Exposure Limit
SOCSO	Malaysian Social Security Organization
STEL	Short Term Exposure Limit
TLV	Threshold Limit Value
TLV-TWA	Threshold Limit Value - Time Weighted Average
TWA	Time Weighted Average
USECHH	Use and Standard of Exposure of Chemical Hazardous to Health
WAR	Waste Reduction
WHO	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, the background of the research problem was explained. It looks into where this study fits in the occupational safety and health in Malaysia. In addition, the main issues to be solved regarding exposure to welding fumes, health risk of welding fumes and development of an index as a risk assessment tool were discussed in the problem statements, objectives, scope, limitations, and significance of the study.

1.2 Background of Study

Millions of people throughout the world are working under conditions that foster ill health or are unsafe. It is estimated that yearly, more than two million people worldwide die of occupational injuries and work-related diseases. In fact, more people die of diseases caused by work than are killed in industrial accidents (Hassim & Hurme, 2010a). There are two main acts in Malaysia for occupational safety: the Factories and Machinery Act (Act 139) (Malaysia, 1967) and the Malaysian Occupational Safety and Health Act (Act 514) (Malaysia, 1994). The Department of Occupational Safety and Health (DOSH) is the only government agency responsible for administrating, managing, and enforcing legislation related to occupational safety and health in Malaysia (Leman *et al.*, 2010a). The Occupational Safety and Health Master Plan for Malaysia 2010 to 2015 had outlined four key strategies for occupational safety and health in Malaysia. One of the key strategies is the "preventive workplace culture" which emphasizes on the promotion of a more effective safety culture and the prevention of occupational diseases as shown in Figure 1.1 (Malaysia Ministry of Human Resources, 2009).

Figure 1.1: Preventive workplace culture key strategies (Malaysia Ministry of Human Resources, 2009)

Malaysian Standard MS 31000: 2010 for Risk Management (Department of Standard Malaysia, 2010), which was published in 2010, address the same issues as follows:

> While all organizations manage risk to some degree, this standard establishes a number of principles that need to be satisfied to make risk management effective. This standard recommends that organizations develop, implement and continuously improve a framework whose purpose is to integrate the process for managing risk into the organization’s overall governance, strategy and planning, management, reporting processes, policies, values and culture. (p. VI)

Fera & Macchiaroli (2010), stated that an effective approach in the prevention of occupational diseases and effective risk management for health and safety at work needs a suitable risk assessment phase. However, less attention has been paid to this phase in practice, using inappropriate tools and methodologies that are either too complex to manage or too simple and subjective, thus not suitable for recognizing hazards and reducing the corresponding risks. The usage of risk matrix to relate between the impact and probability of risk is popular and widely adopted by many organizations. However, difficulty exists in measuring the two quantities in which risk assessment is concerned with, which is; the potential loss and the probability of occurrence. The chance of error in measuring these two quantities is large. Risk with a large potential loss and a low probability of occurring is often treated differently from one with a low potential loss and a high likelihood of occurring. In theory, both are of nearly of equal priority, but in practice, it can be very difficult to manage (Kirch, 2008). Louis (2008) also agreed that risk matrix can mistakenly assign higher qualitative ratings to quantitatively smaller risks or vice versa. A risk assessment would be simpler if it transforms into a single metric that could embody all of the important information (Kirch, 2008). Thus, the transformation of risk assessment into index form would be the suitable alternative solution.

There are approximately 800,000 welders employed full-time worldwide to perform welding processes (Aida & Jan, 2014). According to the American Welding Society (AWS) and the Edison Welding Institute (EWI), welding will continue to be the preferred method of joining for heavy industries, aerospace, petroleum/energy and automotive industries until 2020 (AWS and EWI, 2000). According to Shook (2009), welders will be on demand for 2010 and beyond, with the emerging technology of nuclear and wind power. In U.S alone, employment of welders, cutters, solderers, and brazers is projected to grow 6 percent from 2012 to 2022 (Bureau of Labor Statistics, U.S. Department of Labor, 2014). Malaysia is striving to be industrialized country and is ready to fulfill the demand of workers in the welding industry sector with the establishment of the Malaysian Skill Certification System for welders (Malaysia Ministry of Human Resources, 2010). 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 addressed this matter (Asfahl, 2004). Occupational Safety and Health Association, USA (2013) also highlighted the most frequently cited standards for welding were the standard related to to general requirement (welding material, ventilation, eye protection) and welding in confined spaces. There were less citation on PEL and the health risk of welders.

Welding is a common industrial process. The hazard that has both acute and long-term chronic effects is welding fumes. Fumes are solid particles that originate from welding consumables, base metal, and any coatings present on the base metal. In welding, the intense heat of the arc or flame vaporizes the base metal and electrode coating. This vaporized metal condenses into tiny particles called fumes that can be inhaled. Welding fumes can be deposited in the human respiratory tract (Ashby, 2002; Fiore, 2006; Leman *et al.*, 2010c; Ravert, 2006). Most of the particles in welding fumes are less than 1 µm in diameter when produced, but they appear to grow in size with time due to agglomeration (Isaxon *et al.*, 2009). To protect welders from welding fume hazard, occupational exposure limit (OEL) had been introduced by several organizations. Ashby (2002) highlighted the issues that arise in the determination of welding fume exposure limit as follows:

> Some debate has centered on what the actual exposure limit on total welding fume should be. In 1989, the OSHA permissible exposure limit (PEL) for total welding fume was set at 5 mg/m^3 (5000 g/m^3) as an eight hour TWA (time weighted average). However, this limit was vacated and currently is not enforceable. Since 1989, OSHA has not reestablished a PEL for total welding fume. National Institute of Occupational Safety and Health (NIOSH) indicates that it is not possible to establish an exposure limit for total welding emissions since the composition of welding fumes varies greatly and the welding constituents may interact to produce adverse health effects. Therefore, NIOSH suggests that the exposure limits set for each welding fume constituent should be met and that welding fume emissions should be controlled with recommended exposure limit (REL) considered to be upper limits. The American Conference of Governmental Industrial Hygienists (ACGIH) has a Threshold Limit Value Time Weighted Average (TLV-TWA) for welding fume-total particulate of 5 mg/m^3. The ACGIH TLV-TWA represents conditions under which it is believed that nearly all workers may be repeatedly exposed to day after day without adverse health effects. It should be noted that ACGIH is a private professional society. Its TLVs are updated frequently while PELs cannot be updated without an act of Congress or OSHA. As a result, TLVs are often more current and usually more protective. However, industry is legally required to meet only those levels specified by OSHA PEL. (p. 57)

In Malaysia, industries are legally required to meet the PEL specified by the Occupational Safety and Health Act (1994), under the Use and Standard of Exposure of Chemical Hazardous to Health (USECHH) Regulation (Malaysia, 2000).

1.3 Problem Statement

Malaysia is a developing nation, and the manufacturing sector is the major contributor to the Malaysian economy, with 1,693,154 people engaged in the manufacturing sector in 2009 (Malaysia Department of Statistic, 2010). Welding is a common industrial process in the manufacturing sector that has both acute and long-term chronic hazards mainly from inhaled welding fumes. Currently in Malaysia, under the USECHH regulation, a chemical health risk assessment (CHRA) needs to be carried out by an assessor appointed by the employer (Malaysia, 2000). A CHRA report is produced by the assessor, which includes potential risk, nature of hazard to health, method and procedure in the use of chemical, degree of exposure, and control measures. Currently, the welding fume exposure risk assessment was largely focused on a single welding fume constituent approach because the regulatory standard for compliance only caters for a single constituent. However, in reality, welders are simultaneously exposed to multiple welding fume constituents at once. Little progress has been made in the assessment of the hazards from multiple simultaneous or successive exposures (Aitio, 2008). According to Dominici *et al.* (2010), the shift from single pollutant to multiple pollutant assessment was desired by the scientific community and policy makers. The development of welding fumes health index (WFHI) is not intended as a substitute to CHRA, but rather as one part of the overall assessment tool to be used in order to relate between multiple welding fume constituents with regulatory exposure limit and possible health risk of welders.

Studies on the effect of welding fume exposure to the welder in the automotive industries had been conducted in many parts of the world, including the United States, Taiwan, and Iran (Loukzadeh *et al.*, 2009; Luo *et al.*, 2006, 2009; Kiesswetter *et al.*, 2009; Kobrosly *et al.*, 2009; Sharifian *et al.*, 2010). These researchers had published evidences about the significant health risk of developing respiratory symptoms, inflammatory responses, oxidative stress, and airway irritation symptoms of workers working with automotive industry, particularly when engaging in welding activities compared with control subjects of nonwelders working in the same workplace. However, most of these studies did not consider the welding fume concentration whether the hazardous exposure exceeded the regulations limit. Dasch & D'Arcy (2008) and Loukzadeh *et al.* (2009) conducted welding emission assessment and pulmonary function investigation of welders in automotive plants. The results of the study showed there was a significant pulmonary health risk of welders although the welding fume emission was still within the allowable range of OSHA and American Conference of Governmental Industrial Hygienists (ACGIH). This scenario reveals the need of an effective risk assessment tool to relate between welding fume exposure, welder's possible health risk and regulatory exposure limit.

Several researchers had developed welding hazard risk assessment tools such as, Yeo & Neo (1998) introduced the health hazard scoring system to quantify the environmental impact of the different welding processes before choosing the most environmentally friendly welding processes. However, this model did not consider the quantitative data on welding fume exposure, and the developed tools had not been verified with the actual data. In addition, Leman *et al.* (2010b) had developed an environmental quality index (EQI) for industrial ventilation and an occupational safety and health evaluation of welding processes in manufacturing plants. Although the index has been developed based on actual data on welding exposure, it lacked analysis on the selection of the aggregation model used, and no verification was done on the usability of the developed index in other case studies. Karkoszka & Sokovic (2012), on the other hand, developed the integrated risk estimation in the welding process using the qualitative method of assigning the probability of occurrence, significance, and risk involved in the aspect of occupational safety. However, only a small part of the risk assessment focused on occupational health of the welders and the risk assessment adapted the risk matrix approach. The summary of factors considered in the existing welding hazard risk assessment tools is shown in Table 1.1 (The detailed explanation of these existing welding exposure risk assessment tools can be referred to Section 2.7).

Table 1.1: Summary of factors considered in existing welding hazard risk assessment tools

Assessment Tools and Authors	**Health Based**	**Multiple Constituent**	**Actual Data from Industries**	**Aggregation Model Analysis**	**Tool Verification**
Yeo & Neo (1998)	Yes	Yes	-	Yes	-
Leman *et al.* (2010b)	Yes	Yes	Yes	-	-
Karkoszka & Sokovic (2012)	Yes	-	-	-	-

To this date, there is no tool available that cover the development of welding hazard risk assessment through comprehensive multiple constituent chemical analysis, actual data from industries, aggregation model analysis, and verification of the risk assessment tool as shown in Table 1.1. Thus, this study attempts to develop a new risk assessment tool for welding fumes exposure by fulfilling the factors that had not been considered by the existing welding hazard risk assessment.

National Institute for Occupational Safety and Health, USA (1988) had highlighted research needs to pursue a means of indexing exposure by job type or process by taking into account the intensity of the welding job and work practices. However, welders are not a homogeneous group, and the potential adverse effect of welding fume exposures is oftentimes difficult to evaluate. Differences exist in welder populations, such as industrial setting, types of ventilation, types of welding processes, and materials used (Antonini *et al.*, 2006; Balkhyour & Goknil, 2010). Indexing exposure by job type or process is almost impossible to implement. However, indexing exposure according to locations would be beneficial as ranking tools between different location on the same scale. Kirch (2008) also agreed that a risk assessment would be simpler if a single metric could embody all of the information in the measurement. Hence, there is an urgent need to develop an index that can combine the welding chemical exposure, possible human health risks, and regulatory exposure limit in a single metric.

This study focused on its attempt to develop an assessment tool for multiple welding fume constituents and relate with the multiple possible health risks of welders, which had not been considered in the conventional method of single welding fume constituent assessment. The developed index was also based on comprehensive data collection, analysis, and verified with actual case studies.

1.4 Objective of Study

The purpose of this study was to develop an index as a health risk assessment tool for welding fume exposure in automotive component-related industries in Malaysia. This study embarks on the following main objectives:

1. To obtain customers/welders feedback on health risk information that should be included in the proposed index by using the quality function deployment (QFD) technique
2. To investigate the degree of welding metal fume exposure that exists in two case studies through subjective (persistent symptoms experienced by the welders) and physical measurements (welding fume concentration and pulmonary function test)
3. To develop a Welding Fumes Health Index (WFHI) for welder based on the subjective and physical measurements
4. To verify the proposed index by applying the index to one of the welding industries

1.5 Research Questions

This study was carried out to investigate the following research questions:

1. Does the pulmonary health of welders in the investigated plants are affected from the duration of welding fume exposure, smoking habit, or type of welding?
2. Does the developed index able to provide a mean index value that relates to mean pulmonary functions and significant persistent symptoms of welders in each investigated plant?

1.6 Scope of Study

There are many types of industry involved with welding operations. However, this study only focused on the welding work conducted in an indoor environment because outdoor environment has too many uncontrollable parameters to be considered and may mislead the results obtained. Samples selected for this study were the welders doing the same job scope daily for at least 8 hours per day. Thus, welders working in a production line or an assembly line were selected for this study. Welding works related to maintenance purpose or project-based welding works were not considered in this study because the existence of variance in terms of the type of welding, the material being welded, and the work hours would be difficult to justify in terms of pulmonary functions and persistent symptoms experienced by these welders. This study was carried out in automotive component -related industries located in Rawang, Selangor. Rawang is chosen because this town consists of automotive assembler and automotive component vendor, a good representative of overall automotive component welding-related industries in Malaysia. These industries focused on spot gun, spot weld, and metal inert gas (MIG) welding processes.

There are many hazards that exist in a welding workplace, such as fumes, toxic gases, radiation, noise, and vibration. However, inhalable hazard such as fumes and toxic gases poses higher occupational disease health threat. Because of the limited standard analyze method that can be carried out by the certified laboratory for toxic gas analysis, only welding fumes are currently being considered in the index development.

1.7 Limitation

In this study, an analysis of welding fumes was conducted by an accredited laboratory by using inductively coupled plasma mass spectrometry (ICP-MS). ICP-MS has the advantage to analyze up to 25 multiple constituents in a single sample. From these 25 constituents, only 15 were shortlisted according to the constituents commonly associated with welding, cutting, and brazing, as shown in Table 1.2 (National Institute for Occupational Safety and Health, USA, 2007; Occupational Safety and Health Association, USA, 1996). The PELs for these constituents were referred according to the USECHH Regulation (Malaysia, 2000). Although the hazards of welding fumes include many other constituents such as oxides and fluorides, limitation exists, on the validated method and capability of the instrument used in this study; thus, only selected constituents were chosen as the parameters of the current study.

Table 1.2: Constituents shortlisted for the development of WFHI

No.	**Constituents**	**USECHH PEL (mg/m^3)**
1	Aluminum (Al)	5.000 (resp.), 15.000 (total)
2	Antimony (Sb)	0.500
3	Arsenic (As)	0.010
4	Beryllium (Be)	0.002
5	Cadmium (Cd)	0.010, 0.002 (resp)
6	Chromium (Cr)	0.500
7	Cobalt (Co)	0.100
8	Copper (Cu)	0.200
9	Iron (Fe)	5.000
10	Lead (Pb)	0.050
11	Manganese (Mn)	0.200
12	Molybdenum (Mo)	5.000 (soluble), 10.000 (total insoluble)
13	Nickel (Ni)	1.500
14	Silver (Ag)	0.100
15	Tin (Sn)	2.000

The number of sampling on each case study varies according to the number of welders, the type of welding, and the workplace environment. There are generally two types of sampling done. According to the British Standard (1996), for personal sampling purposes, at least one sample of an employee must be taken in 10 properly selected homogeneous groups performing similar tasks (British Standard Institute, 1996). On the other hand, according to DOSH (2005), if a maximum risk worker cannot be selected with reasonable certainty, it is necessary to resort to random sampling with similar expected worker exposure risk, with a partial sample of 10% and a confidence interval of 0.90 (Malaysian Department of Occupational Safety and Health, 2005). Because of the high analysis cost of welding fumes by accredited laboratories and to make available resources, a sample of selected workers expected to be the maximum risk workers was taken for analysis according to the British Standard Institute (1996). Maximum risk workers were determine according to criteria such as, welders working nearest to the source, duration and frequency of exposure, nature of work or work practice, and availability of control measures.

There are four health risks that were considered in this study: sensitizer, respiratory toxin, target organ toxin, and carcinogenicity. However, only pulmonary function test and persistent symptoms questionnaire were carried out for the assessment of this health risks. The persistent symptoms questionnaire takes into account symptoms relate to sensitizer, respiratory, and target organ toxin (liver, kidney, and blood) health risks. Carcinogenic health risks were extracted directly from the International Agency for Research in Cancer (IARC) and the ACGIH threshold limit value (TLV) carcinogen classification according to investigated metal constituents.

Although, urine, blood, tissue test, and x-ray test would give more accurate assessment results, such medical tests were required only if the welders were exposed or likely to be exposed to any of the chemicals specified in the Schedule II of USECHH Regulation, such as, lead, mercury, arsenic, cadmium, or beryllium significantly or exceeding the regulatory exposure limit in the workplace (Malaysia, 2000). In this study, none of the chemicals investigated had exceeded the regulatory exposure limit. In addition, the investigated plant in this study focused on spot gun, spot weld, and MIG welding processes, which were considered to be less hazardous than the other types of welding (Luo *et al.*, 2006; Loukzadeh *et al.*, 2009). Thus, urine, blood, tissue test, and x-ray test were not considered in this study.

1.8 Significance of Study

To this date, far too little attention has been paid to develop risk assessment tools on welding fumes, which relate to the health risk of welders. In general, risk is often evaluated in terms of its consequences with respect to project performance and rarely in terms of human health (Badri *et al.*, 2011; Smallwood, 2004). Thus, the proposed new index for indoor air pollutant will contribute to new knowledge, especially in the risk assessment of welding fumes.

Assessing the health risk of welding fumes is one the essential parts in the overall risk management in the welding-related industry. According to Hewitt (2001) and Baram (2009), developing countries are facing huge challenges in welding industry's risk assessment. Developing countries are increasingly being drawn within the global economy in which the transfer of technologies such as welding from developed countries into those that do not have similar infrastructures in terms of health and safety may be disastrous. These uncritical adoption of new welding technologies by developing countries potentiates future health problems (Baram, 2009; Hewitt, 2001). Therefore, developing countries such as Malaysia need to develop a risk assessment tool focused on the health risk of welders.

The idea of the development of environmental index for ambient air and water quality risk assessment had been extensively done by Babcock (1970); Green (1966); Horton (1965); Inhaber (1975a); Landwehr & Deininger (1976); Nives (1999); Prati *et al.* (1971); Swamee & Tyagi (2000). However, the indices for indoor air pollutants such as welding fumes are limited and relatively novel. The index is suitably developed as a comparative tool to fulfill the needs of the welders/ management/ stakeholders to determine whether a particular environmental problem becomes better or worse in its simplest possible form (Ott, 1978).

The results of this study show that the proposed Welding Fumes Health Index, WFHI is a promising risk assessment tool to relate between multiple chemical concentrations of welding fumes, regulatory exposure standards and possible health risk of welders, which have not been covered by the previously developed risk assessment tool for welding workplace. WFHI may also be applied in comparing and giving suitable ratings to environmental conditions at different locations. The idea of indexing and ranking each welding workplace would create interest and provoke risk management action from the management. To this date, WFHI is the first index developed for the risk assessment of welding fumes via comprehensive data collection, data analysis, and verification from actual case studies.

1.9 Organization of the Thesis

This thesis contains six chapters. The chapters are arranged according to the sequence of objective and methodology of the research.

Chapter 1 describes the background of the study, problem statements, objective of the study to be achieved, the scope of the study, limitation of the study, the significance of the study, and organization of the thesis.

Chapter 2 gives the overview of the literature review regarding health risk assessment process, environmental index development process with some examples on the indoor pollution index, human health chemical exposure index, and related issues regarding index development. This chapter also outlines the international and national standards and regulations pertaining to welding fumes and occupational health issues by causal agent reported in Malaysia. At the end of this chapter, several developed risk assessment tools for welding hazard are discussed.

Chapter 3 explains the research frame work and methodology carried out in this study. Physical and subjective measurement were carried out on industrial case studies, laboratory case study and verification study of WFHI.

Chapter 4 shows the result and data analysis of the physical and subjective measurement conducted. Statistical analysis was conducted for pulmonary function test and persistent symptoms questionnaire results.

Chapter 5 describes the details of the development of WFHI, which includes derivation of subindex, weights, aggregation model analysis, and verification of WFHI.

Chapter 6 concludes with conclusions and suggestions for future works on this study.

1.10 Summary

In this chapter, welding fume exposure was emphasized as the main concern for its adverse health effect toward welders. Issues on welding fumes were mainly revolved around the permissible exposure limit and welder's health risk. To this date, limited studies had been done on the risk assessment of welding fumes exposure towards welders. Thus, WFHI was developed as a risk assessment tool in order to directly relate between welding fume concentration, welder's possible health risks, and welding fumes regulatory exposure limit for the enhancement of safety and health in welding workplace. The development of WFHI was seen as a positive attempt to fulfill Malaysian strategic vision and effective risk management in welding-related industry. The next chapter reviewed the literature related to health risk assessment, environmental index, issues in index development, and existing risk assessment tool on welding hazard.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Chapter 2 gathered and reviewed the literature related to this study. This review include brief explanations on the health risk assessment process and developed environmental index that relates to human health such as, indoor pollution index, human health chemical exposure index, and issues arising in the index development process. Standards and regulations related to welding fumes used in this study were also highlighted. Malaysian occupational health statistic related to metal constituents and existing welding hazard risk assessment tools were also explained.

2.2 Health Risk Assessment

Malaysian Department of Occupational Safety and Health (2008) defined hazard as a source or a situation with potential for causing harm to human in terms of injury or ill health, damage to property, damage to the environment, or a combination of these. Risk is defined as the potential for an unwanted negative consequence or event. Risk assessment defined as the process of evaluating the risk to safety and health arising from hazards at work. A health risk assessment is the systematic evaluation of factor that might result in adverse human health effect resulting from hazard, and often the attempted quantification of those factors and adverse human health effects (Anderson & Albert, 1999). The health risk assessment process includes five steps as shown in Table 2.1.

Table 2.1: Paradigm for health risk assessment (adapted from the World Health Organization (WHO), 2010)

Step	**Description**
Problem formulation	Establishes the scope and objective of the assessment
Hazard identification	Identifies the type and nature of adverse health effects
Hazard characterization	Qualitative or quantitative description of inherent properties of agent having the potential to cause adverse health effects
Exposure assessment	Evaluation of concentration or amount of a particular agent that reaches a target population
Risk characterization	Advice for decision making

Health risk assessment starts with problem formulation by establishing the scope and objective of the assessment. Usually, health risk assessment is carried out to confirm if existing controls were adequate or not. Generally, health risk assessment relates with chemical exposure in industries. Chemical exposure may exist in a medium with which a person is in contact. These media include air, water, and soil in outdoor and indoor locations. In this study, the health risk assessment focused on airborne welding fume exposure toward welders working in automotive component industries.

Hazard identification is generally the first step in a risk assessment and is the process used to identify the specific chemical hazard and to determine whether exposure to this chemical has the potential to harm human health. Given sufficient time and resources, the surest way for potentially hazardous chemicals to be identified is sample collection and chemical analysis. Once identified, the potential hazard of the chemical can be determined from the available scientific data on the chemical, general data from toxicological or epidemiological studies.

A chemical may be associated with one or more hazards to human health. Several schemes for the classification of hazard information have been developed. In general, chemicals are classified according to human health hazards that they pose, such as sensitizer, neurological, developmental, reproductive, respiratory, cardiovascular, systemic, and carcinogenic effects.

Welding fumes are frequently associated with sensitizer, respiratory toxins, target organ toxicity, and carcinogenicity (International Labor Organization, 2012; National Institute for Occupational Safety and Health, USA, 2007; Occupational Safety and Health Association, USA, 2012). Table 2.2 shows the health hazard commonly associated to welding fumes with the related definition (Occupational Safety and Health Association, USA, 2007).

Table 2.2: Definition of health hazard commonly associated to welding fumes (Occupational Safety and Health Association, USA, 2007)

No.	**Health Hazard**	**Definition**	**Health risk example**
1	Sensitizer	A chemical that causes a substantial proportion of exposed people or animals to develop an allergic reaction in normal tissues after repeated exposure to the chemical.	Asthma
2	Respiratory toxins	Chemicals that irritate or damage pulmonary tissues	Toxin effect to nose, nasal cavities, pharynx, larynx, trachea, lung, bronchioles, and alveoli
3	Target organ toxicity (hepatotoxins, nephrotoxins, hematopoietic, neurotoxins, and reproductive toxins)	(1)hepatotoxins: chemicals that produce liver damage (2)nephrotoxins: chemicals that produce kidney damage (3)hematopoietic: agents that act on blood (4)neurotoxins: chemicals that produce their primary toxic effects on the nervous system. (5)reproductive toxins: chemicals that affect the reproductive capabilities.	Toxicity in liver, kidney, blood, lymphatic, central nervous system, and prostate
4	Carcinogen	A chemical is considered as carcinogen if; (1)it has been evaluated by the IARC and found to be a carcinogen or potential carcinogen (2)it is regulated by OSHA as a carcinogen	Lung cancer and prostate cancer

A considerable amount of research had focused on respiratory toxins as the most significant health effect to be investigated in welders population. Some of the studies have shown a reduction of pulmonary function value in welder's population compared with the control group (Hariri *et al.*, 2014; Loukzadeh *et al.*, 2009; Meo *et al.*, 2003; Sharifian *et al.*, 2010). The significant relationship between the duration of exposure or the long-term effect of welding fume exposure on pulmonary function had been obtained by Bakke *et al.* (1991), Manstrangelo *et al.* (2003), and Meo *et al.* (2003). The welding fume exposures often associate with restrictive disorders to welders (Liu & Peng, 2010; Luo *et al.*, 2006; Erhabor *et al.*, 2001) whereas smoking associates with obstruction disorder (De Marco *et al.*, 2011; Taylor, 2010). Haluza *et al.* (2014), Hariri *et al.* (2014), Bradshaw *et al.* (1998), Holm *et al.* (2012), and Rastogi *et al.* (1991), highlighted that there is a synergistic relationship between the effects of smoking and welding, causing pulmonary disease and the increased respiratory symptom in welders with smoking habit. Only a few studies had been published that analyses the effects of welding exposure on pulmonary function in nonsmokers. Christensen & Bonde (2008), and Meo *et al.* (2003) found a significantly smaller pulmonary function among nonsmoker welders compared with nonsmoker controls in a cross-sectional study.

The health hazard information can be referred from sources of comprehensive risk assessment information for specific chemicals that have been prepared by the World Health Organization (2010) as shown in Table 2.3. These resources include summary or detail in depth reports of sources, uses, hazards, exposures, and toxicities of chemicals that are either common in commerce or known to be hazardous to human health.

Table 2.3: International hazard identification resources (adapted from World Health Organization, 2010)

Resource	**Content**
International Chemical Safety Cards	Summary
Screening Information Datasets for High Production Volume Chemicals	Detailed
IARC monographs	Detailed
Hazardous Substances Data Bank	Detailed
European Chemical Substances Information System	Detailed
International Chemical Control Toolkit	Detailed
NIOSH Pocket Guide to Chemical Hazards	Summary
OSHA Occupational Chemical Database	Summary

Other resources include are:

1. NIOSH Pocket Guide to Chemical Hazards (National Institute for Occupational Safety and Health, USA, 2007)
2. OSHA Occupational Chemical Database (Occupational Safety and Health Association, USA, 2012)

The second step of risk assessment is hazard characterization. The objective of hazard characterization, guidance, or guideline value identification is to obtain a qualitative or quantitative description of the properties of the agent having the potential to cause adverse health effects as a result of exposure. Health-based guidance values are derived and used according to several widely accepted principles and conventions, that is, the risks of adverse effects other than cancer are negligible or minimum when exposure is less than a threshold level, in which adverse effects are unlikely to occur. However, there are two schools of thought concerning minimum or threshold doses of carcinogens. One is that carcinogens are assumed to have a linear relationship with the risk of cancer, and effects are assumed to occur at any level of exposure. Thus, no threshold dose for a known carcinogen exists. The other is that there are measures that the body undertakes to mitigate the risk of carcinogen, and so a threshold dose does indeed exist.

Carcinogens were basically categorized based on the strength of evidence that an agent could develop cancer in humans. The more numerous the positive or conclusive test results and epidemiological studies of a particular material, the higher the cancer risk associated with it (Yeo & Neo, 1998). Table 2.4 shows carcinogen classification by IARC and ACGIH commonly referred to the level of carcinogenicity (IARC France, 2012; American Conference of Governmental Industrial Hygienists, USA, 2010).

Table 2.4: Carcinogen classification by IARC and ACGIH (IARC France, 2012; American Conference of Governmental Industrial Hygienists, USA, 2010)

Institute	**Carcinogen Classification**
IARC	1: The agent is carcinogenic to human 2A: The agent is probably carcinogenic to human with limited evidence of carcinogenicity in human and sufficient evidence of carcinogenicity in experimental animals. 2B: The agent is possibly carcinogenic to human with limited evidence of carcinogenicity in human and absent of sufficient evidence of carcinogenicity in experimental animals. 3: The agent is not classified carcinogenic to human 4: The agent is probably noncarcinogenic to human
ACGIH TLVs	A1: Confirmed human carcinogenicity A2: Suspected human carcinogen A3: Animal carcinogen A4: Not classified as human carcinogen A5: Not suspected as human carcinogen

The third step for risk assessment is exposure assessment. Exposure assessment is used to determine whether people are in contact with a potentially hazardous chemical. How much is the exposure, for how long, and through which route does the chemical expose to humans. Inhalation exposure, such as welding fumes is present in the air. The concentration of airborne exposure of welding fumes differs according to the type of welding, the type of material being welded, or the ventilation of the workplace. Welding fume exposure can be assessed by personal sampling and chemical analysis. Effective sampling strategy needs to be carried out to get an accurate exposure assessment.

The final step of a chemical risk assessment is risk characterization. It is typically a quantitative statement about the estimated exposure relative to the value of the guidelines. OELs are intended for use in the practice of industrial hygiene as standards, guidelines, or recommendations in the control of potential workplace health hazards. OEL is considered as the highest level of exposure an employee may be exposed without incurring the risk of adverse health effects (Occupational Safety and Health Association, USA, 2012). Guideline values are available from a variety of nongovernmental organizations and national authorities. Table 2.5 provides examples of resources for OELs. In Malaysia, the OELs for metal constituents were referred according to the Occupational Safety and Health Act (1994), Under the USECHH PEL.

Table 2.5: Examples of resources for occupational exposure limits (OELs)

OELs	**Organization**
Permissible Exposure Limits (PELs)	Occupational Safety and Health Administration, United States
Recommended exposure limits (RELs)	National Institute for Occupational Safety and Health, United States Centres for Disease Control and Prevention
Workplace exposure limits (WELs)	United Kingdom Health and Safety Executive
Threshold limit values (TLVs)	American Conference of Governmental Industrial Hygienists (ACGIH)

2.3 Occupational Health Issues in Malaysia

There are various types of occupational health risk that exist in the industry. Table 2.6 and Table 2.7 show the selected number of occupational disease by causal agent and invalidity pension cases reported to the Malaysian Social Security Organization (SOCSO) for the years 2009, 2010, and 2011 respectively (Malaysia SOCSO, 2009, 2010, 2011). Although this statistic is in general and did not reflect directly to welders, the main concern would be the poor health status of employees because of not knowing and not being aware of the causal agent and health risk that exist in their working environment. Poor safety and health precaution lead to higher rates of occupational diseases. Although the employees are the most affected personnel caused by exposure to chemicals hazardous to health, human health risk assessments are often neglected and focused more on project performance, planning, and cost (Badri *et al.*, 2011; Smallwood, 2004).

Table 2.6: Number of occupational disease reported by causal agents (Malaysia SOCSO, 2009; Malaysia SOCSO, 2010; Malaysia SOCSO, 2011)

No	**Causal agent**	**No. of cases reported**		
		2009	**2010**	**2011**
Disease cause by chemical agent				
1	Diseases caused by beryllium/ toxic compounds	2	8	2
2	Diseases due to copper or its compounds	2	0	0
3	Diseases due to tin or its compounds	1	0	1
4	Diseases due to zinc or its compounds	2	1	2
5	Diseases due to irritants	5	7	8
6	Diseases caused by manganese/toxic compounds	1	1	1
Disease by target organ system				
1	Bronchopulmonary diseases caused by hard metal dust	2	3	6
2	Occupational asthma caused by sensitizing agents or irritants inherent to the work process	10	23	34
3	Extrinsic allergic alveolitis	2	0	2
4	Chronic obstructive pulmonary diseases	4	2	5
5	Diseases of lung, due to aluminium	17	39	14
6	Upper airways disorders	1	0	6
7	Any other respiratory diseases	11	28	35
Occupational Cancer				
1	Cancer caused by any agents not mentioned	11	8	5

Table 2.7: Number of invalidity pension cases reported (Malaysia SOCSO, 2009; Malaysia SOCSO, 2010; Malaysia SOCSO, 2011)

No	**Type of diseases**	**Invalidity cases reported**		
		2009	**2010**	**2011**
1	Tuberculosis (eg. pulmonary tuberculosis)	52	50	60
2	Malignant neoplasm of lip, oral cavity, pharynx	45	17	29
3	Malignant neoplasm of respiratory, intrathoracic	50	49	35
4	Malignant neoplasm of lymphatic & haemopoietic tissues	35	30	23
5	Diseases of blood & blood forming organs	99	118	170
6	Diseases of the nervous system (eg. epilepsy)	483	610	652
7	Diseases, pulmonary circulation & other heart disease	207	198	243
8	Diseases of the upper respiratory tract	18	13	19
9	Other diseases of the respiratory system	111	127	156

2.4 Environmental Index

The purpose of environmental index is to summarize a large volume of information and represent it as a single ordinal number that is easy to understand. The first serious discussion and analyses on environmental index emerged in the 1970s, with the first book published by Ott (1978) on environmental indices theory and practice. Environmental indices are used to describe the quality or health of a specific environmental system such as air, water, soil, and sediments (Sadiq *et al.*, 2010). The index is defined as a single number aggregated mathematically from two or more environmental indicators, where an indicator is a single quantity derived from one pollutant variable (Ott, 1978; Sofuoglu & Moschandreas, 2003). According to Sofuoglu & Moschandreas (2003),

> An index is constructed from several indicators weighted together to describe the total impact on certain aspect of the broader state of the environment. The aggregations process simplifies the complexity of the issues at hand and forms the link between the scientific community, the public and decision makers because index communicate the state of environment in terms that the public can comprehend easily. (p.332 and 333)

The development of index to rank and provide a composite picture of an environmental condition derived from a series of observed measurements and parameters should benefit the industrial field where the causal exposure is well defined, such as on welding-related process. From a regulatory compliance perspective, the threshold levels of parameters are established in the context of possible adverse human health impacts. These threshold values can be standard, guidelines, self-imposed limits, or best practice. As a result, it is useful to relate the index to some sort of acceptability measures. The development of environmental index involves the following four basic steps (Sadiq *et al.*, 2010):

1. Selection of relevant factors and parameters.
2. Transformation of selected parameters into subindex
3. Derivation of weights
4. Aggregation of subindex to determine the value model using a specific model

In selecting appropriate and relevant parameters, the overall index must first have a specific goal or objective. Practically, it is impossible to include every single parameter related to the index. Therefore, few representative measurable parameters are selected for practical and cost-effective purpose. After the selection of relevant factors and parameters, they are converted into subindex on a nondimensional scale. The weights are assigned based on their importance and possible impact on an environmental system investigated. The last step in index development is to combine all subindex using an aggregation model that describes the overall condition of environmental systems. Some of the information is lost during this process; however, the loss of information should not lead to the results being misinterpreted. Otherwise the usefulness of the index will decline (Ott, 1978; Sadiq *et al.*, 2010). According to Ott (1978), aggregation models usually consist of the following forms of combination:

1. Additive: subindices are combined through summation
2. Multiplicative: subindices are combined through multiplicative operation
3. Logical: selection of index value according to maximum or minimum value of subindex

Table 2.8 shows the list of aggregation model that had been used by various researchers in index development.

Table 2.8: List of aggregation model

No.	**Aggregation Model**	**Formulation**	Researchers
Additive form			
1	Unweighted linear sum	$I_{ls} = \sum_{i=1}^{N} S_i$	Babcock (1970); Leman *et al.* (2010b)
2	Root sum power addition	$I_{rspa} = \left(\sum_{i=1}^{N} S_i^4\right)^{1/4}$	Bisselle *et al.* (1972)
3	Weighted root sum power	$I_{wrsp} = \left(\sum_{i=1}^{N} w_i S_i^{10}\right)^{1/10}$	Kumar & Alappat (2004)
4	Arithmetic mean	$I_{am} = \frac{1}{N} \sum_{i=1}^{N} S_i$	Green (1966); Moschandreas & Sofuoglu (2004); Sofuoglu & Moschandreas (2003)
5	Weighted arithmetic mean	$I_{wam} = \sum_{i=1}^{N} w_i S_i$	Inhaber (1975a); Miller & George (1976); Shi, M.H andTao (2000)
6	Square root harmonic mean	$I_{srhm} = \left(\sum_{i=1}^{N} S_i^2\right)^{0.5}$	Ott (1978)
7	Weighted root sum square	$I_{wrss} = \left(\sum_{i=1}^{N} w_i S_i\right)^{0.5}$	Sadiq *et al.* (2010)
8	Root mean square addition	$I_{rmsa} = \left(\sum_{i=1}^{N} \frac{1}{N} S_i^2\right)^{1/2} where\, p \geq 1$	Inhaber (1975b)
Multiplicative form			
1	Weighted product	$I_{wp} = \prod_{i=1}^{N} S_i$	Sadiq *et al.* (2010)
2	Geometric mean	$I_{gm} = \left(\prod_{i=1}^{N} S_i\right)^{1/N}$	Landwehr & Deininger (1976)
Maximum or minimum operator form			
1	Maximum operator	$I_{max} = max\left\{S_1, S_2, S_3 ..., S_N\right\}$	Ott (1978); Sekhar *et al.* (2003b)
2	Minimum operator	$I_{min} = min\left\{S_1, S_2, S_3 ..., S_N\right\}$	Smith (1990)

where

$I\ :\ Index$

$N:\ number\, of\, subindices$

$S_1 ... S_N:\ subindices\, value$

$w_1 ... w_N:\ weight\, of\, each\, sub-indices,\ where\ \sum_{i=1}^{N} w_i = 1$

REFERENCES

Abbasi, T. & Abbasi, S. (2012). *Water Quality Indices.* Oxford: Elsevier.

Adu, I.K., Sugiyama, H., Fischer, U. & Hungerbahler, K. (2008). Comparison of methods for assessing Environmental, Health and Safety (EHS) hazards in early phases of chemical process design. *Process Safety and Environmental Protection*, 86(2), pp. 77–93.

Aida, N. & Jan, J. (2014). Exposure to PM10 and lung function among welders of metal working factory in Selangor. *Health and the Environment Journal*, 5(1), pp. 113–125.

Aitio, A. (2008). Research needs for environmental health risk assessment. *Journal of Toxicology and Environmental Health, Part A*, 71(18), pp. 1254–1258.

Akao, Y. (1990). *Quality Function Deployment- Integrating Customer Requirements Into Product Design.* New York: Productivity Press.

American Conference of Governmental Industrial Hygienists, USA (2010). *2010 TLVs and BEIs.* Ohio: American Conference of Governmental Industrial Hygienists (ACGIH) USA.

American Society for Testing and Materials (2008). *Determination of Elements in Airborne Particulate Matter by Inductively Coupled Plasma-Mass Spectrometry.* Pennsylvania: ASTM D7439-08.

Aminravan, F. (2014). Multifaceted information fusion: a decision support system for online monitoring in water distribution networks.

Anderson, E. & Albert, R. (1999). *Risk Assessment and Indoor Air Quality.* Florida: CRC Press.

Anderson, K., Fagerlund, I., Bodin, L. & Ydreborg, B. (1988). Questionnaire as an instrument when evaluating indoor climate. *Healthy Building*, 3, pp. 139–145.

Antonini, J.M., Afshari, A.A., Stone, S., Chen, B., Schwegler-Berry, D., Fletcher, W.G., Goldsmith, W.T., Vandestouwe, K.H., McKinney, W., Castranova, V. & Frazer, D.G. (2006). Design, construction, and characterization of a novel robotic welding fume generator and inhalation exposure system for laboratory animals. *Journal of Occupational and Environmental Hygiene*, 3(4), pp. 194–203.

Asfahl, C. (2004). *Industrial Safety and Health Management.* New Jersey: Pearson Prentice Hall.

Ashby, H.S. (2002). Welding fumes in the workplace: Preventing potential health problems through proactive controls. *Professional Safety*, (*April 2002*), pp. 55–60.

Attfield, M.D. (1986). Respiratory questionnaires. *NIOSH Publication 86-102*, pp. 171–179.

AWS and EWI (2000). *Welding Technology Roadmap*: *Vision.* Miami: American Welding Society and Edison Welding Institute.

Babcock, L. (1970). A combined pollution index for measurement of total air pollution. *Journal of Air Pollution Control Association*, 20(10), pp. 653–659.

Badri, A., Nadeau, S. & Gbodossou, A. (2011). Proposal of a risk-factor-based analytical approach for integrating occupational health and safety into project risk evaluation. *Accident Analysis and Prevention*, pp. 223–234.

Bakke, P.S., Baste, V., Hanca, R. & Gulsvik, A. (1991). Prevelance of obstructive lung disease in a general population: Relation to occupational title and exposure to some airborne agents. *Thorax*, 46, pp. 863–870.

Balkhyour, M.A. & Goknil, M.K. (2010). Total fume and metal concentrations during welding in selected factories in Jeddah, Saudi Arabia. *International Journal of Environmental Research and Public Health*, 7(7), pp. 2978–2987.

Baram, M. (2009). Globalization and workplace hazards in developing nations. *Safety Science*, 47(6), pp. 756 – 766.

Bas, E. (2014). An integrated quality function deployment and capital budgeting methodology for occupational safety and health as a systems thinking approach: The case of the construction industry. *Accident Analysis & Prevention*, 68(0), pp. 42 – 56, systems thinking in workplace safety and health.

Bisselle, C., Lubore, S. & Pikul, R. (1972). *National Environmental Indices: Air Quality and Outdoor Recreation MITRE Corporation Report Number MTR-6159.* McLean: MITRE Corporation.

Bradshaw, L., Fishwick, D., Slater, T. & Pearce, N. (1998). Chronic bronchitis, work related respiratory symptoms, and pulmonary function in welders in new zealand. *Occup Environment Med*, 55, pp. 150–154.

British Standard Institute (1996). *Workplace atmospheres guidance for the assessment of exposure by inhalation to chemical agents for comparison with limit values and measurement strategy.* London: BS EN 689:1996.

British Standard Institute (2010). *Wokplace Air -Determination of metal and metalloids in airborne particulate matter by inductively coupled plasma mass spectrometry.* London: British Standard Institute (BSI).

British Standard Institute (2011). *Health and safety in welding and allied processes - Laboratory method for sampling fume and gases Part 5: Identification of thermaldegradation products generated when welding or cutting through products composed wholly or partly of organic materials using pyrolysis-Gas Chromatography-Mass Spectrometry.* London: BS EN ISO 15011-5:2011.

Bureau of Labor Statistics, U.S. Department of Labor (2014). Occupational outlook handbook, 2014-15 edition: Welders, cutters, solderers, and brazers.

Burney, P.G., Laitinen, L.A., Perdrizet, S., Huckauf, H., Tattersfield, A.E., Chinn, S., Poisson, N., Heeren, A., Britton & Jones, T. (1989). Validity and repeatability of the IUATLD (1984) bronchial symptoms questionnaire: An international comparison. *European Respiratory Journal*, 2(10), pp. 940–945.

Carnevalli, J.A. & Miguel, P.C. (2008). Review, analysis and classification of the literature on qfd: Types of research, difficulties and benefits. *International Journal of Production Economics*, 114(2), pp. 737 – 754, special Section on Logistics Management in Fashion Retail Supply Chains.

Chan, L.K. & Wu, M.L. (2002). Quality function deployment: A literature review. *European Journal of Operational Research*, 143(3), pp. 463 – 497.

Christensen, S. & Bonde, J.P.and Omland, O. (2008). A prospective study of decline in lung function in relation to welding emissions. *Journal of Occupational Medicine and Toxicology*, 3(6), pp. 6–13.

Cohen, L. (1995). *Quality Function Deployment: How to Make QFD Work for You*. Reading :Addison Wesley Publishing Company.

Commomwealth of Australia (2004). *Environmental Health Risk Assessment: Guidelines for Assessing Human Health Risk from Environmental Hazard*. Canberra: Commomwealth of Australia.

Cox, L., Babayev, D. & Huber, W. (2005). Some limitations of qualitative risk rating systems. *Risk Analysis*, 25(3), pp. 651–662.

Dasch, J. & D'Arcy, J. (2008). Physical and chemical characterization of airborne particles from welding operations in automotive plants. *Journal of Occupational and Environmental Hygiene*, 5(7), pp. 444–454.

De Marco, R., Accordini, S., Marcon, A., Cerveri, I., Josep Anto, J.M., Gislason, T., Heinrich, J., Janson, C., Jarvis, D., Kuenzli, N., Leynaert, B., Sunyer, J., Svanes, C., Wjst, M. & Burney, P. (2011). Risk factors for chronic obstructive pulmonary disease in a European cohort of young adults. *American Journal of Respiratory and Critical Care Medicine*, 183, pp. 891–897.

Department of Health, Australia (2010). *Health Risk Assessment (Scoping) Guidelines*. Perth: Department of Health Australia.

Department of Safety and Health, Malaysia (2014). *Occupational Health Doctor*. Retrieved November 2014, from http://www.dosh.gov.my.

Department of Standard Malaysia (2010). *Risk Management: Principles and Guidelines*. Selangor: MS ISO 31000:2010.

Dominici, F., Peng, R.D., Barr, C.D. & Bell, M.L. (2010). Protecting human health from air pollution: Shifting from a single-pollutant to a multi-pollutant approach. *Epidemiology*, 21(2), pp. 187–194.

Erhabor, G., Fatusi, S. & Obembe, O. (2001). Pulmonary function in arc-welders in ile-ife, nigeria. *East African medical journal*, 78(9), pp. 461–464.

Fera, M. & Macchiaroli, R. (2010). Appraisal of a new risk assessment model for sme. *Safety Science*, *48(10)*, pp. 1361–1368.

Ferris, B. (1978). Epidemiology standardization project II: Recommended respiratory disease questionnaires for use with adults and children in epidemiological research. *American Review of Respiratory Disease*, pp. 7–52.

Fiore, S.R. (2006). Reducing exposure to hexavalent chromium in welding fumes. *Welding Journal*, (*August 2006*), pp. 38–43.

Francisque, A., J., R.M., Sadiq, R., Miranda, L. & Proulx, F. (2011). Reconciling actual risk with perceived risk for distributed water quality: A QFD-based approach. *Journal of Water Supply: Research and Technology*, pp. 321–342.

Green, M. (1966). An air pollution index based on sulfur dioxide and smoke shade. *Journal of Air Pollution Control Association*, 11(12), pp. 703–706.

Haluza, D., Moshammer, H. & Hochgatterer, K. (2014). Dust is in the air Part II: Effects of occupational exposure to welding fumes on lung function in a 9-year study. *Lung*, 192(1), pp. 111–117.

Han, H. & Baulch, A. (1994). *Dow's Chemical Exposure Index Guide*. New York: American Institute of Chemical Engineers (AIChE).

Hariri, A., Yusof, M. & Leman, A.M. (2013). Comparison of welding fumes exposure during standing and sitting welder's position. *World Academy of Science, Engineering and Technology*, 82, pp. 640–643.

Hariri, A., Leman, A.M. & Yusof, M. (2012). Application of malaysian anthropometric data in dummy welder design. In: *International Conference on Design and Concurrent Engineering*, pp. 20–24.

Hariri, A., Paiman, N.A., Leman, A.M. & Yusof, M.Z.M. (2014). Pulmonary function status among welders in malaysian automotive industries. *Journal of Clean Energy Technologies*, 2, pp. 108–111.

Hassim, M. & Edwards, D. (2006). Development of a methodology for assessing inherent occupational health hazards. *Process Safety and Environmental Protection*, 84(5), pp. 378–390.

Hassim, M. & Hurme, M. (2010a). Inherent occupational health assessment during process research and development stage. *Journal of Loss Prevention in the Process Industries*, 23(1), pp. 127–138.

Hassim, M.H. & Hurme, M. (2010b). Inherent occupational health assessment during basic engineering stage. *Journal of Loss Prevention in the Process Industries*, 23(2), pp. 260–268.

Hewitt, P. (2001). Strategies for risk assesment and control in welding: Challenges for developing countries. *The Annals of Occupational Hygiene*, 45(4), pp. 295–298.

Holm, M., Kim, J.L., Lillienberg, L., Storaas, T., Jogi, R., Svanes, C., Schlunssen, V., Forsberg, B., Gislason, T., Janson, C., Toren, K. & RHINE Study Group Northern Europe (2012). Incidence and prevalence of chronic bronchitis: Impact of smoking and welding: The RHINE study. *International Journal of Tuberculosis and Lung Disease*, 6, pp. 553–557.

Horton, R. (1965). An index number system for rating water quality. *Journal of the Water Pollution Control Federation*, 37(3), pp. 300–306.

Howe, A. (2009). European and international standards on health and safety in welding. *Journal of Physics: Conference Series*, 151(1), pp. 1–10.

Hui, I.K., Li, C.P. & Lau, H.C.W. (2003). Hierarchical environmental impact evaluation of a process in printed circuit board manufacturing. *International Journal of Production Research*, 41(6), pp. 1149–1165.

Hui, I., Lau, H.W., Chan, H. & Lee, K. (2002). An environmental impact scoring system for manufactured products. *International Journal of Advance Manufacturing Technology*, 19, pp. 301–312.

IARC France (2012). *Agents Classified by the International Agency for Research on Cancer (IARC) Monographs Volumes 1 to 109*. Retrieved June 2012, from http://monographs.iarc.fr/eng/classification/.

Ingelheim Boehringer (1992). *Pneumobile Project, Indonesia*. Ingelheim Boehringer.

Inhaber, H. (1975a). An approach to a water quality index for Canada. *Water Research*, 9, pp. 821–833.

Inhaber, H. (1975b). A set of suggested air quality indices for Canada. *Atmospheric Environment*, 9(3), pp. 353–364.

International Labor Organization (2012). *International Labor Organization (ILO), International Chemical Safety Cards*. Retrieved June 2012, from http://www.ilo.org/dyn/icsc/showcard.home.

International Organization for Standardization (2011). *International Standard Organization: Health and safety in welding and allied processes -Sampling of airborne particles and gases in the operator's breathing zone Part 1: Sampling of airborne particles.* Geneva: ISO 10882-1:2011.

Isaxon, C., Pagels, J., Gudmundsson, A., Asbach, C., John, A., Kuhlbusch, T.A.J., Karlsson, J.E., Kammer, R.and H Tinnerberg, H. & Nielsen, J.and Bohgard, M. (2009). Characteristics of welding fume aerosol investigated in three Swedish workshops. *Journal of Physics: Conference Series*, 151(*1*), pp. 1–6.

Jafari, A.J. & Assari, M.J. (2004). Respiratory effects from work-related exposure to welding fumes in hamadan, iran. *Archives of Environmental Health: An International Journal*, 59(3), pp. 116–120.

James, S. (2010). *Use of Aggregation Functions in Decision Making.* Technical report, Deakin University: Ph.D Thesis.

Karkoszka, T. & Sokovic, M. (2012). Integrated risk estimation of Metal Inert Gas (MIG) and Metal Active Gas (MAG) welding processes. *Metalurgija*, 51, pp. 179–182.

Khan, F.I. & Abbasi, S.A. (1998). Multivariate hazard identification and ranking system. *Process Safety Progress*, 17(3), pp. 157–170.

Khan, F., Husain, T. & Abbasi, S. (2001). Safety Weighted Hazard Index (SWeHI): A new, user-friendly tool for swift yet comprehensive hazard identification and safety evaluation in chemical process industries. *Process Safety and Environmental Protection*, 79(2), pp. 65 – 80.

Kiesswetter, E., Schaper, M., Buchta, M., Schaller, K., Rossbach, B., Kraus, T. & Letzel, S. (2009). Longitudinal study on potential neurotoxic effects of Aluminum II: Assessment of exposure and neurobehavioral performance of Al welders in the automobile industry over 4 years. *International Archives of Occupational and Environmental Health*, 82(10), pp. 1191–1210.

Kirch, W.E. (2008). *Encyclopedia of Public Health.* London: Springer.

Kobrosly, R.W., Meliker, J.R. & Nriagu, J.O. (2009). Automobile industry occupations and bladder cancer: a population-based case-control study in Southeastern Michigan, USA. *Occupational and Environmental Medicine*, 66(10), pp. 650–656.

Koller, G., Fischer, U. & Hungerbahler, K. (2001). Comparison of methods suitable for assessing the hazard potential of chemical processes during early design phases. *Process Safety and Environmental Protection*, 79(3), pp. 157– 166.

Koller, G., Fischer, U. & Hungerbahler, K. (1999). Assessment of environment-, health- and safety aspects of fine chemical processes during early design phases. *Computers , Chemical Engineering*, 23, pp. 63 – 66.

Kumar, D. & Alappat, B.J. (2004). Selection of the appropriate aggregation function for calculating Leachate Pollution Index. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 8, pp. 253–264.

Landwehr, J. & Deininger, R. (1976). A comparison of several water quality indexes. *Journal of Water Pollution Control Federation*, 48(5), pp. 954–958.

Leman, A., Omar, A., Jung, W. & Yusof, M. (2010a). The development of an industrial air pollution monitoring system for safety and health enhancement and sustainable work environment using QFD approach. *The Asian Journal on Quality*, *11*, pp. 165–182.

Leman, A., Yusof, M., Omar, A. & Jung, W. (2010b). Environmental Quality Index (EQI) for industrial ventilation and occupational safety and health evaluation in manufacturing plant. *The Asian Journal on Quality*, 11(3), pp. 210–222.

Leman, A., Yusof, M., Omar, A. & Rahman, K. (2010c). Toxic gas monitoring of welding process in malaysian small and medium industries. *Proceeding of the 11th Asia Pacific Industrial Engineering and Management Systems Conference (APIEMS).* Melaka: Universiti Malaya.

Li, C.P. & Hui, I.K. (2001). Environmental impact evaluation model for industrial processes. *Environmental Management*, 27(5), pp. 729–737.

Liu, S. & Peng, A.Y. (2010). Result analysis of the lung function test of welders. *Occupation and Health*, 6, pp. 12–20.

Louis, A. (2008). What's wrong with risk matrices? *Risk Analysis*, 28(2), pp. 497–512.

Loukzadeh, Z., Sharifian, S., Aminian, O. & Shojaoddiny-Ardekani, A. (2009). Pulmonary effects of spot welding in automobile assembly. *Occupational Medicine*, 59(4), pp. 267–269.

Luo, J.C.J., Hsu, K.H. & Shen, W.S. (2006). Pulmonary function abnormalities and airway irritation symptoms of metal fumes exposure on automobile spot welders. *American Journal of Industrial Medicine*, 49(6), pp. 407–416.

Luo, J.C.J., Hsu, K.H. & Shen, W.S. (2009). Inflammatory responses and oxidative stress from metal fume exposure in automobile welders. *Journal of Occupational and Environmental Medicine*, 51(1), pp. 95–103.

Malaysia (1967). *Factories and Machinery Act*: Act 139.

Malaysia (1994). *Occupational Safety and Health Act*: Act 514.

Malaysia (2000). *Occupational Safety and Health (Use and Standards of Exposure to Chemical Hazardous to Health) (USECHH)* : Regulation P.U. (A) 131.

Malaysia Department of Statistic (2010). *Annual Survey of Manufacturing Industries.* Putrajaya: Malaysia Department of Statistic.

Malaysia Ministry of Human Resources (2009). *Occupational Safety and Health Master Plan for Malaysia 2015 (OSH MP15).* Kuala Lumpur: Malaysia Ministry of Human Resources.

Malaysia Ministry of Human Resources (2010). *Occupational Job Structures for Welding Industry Sector.* Department of Skills Development, Ministry of Human Resources, Malaysia.

Malaysia SOCSO (2009). *Malaysian Social Security Organization (SOCSO) Annual Report.* Kuala Lumpur: Malaysian Social Security Organization (SOCSO).

Malaysia SOCSO (2010). *Malaysian Social Security Organization (SOCSO) Annual Report.* Kuala Lumpur: Malaysian Social Security Organization (SOCSO).

Malaysia SOCSO (2011). *Malaysian Social Security Organization (SOCSO) Annual Report.* Kuala Lumpur: Malaysian Social Security Organization (SOCSO).

Malaysian Automotive Institute (2012). *Malaysian Automotive Institute (MAI) Automotive Database.* Retrieved January 2012, from http://www.mai.org.my/.

Malaysian Department of Environment (1997). *A guide to Air Pollutant Index in Malaysia.* Putrajaya: Malaysian Department of Environment.

Malaysian Department of Occupational Safety and Health (2001). *Department of Occupational Safety and Health: Guidelines on the Control of Chemical Hazardous to Health.* Putrajaya: Malaysian Department of Occupational Safety and Health (DOSH).

Malaysian Department of Occupational Safety and Health (2005). *Guidelines on Monitoring of Airborne Contaminant for Chemicals Hazardous to Health.* Putrajaya: Malaysian Department of Occupational Safety and Health (DOSH).

Malaysian Department of Occupational Safety and Health (2008). *Department of Occupational Safety and Health) Guidelines for hazard identification, risk assessment and risk control (HIRARC).* Putrajaya: Malaysian Department of Occupational Safety and Health (DOSH).

Malaysian Department of Occupational Safety and Health (2010). *Department of Occupational Safety and Health: Industry Code of Practise on Indoor Air Quality.* Putrajaya: Malaysian Department of Occupational Safety and Health (DOSH).

Malaysian Department of Safety and Health (1994). *Guidelines on Occupational Safety and Health Act (Act 154).* DOSH.

Mallick, S.K., Cabezas, H., Bare, J.C. & Sikdar, S.K. (1996). A pollution reduction methodology for chemical process simulators. *Industrial & Engineering Chemistry Research*, 35(11), pp. 4128–4138.

Manstrangelo, G., Tartari, M., Fedeli, U., Fadda, E. & Saia, B. (2003). Ascertaining the risk of of chronic obstructive pulmonary disease in relation to occupation using a case-control design. *Occupational Medicine (London)*, 53, pp. 165–172.

Matell, M. & Jacoby, J. (1972). Is there an optimal number of alternatives for likert scale items? effects of testing time and scale properties. *Journal of Applied Psychology*, 56, pp. 506–509.

McDonald, J.A., Burnett, N., Coronado, V.G. & Johnson, R.L. (2003). *Questionnaire Design :Reproductive Health Epidemiology Series Module 4.* Georgia: Centers for Disease Control and Prevention U.S.A.

Mendell, M.J. (2003). Commentary: Indices for IEQ and building-related symptoms. *Indoor Air*, 13(4), pp. 364–368.

Meo, S.A., Azeem, M.A. & Subhan, M.M.F. (2003). Lung function in Pakistani welding workers. *Journal of Occupational and Environmental Medicine*, 45(10), pp. 1068–1073.

Miller, A. (1992). Lung function testing: Selectionof reference values and interpretative strategies. *American Journal of Respiratory and Critical Care Medicine*, 146(5 Pt 1), pp. 1368–1369.

Miller, C. & Prihoda, T. (1999). The Environmental Exposure and Sensitivity Inventory (EESI): a standardized approach for measuring chemical intolerances for research and clinical applications. *Toxicological Industrial Health*, 15(3-4), pp. 370–385.

Miller, M. & George, C. (1976). An atmospheric diffusionmodel for metropolitan areas. *Journal of Air Pollution Control Association*, 7(1), pp. 46–50.

Miller, M., Hankinson, J., Brusasco, V., Burgos, F., Casaburi, R., Coates, A., Crapo, R., Enright, P., Grinten, C.V.D., Gustafsson, P., Jensen, R., Johnson, D., MacIntyre, N., McKay, R., Navajas, D., Pedersen, O., Pellegrino, R., Viegi, G. & Wanger, J. (2005). Standardisation of spirometry. *European Respiratory Journal*, 26, pp. 319–338.

Molhave, L. (2003). Commentary: Biomarkers and other substitute measures in indoor air sciences. *Indoor Air*, 13(4), pp. 369–370.

Moschandreas, D.J. & Sofuoglu, S.C. (2003). Commentary: What indices of indoor air pollution can and can't do. *Indoor Air*, 13(4), pp. 375–376.

Moschandreas, D.J. & Sofuoglu, S.C. (2004). The indoor environmental index and its relationship with symptoms of office building occupants. *Journal of the Air and Waste Management Association*, 54(11), pp. 1440–1451.

National Institute for Occupational Safety and Health, USA (1988). *Criteria for Recommended Standard: Welding, Brazing and Thermal Cutting.* Washington: National Institute for Occupational Safety and Health, USA (NIOSH USA).

National Institute for Occupational Safety and Health, USA (2003). *NIOSH Manual of Analytical Method 7300 :Elements by ICP.* 4th ed. Atlanta: National Institute for Occupational Safety and Health, USA (NIOSH USA).

National Institute for Occupational Safety and Health, USA (2007). *NIOSH Pocket Guide to Chemical Hazards*. Atlanta: National Institute for Occupational Safety and Health, USA (NIOSH USA).

Neha, K. (2000). Measuring environmental quality: An index of pollution. *Ecological Economics*, 35(2), pp. 191–202.

Nives, N. (1999). Water quality evaluation by index in Dalmatia. *Water Research*, 33(16), pp. 3423–3440.

Occupational Safety and Health Association, USA (1996). *Welding Health Hazards*. Washington: Occupational Safety and Health Association, USA (OSHA USA).

Occupational Safety and Health Association, USA (2007). *Guidance for Hazard Determination for Compliancce with the OSHA Hazard Communication Standard (29 CFR 1910.1200)*. Washington: Occupational Safety and Health Association, USA (OSHA USA).

Occupational Safety and Health Association, USA (2012). *Occupational Safety and Health Association (OSHA) Occupational Chemical Database*. Retrieved June 2012, from https://www.osha.gov/chemicaldata/.

Occupational Safety and Health Association, USA (2013). *General Industry Digest*. Washington: Occupational Safety and Health Association, USA (OSHA USA).

Ojima, J. (2009). Laboratory evaluation of carbon monoxide exposure in carbon dioxide arc welding. *Journal of Occupational Health*, 51, pp. 377–379.

Ott, W.R. (1978). *Environmental Indices Theory and Practise*. Michigan: Ann Arbor Science Publisher Inc.

Pellegrino, R., Viegi, G., Brusasco, V., Crapo, R.O., Burgos, F., Casaburi, R., Coates, A., van der Grinten, C.P.M., Gustafsson, P., Hankinson, J., Jensen, R., Johnson, D.C., MacIntyre, N., McKay, R., Miller, M.R., Navajas, D., Pedersen, O.F. & Wanger, J. (2005). Interpretative strategies for lung function tests. *European Respiratory Journal*, 26(5), pp. 948–968.

Prati, L., Pavanello, R. & Pesarin, F. (1971). Assesment of surface water quality by single index pollution. *Water Research*, 5(9), pp. 741–745.

Rastogi, S.K., Gupta, B.N., H.T, M. & S., S. (1991). Spirometric abnormalities among welders. *Environmental Research*, 56, pp. 15–24.

Ravert, E. (2006). Controlling chromium fumes. *Welding Journal*, (*November 2006*), pp. 1–4.

Roscoe, J.T. (1975). *Fundamental Research Statistics for the Behavioral Sciences.* 2nd ed. New York: Holt, Rineheart and Winston.

Rosenman, K. (2012). Recommended Medical Screening Protocol for Workers Exposed to Fumes. Michigan: Michigan State Univesity.

Sadiq, R., Haji, S.A., Cool, G. & Rodriguez, M.J. (2010). Using penalty functions to evaluate aggregation models for environmental indices. *Journal of Environmental Management*, 91(3), pp. 706–716.

Sekaran, U. (2006). *Research methods for business: A skill building approach.* John Wiley & Sons.

Sekhar, S.C., Tham, K.W. & Cheong, K.W. (2003a). Commentary: Response to comments from Mark Mendell, Lars Molhave and Peder Wolkoff. *Indoor Air*, 13(4), pp. 373–374.

Sekhar, S.C., Tham, K.W. & Cheong, K.W. (2003b). Indoor air quality and energy performance of air-conditioned office buildings in Singapore. *Indoor Air*, 13(4), pp. 315–331.

Shah, S., Fischer, U. & Hungerbuhler, K. (2003). A hierarchical approach for the evaluation of chemical process aspects from the perspective of inherent safety. *Process Safety and Environmental Protection*, 81(6), pp. 430–443.

Shah, S., Fischer, U. & Hungerbuhler, K. (2005). Assessment of chemical process hazards in early design stages. *Journal of Loss Prevention in the Process Industries*, 18, pp. 335–352.

Sharifian, S., Loukzadeh, Z., Shojaoddiny-Ardekani, A. & Aminian, O. (2010). Pulmonary adverse effects of welidg fumes in automotive assembly welders. *Acta Medica Irania*, 49, pp. 98–102.

Sheng, P. & Hertwich, E. (1998). Indices for comparative waste assessment in environmentally-conscious manufacturing. *Journal of Manufacturing Science and Engineering*, 120(1), pp. 129–140.

Shi, M.H andTao, A. (2000). Investigation on the Comfort Evaluation Index CPD of indoor environments. *International Journal of Architectural Science*, 1, pp. 123–125.

Shook, R. (2009). *Welding Trends for 2010 and Beyond.* Retrieved November 2014, from http://www.weldingandgasestoday.

Smallwood, J.J. (2004). The influence of engineering designers on health and safety during construction. *Journal of the South African Institution of Civil Engineering*, 46(1), pp. 2–8.

Smith, D. (1990). A better water quality indexing system for rivers and stream. *Water Res.*, 24, pp. 1237–1244.

Sofuoglu, S.C. & Moschandreas, D.J. (2003). The link between symptoms of off ice building occupants and in-office air pollution: The Indoor Air Pollution Index. *Indoor Air*, 13(4), pp. 332–344.

Swamee, P.K. & Tyagi, A. (1999). Formulation of an air pollution index. *Journal of Air Waste Management Association*, 49, pp. 88–91.

Swamee, P. & Tyagi, A. (2000). Describing water quality with aggregate index. *ASCE Journal of Environment Engineering*, 126(5), pp. 451–155.

Taylor, J.D. (2010). COPD and the response of the lung to tobacco smoke exposure. *Pulmonary Pharmacology & Therapeutics*, 23(5), pp. 376–383.

Terninko, J. (1997). *Step-by-step QFD: customer-driven product design.* St. Lucie Press Boca Raton, FL.

Terwee, C., Bot, S., De Boer, M., Van Der Windt, D., Knol, D., Dekker, J., Bouter, L. & De Vet, H. (2007). Quality criteria were proposed for measurement properties of health status questionnaires. *Journal of Clinical Epidemiology*, 60(1), pp. 34–42.

Tsai, P.J. & Vincent, J.H. (2001). A study of workers exposures to the inhalable and total aerososl fractions in the primary nickel production industry using mannequins to simulate personal sampling. *Annals of Occupational Hygiene*, 45(5), pp. 385–394.

U.S. Environment Protection Agency (1993). *EPA's Approach and Progress in Targeting Indoor Air Pollution.* United States: U.S. Environment Protection Agency (EPA).

Wolkoff, P. (2003). Commentary: Are we ready for indoor air pollution indices? *Indoor Air*, 13(4), pp. 371–372.

Worcester, R. & Burns, T. (1975). A statistical examination of the relative precision of verbal scales. *Journal of Market Research Society*, 17, pp. 181–197.

World Health Organization (2010). *Human health risk assessment toolkit: Chemical hazards. (IPCS harmonization project document; no.8)*. Geneva: World Health Organization (WHO).

Yeo, S.H. & Neo, K.G. (1998). Inclusion of environmental performance for decision making of welding processes. *Journal of Materials Processing Technology*, 82(1-3), pp. 78–88.

Yeo, S.H., Neo, K.G. & Tan, H.C. (1998). Assessment of health hazards in production of printed paper packages. *The International Journal of Advanced Manufacturing Technology*, 14(5), pp. 376–384.