EXTENSION OF THE ADVANCED REACH TOOL (ART)

TO INCLUDE WELDING FUME EXPOSURE

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ABSTRACT

Introduction: Welding is basic process commonly carried out in the workplace. Robot or automated welding are typically used in welding processes where the weld required is repetitive and quality and speed are crucial. Not every welding operation is suitable for automated welding. If the project is limited to a single non-repetitive process, manual welding may be more suitable. The welding process is applied in various production fields and the demand for welders worldwide is increasing. Welders are exposed to health hazard from inhalation of metal fumes produced as a by-product of the process. The concentrations of welding fumes inhaled by workers can be measured, but it would be advantageous if there were also predictive exposure models to estimate exposure. However, presently, there are few reliable estimation models for welding fume exposure.

Objectives: To develop estimation model for welding fume exposure.

Methods: This study consisted of five main stages. The first stage comprised a literature review, including an evaluation of relevant generic exposure models, particularly the Advanced REACH Tool (ART), principles of exposure modelling, and various research studies related to welding fumes. The second stage describes an investigation to measure welding fume exposure at a production site. The third stage comprised welding fume exposure model development by adapting the ART model (to be the weldART model), including the identification of key modifying factors (MF) and a suitable computational form to undertake the model calculations. The fourth stage was modelling calibration, which used data obtained from the sampling in stage 2. The last stage was model verification, which applied welding fume measurement data from reports and published papers to test the reliability and uncertainty of the weldART model.

Results: The model was developed within a well-mixed mass-balance computational framework. An important MF to be used in model development was fume formation rate (FFR), i.e., the mass emission rate of total metal fume from the welding process. The identified variables that affect fume formation rate were type of welding process, electrical current and input power, shielding gas, and welding consumables. In addition, the model also incorporates other important factors, such as convective dissipation of the welding fume away from the welding area and the welder's interaction with the fume plume. The review indicated that welding process types with the highest to lowest welding fume particulate emission rates were flux-cored arc welding (FCAW), shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). In order to develop effective and probabilistic weldART model, variables, namely welder's head (WH) and localized control (LC) were also taken into consideration. A deterministic four-compartment mass-balance mathematical model, the weldART model, was developed. In the measurement study two types of sample were collected: a Swinnex sampler to collect fume for gravimetric analysis and a MicroPEM direct-reading aerosol monitor. The comparison of fume concentrations between these two samplers showed that the MicroPEM monitors significantly underestimated exposure concentrations and had low correlation with the corresponding data from the Swinnex samplers. It was concluded that it was possible that particles were lost in the sampling tube of the MicroPEM due to the electrostatic deposition before the entering the aerosol sensor, and these data were only used to indicate the duration of welding activity. Meanwhile, estimation of the calibrated four-compartment mass-balance weldART model gave a strong correlation with the welding fume exposure measurements made during this research. To accommodate the uncertainties involved in verifying the model using published exposure data, the weldART was extended to incorporate a probabilistic aspect. This may be due to a positive systematic bias across the whole applicability domain, which becomes dominant at low measured values.

Conclusions: The weldART model can produce reliable and accurate estimates of welding fume exposure. Especially, if factors related to distance of welder's head and localized control were taken into account, along with the presence of additional workplace exposure sources. The weldART could offer an alternative approach to evaluate fume concentration for occupational hygienists. At present the model is available as standalone R-code that is freely available, but it lacks a suitable user-friendly user interface. The weldART is calibrated and has had a limited verification exercise completed, but further development and evaluation is necessary.

DEDICATION

I would like to dedicate my thesis work to my family and supporters. A special feeling of gratitude to my mother, Mrs Kobkun Sailabaht, for her love for me and for being my greatest supporter not only in my Doctorate degree programme but also in other parts of my life. She would always support and encourage me. In addition, I would like to tell my Dad, Mr Chaimana Sailabaht, who had passed away, that today I have realised my dream. Although, he is not here to celebrate this success with me but I believe that if he was still alive, he would be proud of his child and feel so happy for me. I also dedicate this thesis work to my sister, Miss Chunvipa Sailabaht, for her continuous support and care even from a distance. I also offer my appreciation to Mr Totsapon Butmee, Miss Yaifa Trakulsunti, Mr Panu Sahassanon, who spent their time with me while studying and living abroad for 4 years, for their encouragement and keeping me company. Our friendship is very precious, especially for me as I have to live in unfamiliar place. Moreover, I would like to thank my first and only foreign friend, Mr Youhu Wang. Even though we have different cultures and languages but they are not barrier to our friendship. Thanks to Mr Panupon Khumsupan for his language assistance. Initially, I contacted him for help with my language but we ended up being good friends with genuine relationship. Lastly, I devote this work and give utmost appreciation to my life partner, Mr Jiradesh Panyasuttikit, who has never left my side and being everything for me. Thank you for your love from the first day that we met and forever.

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DECLARATION STATEMENT

Research Thesis Submission

Name*:*	Aduldatch Sailabaht		
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Citation details	**A. Sailabaht**, F. Wang, and J. Cherrie, "Extension of the advanced REACH tool (ART) to include welding fume exposure," *Int. J. Environ. Res. Public Health*, vol. 15, no. 10, 2018.
Author 1	Conceived and designed the study, interpreted the results, and prepared and revised the manuscript. Read and approved the final manuscript.
Author 2	Participated in the study design and interpretation. Read and approved the final manuscript.
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Author 1	Conceived and designed the study and interpreted the results. Prepared and revised the manuscript. Coordinated the fieldwork and analysed the data. Read and approved the final manuscript.
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AC	Alternating Current
ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variance
ART	Advanced REACH Tool
ASTM	American Society for Testing and Materials
BAuA	Federal Institute for Occupational Safety and Health
BEAM	Benzene Exposure Assessment Model
CDF	Cumulative Distribution Function
COPD	Chronic Obstructive Pulmonary Disease
COSHH	Control of Substances Hazardous to Health Regulations 2002
D	Dispersion
DC	Direct Current
DCEN	Direct Current Electrode Negative
DCEP	Direct Current Electrode Positive
DLPW	Department of Labour Protection and Welfare
E	Substance Emission Potential
ECETOC TRA	European Centre for Ecotoxicology and Toxicology of Chemicals' Targeted Risk Assessment
ECHA	European Chemicals Agency
EMKG-Expo-Tool	Einfaches Maßnahmenkonzept für Gefahrstoffe Exposure Tool
EPA	Environmental Protection Agency
FCAW	Flux-cored Arc Welding
FF	Far-Field
FFR	Fume Formation Rate
GM	Geometric Mean
GMAW	Gas Metal Arc Welding
GSD	Geometric Standard Deviation
GTAW	Gas Tungsten Arc Welding
H	Activity Emission Potential
HSE	Health and Safety Executive
IARC	International Association for Research on Cancer
IOELV	Indicative Occupational Exposure Limit Value
LC	Localized Control
LEV	Local Exhaust Ventilation
MAC	Maximum Allowable Concentration
MAG	Metal Active Gas
MAK	Maximale Arbeitsplatz-Konzentration
MDHS	Methods for Determination of Hazardous Substances

MF	Modifying Factor
MIG	Metal Inert Gas
MMA	Manual Metal Arc
MMAW	Manual Metal Arc Welding
NF	Near-Field
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
OEL	Occupational Exposure Limit
OSHA	Occupational Safety and Health Administration
P	Personal Behaviour
PAW	Plasma Arc Welding
PEL	Permissible Exposure Limit
PNOR	Particulate Not Otherwise Regulated
PNOS	Particles Not Otherwise Specified
Q	Flowrate
REACH	Registration, Evaluation, Authorisation & restriction of Chemicals
REL	Recommended Exposure Limits
RM	Room Zone
RPE	Respiratory Protective Equipment
SAW	Submerged Arc Welding
Seg	Segregation
SEG	Similar Exposure Group
Sep	Personal Enclosure or Separation
SHAPE	Simulation of Human Air Pollution Exposure
SMAW	Shielded Metal Arc Welding
Su	Surface Contamination
TIG	Tungsten Inert Gas
TLV	Threshold Limit Value
TP	Total Particulate
TRGS	Technical Rules for Hazardous Substances
TWA	Time-weighted Average
UV	Ultraviolet
WEL	Workplace Exposure Limit
weldART	Welding Advanced REACH Tool
WES	Workplace Exposure Standard
WH	Welder's Head
WHEC	Workplace Health Expert Committee
WP	Welding Fume Plume

LIST OF PUBLICATIONS BY THE CANDIDATE

(Please refer to Appendix C for a more detailed list of publications)

1. **A. Sailabaht**, F. Wang, and J. Cherrie, "Extension of the advanced REACH tool (ART) to include welding fume exposure," *Int. J. Environ. Res. Public Health*, vol. 15, no. 10, 2018.
2. **A. Sailabaht**, F. Wang, and J. W. Cherrie, "Calibration of the Welding Advanced REACH Tool (weldART)," *Int. J. Hyg. Environ. Health*, vol. 227, p. 113519, Jun. 2020.

CHAPTER 1
INTRODUCTION

1.1 Welding and Welding Fumes

Welding is a process where materials, particularly metals or thermoplastics, are joined using heat [1]. The method is increasingly utilised in many production fields, resulting in an increasing number of welders [2]. In the UK, more than 190,000 workers perform welding as a part of their job, globally there are over 11 million welders and more than 110 million people are exposed to welding activities as welders or bystanders sharing the same indoor space [3]–[6].

Despite being a common practice, welding poses workplace health hazards including heat or fire dangers, electrical shock threats, ultraviolet (UV) radiation from the arc and exposure to metal fume and gases. Welding fumes are generated when consumable electrode and/or the base metal are evaporated by the high electrical current or gas burning used in the process [1]. The US National Institute for Occupational Safety and Health (NIOSH) has recognized the hazards of welding fume. Welding is a fundamental work in almost every industry, especially in the maintenance of machinery and equipment, which tend to perform welding activities almost every day. As a result, there are chances that the activities may cause danger not only to the welder but also to other workers working in the surrounding area. Moreover, it has previously been recommended to use modelling tools [7], which could yield similar results to current standard methods, to assess the exposure of fume to human health.

1.1.1 Types of Welding Process

Gas Welding

Gas welding, or oxyacetylene welding, is one of the traditional and generally used methods of welding. The versatility, low cost and simplicity make it suitable for metal fabrication and repair [8]. The process involves the combustion of oxygen and acetylene in a controlled hot flame with the temperature of 3,100 - 3,200 °C. The temperature is lower than that of the electric arc and can be adjusted by altering the proportion of oxygen and acetylene [9], [10]. Lowering the joining temperature, which is useful for welding lower melting point non-ferrous metals, can be achieved by using different gases such as propane, hydrogen and coal gas.

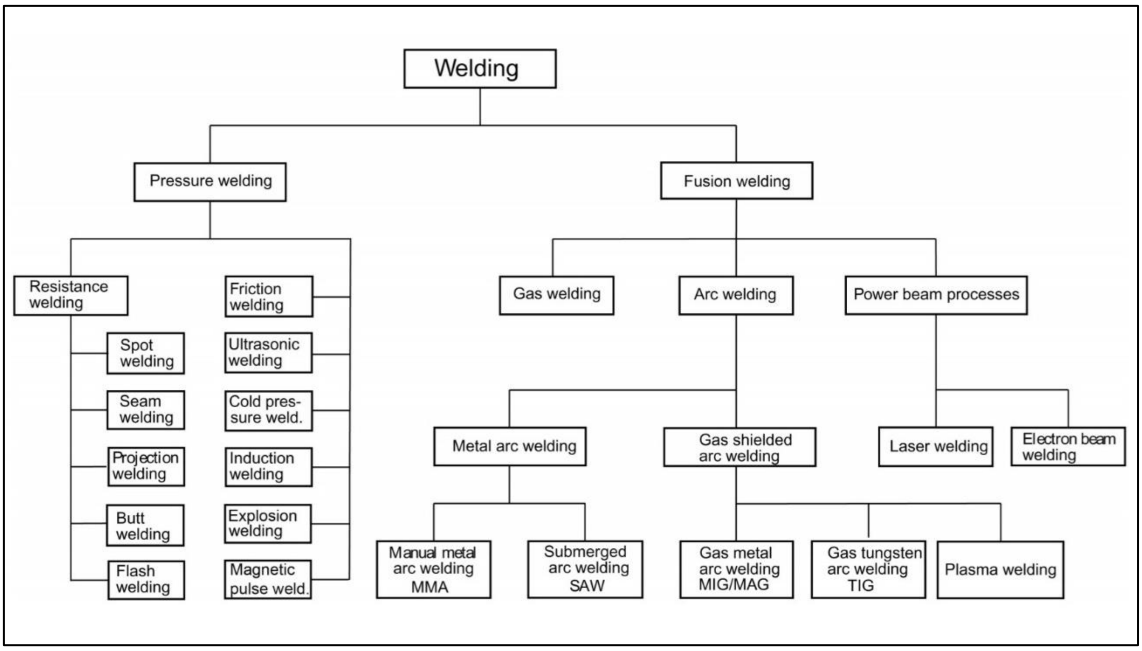

Figure 1 Schematic of the welding methods.

Arc Welding

A welding arc is created from passing high electrical current between an anode (attracts electrons in the arc) and cathode (produces electrons in the arc) [11]. The process involves the use of plasma (heated and ionised gas) to carry the welding current from the electrode to the workpiece, in which the discharged electrical power is determined by the voltage drop and flow in the arc. The induced heat that melts the electrode and the joint faces result in welding.

The intense heat from the arc causes the vaporisation the electrode and base metal, which forms welding fumes after being oxidised. The amount of fume increases when other materials with a lower vaporisation temperature, such as flux in a flux-cored arc welding wire, zinc, paint, or oil coating, are present.

Two types of arcs are used in welding [12]. The first is the non-consumable electrode arc commonly used in gas tungsten arc welding (GTAW, also known as tungsten inert gas, or TIG welding) and plasma arc welding (PAW). Non-consumable electrode arcs do not melt in the arc and the filler metal is not transferred across the arc stream. The second type of arc is the consumable electrode arc used in gas metal arc welding (GMAW, also known as Metal Inert Gas (MIG) welding), shielded metal arc welding (SMAW), flux-cored arc welding (FCAW), and submerged arc welding (SAW). The electrode of this arc melts and the filler metal is transferred as a result of the electrode having a complete electrical circuit.

Gas Tungsten Arc Welding (GTAW)

Gas tungsten arc welding, or Tungsten inert gas welding (TIG) uses a non-consumable tungsten electrode and the workpiece to strike an arc. An inert gas, such as argon from the welding torch gas cup where the electrode is located, protects the weld pool and the electrode.

Advantages of GTAW welding include the stable arc and predictable welding outcome. Moreover, GTAW is compatible with filler materials and can be used manually in a rod form similar to gas welding. Automation of GTAW allows for the incorporation of advanced features such as mechanised supply of filler wire and, for example, enables a more rapid joining of pipes and tubes welding process into the frames and plates heat exchangers. Other applications of GTAW include welding stainless steel and relatively low-density metals, e.g., copper and alloy that contain of aluminium, titanium or magnesium. However, GTAW yields the best results with thin materials of 0.5-3 mm thick and cannot be used to weld lead or zinc. Due to these limitations, other methods, such as short arc welding, are more commonly seen than GTAW.

Plasma Arc Welding (PAW)

The plasma arc welding method utilises an inert plasma gas and an outer shielding gas. The plasma gas flows around a retracted centred tungsten electrode while the shielding gas (such as oxygen, carbon dioxide and argon) flows through the outer nozzle and operates the same purpose as that in GTAW. However, PAW is less affected by the variation in arc length, which results from the more straight and concentrated plasma arc than the GTAW arc. The variation in arc length of 2-3 mm does not significantly affect the heat input in a workpiece, which is better than the GTAW about 10 times. Compared to GTAW, PAW has a higher energy concentration and a greater arc stability. Despite this advantage, the method is mostly used in mechanised welding because it requires a precise transverse control of the narrow arc.

Metal Inert Gas (MIG) Welding and Metal Active Gas (MAG) Welding

Metal inert gas welding and metal active gas welding succeeded manual metal arc (MMA), which was the most common welding method until the 1970s, as the most common welding process. MIG is also referred to as gas metal arch welding (GMAW) when inert gas is used in shielding or MAG when an active gas is employed. MIG welding is a process where an arc forms between a wire electrode and a work piece. It uses inert gases or gas mixtures to form the shield gas. Argon and helium are typically used for the MIG welding of non-ferrous metals such as aluminium. A MAG welding process involves the use of an arc welding tool and a consumable wire electrode. The material to be joined is then heated using an active shielding gas. These shielding gases are mixtures of carbon dioxide, argon and oxygen. Examples of these active gases include CO_2, Ar + 2 to 5% O_2, Ar + 5 to 25% CO_2 and Ar + 10% CO_2 + 5% O_2. MIG and MAG welding is advantageous in its flexibility with various applications including:

(1) Welding plate with a thickness of 0.5 mm or more. The low heat input in MIG welding allows for welding thin sheets because it reduces the chance of deformation and distortion of the sheet.
(2) Improve efficiency in welding thicker metal than many other techniques.
(3) Able to weld all structural materials not only stainless steels and alloys but also non-ferrous metals.
(4) No limitation for welding the surface coated metals.
(5) Suitable for all welding positions.

The main restrictions of the metal inert gas welding method are the size and complexity of the welding equipment, and therefore it is less mobile. Moreover, the effectiveness of the shielding gas is dependent on humidity and as a result, MIG is usually performed indoor.

Shielded Metal Arc Welding (SMAW)

Shielded metal arc welding (also known as manual metal arc welding (MMAW) or stick electrode welding) was the most popular form of fusion welding until the early 1980s. The electrode rod of MMAW consists of a wire core coated with a mixture chemicals, minerals and iron powder. The rod is available in various core diameters suitable for a different application. The welding process involves striking high-temperature arc between the electrode and the workpiece, which subsequently melts the electrode coating to form a protective slag. The core electrode wire and iron powder in the coating would form the weld metal. Moreover, the layer of slag on top of the joint is removed after welding.

Submerged Arc Welding (SAW)

Submerged arc welding is an extremely efficient welding technique. It is usually mechanically assisted and 1–3 continuous wire electrodes are normally used. The process begins with striking and burning the arc or arcs under flux layer, which is supplied to the welding head. The slag is formed as a result of the flux nearest to the arc melting on the surface of the weld, and therefore prevents the oxidation and nitrogenation of the molten metal. Residual powder is recycled through the flux hopper. Moreover, SAW can be utilised either direct current (DC) or alternating current (AC).

1.1.2 The Formation of Fumes and Fume Characteristics

Fumes are vapours that are condensed into small solid particles and are generated when metal is heated above its boiling point [1]. The process of volatilisation, oxidation and condensation of the base material and especially the electrode creates fume. In addition, fume can also be produced from the arc area where heated vapours are dispersed into the atmosphere [13]. The vapours are subsequently oxidised by air and condensed into fumes. The processes of arc welding involve the formation of toxic air-dispersed particles in the size range of 0.005-20 µm, which are known as welding fume [14]. Mostly the size of welding fumes are fine particles (<1 µm) or ultra-fine particles (<100 nm) [6]. The size distribution of welding fume can be measured using cascade impactors [15], [16] or airborne particle counters [15], [17], [18]. For example, some authors have measured the size distribution of a welding fume generated by SMAW to be in the size range of 0.05-10 µm [19], [20]. The composition of fumes created during the welding process depends on the welded metal and may consist of various metals namely beryllium (Be), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), vanadium (V) and zinc (Zn) [21]. For instance, fumes generated when welding mild steel are mainly comprised of iron oxide and a small amount of manganese used in welding rods.

The effects of welding conditions to fume formation have been extensively studied [22]–[24]. A study by Heile and Hill [22] demonstrated that there was a correlation between the formation of fume and welding conditions including shielding gas, current, voltage, and metal transfer mode (including welding process parameters such as the electrode wire) from GMAW. However, not much is known about fume plume dispersion and identifying individual factors that affect the dispersion is complicated by many confounding factors.

Welding Conditions - Current and Voltage

Changing the heat input through altering the current and voltage can significantly change the rate of welding fume generation [22]. In particular, changing the current induces a shift in temperature of the electrode and the arc caused by a more concentrated pool of electrons at the tip. The increase in temperature results in a higher evaporation rate and therefore more fume is generated. Moreover, the higher current also allows electrode to melt more rapidly, causing more electrode materials to transfer through the arc. By changing in the current and voltage, in addition to the shielding gas, the rate of fume production could alter in response to the metal transfer mode, electrode tip temperature, and the rate at which the metal drops are transferred across the arc.

Type of Current and Its Polarity

Several studies indicated that the fume formation rate (FFR) is correlated with a direct current electrode positive (DCEP) because the temperature on the tip of the electrode is higher when welding with an electrode positive [25]. Specifically, the high rate of fume propagation and subsequent fume emission are caused by the rising heat and tip temperature when welding with a DCEP. During welding with positive and negative electrodes, fume formation rate can fluctuate up to 30% depending on the type of flux coating, with a lime-coated electrode appearing to have a greater polarity effect. However, the rate of fume formation is not significantly different between AC and DC electrode negative welding [13].

Electrode Influence

The generation of fume is influenced by various factors. Firstly, the composition of the fume produced depends on the electrode wires (or filler metal), which are similar to the base metal being welded. While a range of alloyed steels that contain metals, including chromium, aluminium, cobalt, molybdenum, vanadium or tungsten, is used, the most common metal in welding is carbon steel. Secondly, the vapour pressure of the wire components dictates the overall fume composition. Electrodes comprising elements that are highly volatile generate more fumes than those that contain less volatile components [22]. Lastly, the moisture content of the electrode also influences the amount of fume. Higher moisture content leads to an increased amount of fume because of the change in the arc behaviour. In a real welding process this factor cannot be controlled, and it can only be investigated in experimental studies.

Electrode Coating

The composition of the flux-cored electrode has a direct effect on fume generation during welding. This is because parts of the flux contribute to fume formation, and depending on the substances, such as metal alloys, silicates, metal oxides and arc stabilisers, the core composition of the fumes can change [25]. However, the composition of the fume is not directly proportional to the composition of the electrode.

Electrode Diameter

Electrode diameter also influences the rate of fume formation though at a relatively moderate level. The effect of the electrode diameter is attributed to the change in welding current and voltage. In addition, the transfer mode with bigger wire diameter likely causes a higher fume formation rate when a large current is applied [22], [26]. Moreover, a larger electrode accumulates more materials on a workpiece and disperses more fume compared to a smaller electrode with similar accumulation rates [13].

Arc Length

An increase in arc length, which is defined as the distance from the electrode tip to the workpiece, accelerates the fume production [13]. Furthermore, studies have suggested that the increase in arc contact with the air causes an elevated fume dispersion.

Metal Transfer Mode

The three main metal transfer modes are dip (short arc), globular, and spray [27]. The method by which metal transfers from the electrode tip to the work piece through the arc not only influences the welding performance but also the fume production. Welding parameters including arc stability, droplet transfer and spatter formation can affect the metal transfer and fume generation [22]–[24]. Welding fume formation by metal transfer can be mitigated through a more stable arc control [24]. The correct voltage and orientation of the arc are important factors to ensure stable metal transfer and low fume formation rate. In addition, the size of the droplet and the transit time are important to factors determining the formation of fume [28].

Shielding Gas Effects

As fumes are generated by the evaporation, condensation, and oxidation of metal vapour, an increase in shielding gas oxidation has a direct impact on the fume level. The higher oxidation potential of the shielding gas translates to an increase in fume formation. A study has shown that an elevated level activating agents (oxygen and carbon dioxide) in the shielding gas led to an increase in oxidation and, consequently, more fume [22]. Most shielding gases, such as helium and argon, contain activating agents and oxygen to entrain the surrounding air from the higher shielding gas flow rate. In particular, helium and helium mixtures produce more fume than the argon counterpart [13]. The addition of CO_2 improves the arc stability and produces a higher quality weld bead. However, the addition of an active gas will cause a degradation in the quality of the weld bead [13].

Shielding Gas Consumption Rate

The fume formation rate (FFR) is directly influenced by the shielding gas consumption rate as FFR increases with higher gas flow. The shielding gas flow has to be balanced so that it is high enough to protect the weld and maintain the arc stability but also low enough to prevent the turbulence (drawing ambient oxygen into the arc zone). An unoptimised shielding gas flow can result in an increased oxidation rate of particulate matter, leading to the production of welding fume.

Base Metal (Compositions and Coatings)

In general, the base materials do not contribute to as much welding fume when compared to fume produced from the electrode. However, the fume formation from the base materials can become more significant when they are composed of highly volatile compounds or have paint or metallic coating. This is due to the surface coating having a high potential to generate a greater amount of harmful fumes.

Welding Speed

Welding speed has a small influence to fume generation relative to other parameters. Doubling the welding speed decreased the FFR by 5% [22]. However, the increase in FFR could be up to 20% when the welding speed is halved.

Welding Geometry and Orientation

FFR will be influenced by the position and angle of the electrode relative to the workpiece. The change in FFR incurred as a result of differences in inclination of the electrode which is caused by arc lengthening and degradation of melting zone protection against the ambient oxygen [13]. Welding perpendicularly to the base material produces the least amount of fume while more fumes are produced with angle variation of 30° to the workpiece, which translates to a 15-20% increase in arc length.

The amount of fume exposure can also be affected by the welder’s orientation to the welding torch because there is a difference in concentration of fumes within the welding space [13]. The highest concentration of fume is directly above the source within the fume plume. A welder is exposed to less fume when the welder’s head is on the side of the rising plume (vertical operation).

1.1.3 Welding Fume Plumes and Air Movement

A welding fume plume comprises a mixture of hot gas and particles produced from the weld point that arises vertically as shown in Figure 2. It is a free convection process when using a welding torch with no local ventilation extraction.

Heat generated during welding causes a dispersion of buoyant plume of particulates [29]. The released plume takes the shape of an inverted cone characterised by the upward air volume flowing and decreased particulate concentration on top of the plume as it spreads into the atmosphere where the welder’s head is located [13].

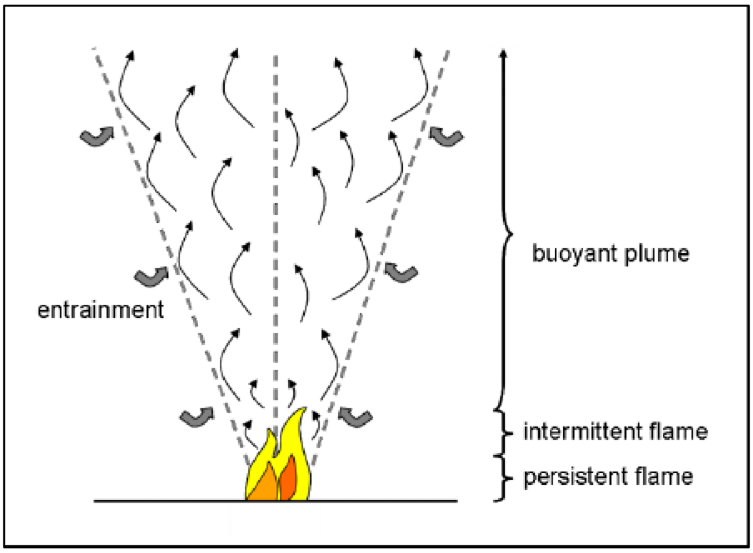

Figure 2 Schematic diagram of plume regions and lateral entrainment between the edges and surrounding air.

1.2 Health Risks from Exposure to Welding Fumes

Welders are exposed to occupational health problems caused by UV radiation from the arc, electrical shock hazards, heat or fire dangers along with metal fume and gases [30]. In particular, the main health hazard is caused by inhaling welding fumes produced from manual metal arc and metal inert gas welding [31] operation. They may contain oxidised metals formed during welding [30]. The danger of fumes lie in the size of particles and the chemical composition. Monteiller *et al*. [32] concluded that the surface area of the particles related to the inflammatory response, especially in small submicron particles. Ultra-fine particles are especially harmful because they can escape from the lung to the blood stream and damage other organs [33]. Out of all metals, stainless steel welding is the most hazardous because the released fumes contain nickel and chromium VI oxides, which are carcinogenic and can cause asthma [3]. Moreover, manual metal arc-stainless steel welding fume induces atypical hyperplastic changes that lead to lung inflammation and injury. A study by Kalliomaki *et al*. [34] conducted on shipyard mild steel arc welders found that the estimated net rate of alveolar deposition of particles in full-time welders was 70 mg of iron per year, and after 10 years of welding the average burden of ferrous metal particles in the lungs was 700 mg, which represented a balance between retention and clearance. Furthermore, retired welders cleared only 10-20% of the accumulated particulate burden per year [30]. These hazards could cause many health problems including respiratory tract irritation, increased for developing asthma, neurological disorder, chronic obstructive pulmonary disease (COPD), and lung cancer [4], [35], [36]. Guha *et al*. [6] stated that welders who were exposed welding fumes were at increased risk of lung cancer. Each year in the UK alone, about 175 welders suffer from lung cancer caused by welding fume and die prematurely [37]. The International Agency for Research on Cancer (IARC) concluded that welding fume should be classified as a Group 1 carcinogens (carcinogenic to humans) [38], [39]. Small submicron particles (i.e., hexavalent chromium compounds) are known to cause lung cancer. However, Cherrie and Levy [40] argued that the individual component metals are not primarily associated with the risks of getting lung cancer but rather the total welding fume determines the risk. Hobson *et al.* [41] studied welding fume exposures based on total welding fume and Mn concentrations. They concluded that the manganese concentrations constitute 4% of total welding fume concentration. Although the weldART model could be adjusted to estimate metal concentrations in the fume by multiplying an estimate of total fume by the proportion of specific metals in the fume, this would likely add a level of uncertainty to the assessment of the fume. Therefore, this justifies a focus on the total welding fume rather than the individual metal components.

In addition to respiratory problems, welding fumes can also damage the nervous system in the body. Prolonged exposure to fume from high alloy manganese electrodes can induce and exacerbate the risk of neurological impairment [41]. Many lines of evidence have shown that welders exposed to manganese fume can develop symptoms in the sensory, motor, peripheral nervous system, and have a higher prevalence of insomnia [42].

The severity and hazard of welding particulate are subject to on the composition, concentration and duration of exposure. The variation in exposure is also subject to welding length, welding materials, methods and control measures. Determination of the particulate concentration and intensity of dominant hazardous substances is key to examining the work condition and strategies precautions to prevent health risks. As most workplaces have different structure, a thorough fume exposure assessment should be conducted prior to implementing appropriate control measures in any specific workplace.

Due to serious health hazards of welding fumes, risk assessment is a crucial tool to predict the likelihood of adverse effects to welders and to identify the need for preventive actions. An effective risk management to mitigate exposure is required to control welding fume exposure. Also, precautions are needed to control the exposure to below the appropriate occupational limit [40], [43]. Ensuring limited exposure entails undertaking risk assessment, which determines the fume exposure to welders and identifies necessary methods to control the exposure where appropriate. The assessment is performed by measuring or assessing the fume concentration inhaled by welders under particular circumstances and/or by using a mathematical model to estimate the welding fume exposure. The results from these evaluations can then be compared to the occupational exposure limits (OELs) and used as the basis to identify control strategies and/or regulatory interventions [44].

1.3 Occupational Exposure Assessment

Exposure assessment encompasses the evaluation process of exposure to biological, chemical or physical contaminants through, but not limited to, inhalation, ingestion, or dermal contact [44]–[46]. The characteristic of contaminant transport, depending on the properties of contaminants such as particle size, volatility, and vapour pressure, may dictate the severity of the adverse health effects [44], [47]. Moreover, the severity of the exposure and effects on health can also be exacerbated by other factors including chemical concentrations in the media, exposure characteristics (e.g., intensity, frequency, and duration), and human characteristics (e.g., body weight, diet, age, skin absorption capacity) [48]. Measuring the exposure can be performed by monitoring, measuring, modelling, and representing data as the number of particles per cubic meter of air or in units of mass of contaminant per cubic meter of air [44], [48].

The WL3 guidance from the Health and Safety Executive (HSE) [49], gives practical advice on how risks can be managed by applying the principles of good practice to the control of exposure to welding fume, as required by the British Control of Substances Hazardous to Health Regulations 2002 (COSHH). Additionally, occupational exposure limits are useful guidelines to consult and control the exposure to the chemical and physical agents. A small number of countries have dedicated organisations that provide appropriate resources to continuously maintain and review such guidelines. Most other countries base their criteria on one of the following occupational exposure limit systems shown in Table 1.

Table 1 Summary of occupational exposures limits in different countries.

Country / Union	Occupational Exposure Limits
Australia and New Zealand	Workplace Exposure Standard (WES)
Europe	Indicative Occupational Exposure Limit Value (IOELV)
Germany	Maximale Arbeitsplatz-Konzentration (MAK)
Russia	Maximum Allowable Concentration (MAC)
United Kingdom	Workplace Exposure Limit (WEL)
USA	Threshold Limit Value (TLV)

The limit for welding fume exposure is not standardised for different countries or organisations. Increased awareness of welding fume hazards were raised when the American Conference of Governmental Industrial Hygienists (ACGIH) highlighted the need to address the danger of individual particulates and therefore no longer categorised welding fume as total particulate in 2003 [39]. The hazard was considered related to specific metal components rather than the overall fume. ACGIH treats welding fume as a Particles Not Otherwise Specified (PNOS) [50]. This guideline applies the OEL based on particle size in the mixture and the recommended airborne concentration of PNOS should be below 3 mg/m^3 for the respirable fraction and 10 mg/m^3 for the inhalable fraction. However, this guideline is applicable for substances of low toxicity and therefore is not most suitable for welding fumes. The US Occupational Safety and Health Administration (OSHA) do not have an exposure standard for welding fume and classifies it in the broad category of Particulate Not Otherwise Regulated (PNOR) with the permissible exposure limit (PEL) of 5 mg/m^3 for the respirable particulate and 15 mg/m^3 for total particulate for a 40-hour week [12]. NIOSH also views welding fume as PNOR, with recommended exposure limits (RELs) of 15 mg/m^3 (total particulate) and 5 mg/m^3 (respirable particulate). In 2005, the British Health and Safety Executive (HSE) withdrawn the welding fume exposure limit as total inhalable particulate (5 mg/m^3) [51], and recommend compliance be assessed against the specific limits for each hazardous metal in the fume. However, the Workplace Health Expert Committee (WHEC) of the HSE and the IARC Monograph Working Group both concluded that there is not identifiable safe level of the welding fume exposure [40]. At present, in Britain, the WEL relevant to welding fume is specified for cadmium oxide (Cd), chromium (Cr), copper

(Cu), iron oxide (Fe), magnesium oxide (Mg), manganese (Mn), rhodium (Rh), as shown in Table 2 [40]. In Germany, the Federal Ministry of Labour and Social Affairs has set an OEL for inhalable (10 mg/m^3) and respirable (3 mg/m^3) particulate matter, which also applies for welding fume [52]. They argued that the danger of fume depended on both the quantity and composition of welded alloy, the process and electrodes. In Thailand, the Department of Labour Protection and Welfare (DLPW) also applies PNOS for welding fume in the same way as the US NIOSH.

Table 2 The list of WELs relevant to metal component of welding fume by the HSE.

Substance	WEL (mg/m^3)	
	Long-term Exposure Limit (8-hour TWA)	Short-term Exposure Limit (15-minute)
Cadmium oxide fume (Cd)	0.025	0.05
Chromium (Cr)	0.5	-
Chromium (VI) compounds	0.05	
Copper fume (Cu)	0.2	-
Iron oxide fume (Fe)	5	10
Magnesium oxide (Mg) (Inhalable dust fume)	10	-
Manganese (Mn) (Inhalable fraction)	0.2	-
Manganese (Mn) (Respirable fraction)	0.05	-
Rhodium (Rh) (Metal fume)	0.1	0.3

The level of welding fume hazard is exacerbated by the absence of good ventilation, leading to a quick air contamination especially within a confined space. When a welder generates 1 g/min of fume in a closed 3 m^3 room, the concentration of respirable fume would likely exceed the Threshold Limit Value of 5 mg/m^3 for nontoxic nuisance particulates averaged over an 8-hour workday [53]. Poor ventilation can increase the amount of respirable fume inhaled by workers and therefore increase the potential for debilitating lung diseases. For instance, a case study has shown a strong correlation between a welder who worked in a confined space for 27 years with inadequate ventilation and no respiratory protection and lung iron accumulation that led to interstitial lung fibrosis [30].

1.4 Aims of the Research

Presently, pollutant exposure assessment tools are available in both direct-reading instrument and exposure modelling. The advantages of direct-reading instruments are easy to use, provide real-time values. However, the disadvantages are that the instruments are expensive, usually have lower accuracy than time-integrated (gravimetric) analysis and cannot be used for epidemiological predictions. On the other hand, exposure modelling can solve these disadvantages of direct-reading instrument. There is no requirement to purchase exposure assessment tools. In addition, the modelling can also be used to conduct epidemiological investigations.

However, the present state of exposure modeling does not covering all pollutants, especially welding fume. There is no accepted exposure modeling tools to be used as an exposure assessment method for welding fume. Therefore, this research aims to develop a reliable and effective welding fume exposure model.

The general objective of this research is to formulate the model to provide schematic elaboration on welding fume exposure. Specifically, this study aims:

(1) To develop a mechanistic model for welding fume exposure assessment and improve the model as appropriate.
(2) To calibrate the mechanistic model to be suitable to quantify welding fume exposure.
(3) To assess the reliability of the finally developed mechanistic model for welding fume exposure in workplace settings not used to develop the model.

CHAPTER 2
LITERATURE REVIEW

This chapter reviews the published literature to aid the formulation of model to be used to predict welding fume exposure by further development of ART model approach, which is an accepted exposure model and classified as a Tier 2 for the exposure assessment within the European chemical regulations system. The ART can currently be used to predict the concentration of many pollutants, although not welding fume. It is a web-based tool (https://www.advancedreachtool.com/) that evaluates exposure scenarios that cannot adequately be assessed using screening risk assessment tools (i.e., Tier 1 tools), such as the ECETOC Targeted Risk Assessment (TRA) tool (https://www.ecetoc.org/targeted-risk-assessment-tra/). Therefore, in addition to studying the principle of welding and the nature of the fume exposure during welding, the literature review for this research also examines the principles of the ART model as the it will be used as the basis for the development of a welding fume exposure model. After understanding the principles of the ART model, the next important step is the development of a suitable exposure model for welding fume. In this chapter, theory, principles, and related research will be explained in twelve topics as follows:

- Welding Emission
- Exposure Assessment
- Welding Fume Buoyant Plume
- Fume Formation Rates
- Exposure Modelling and the ART Model
- Procedure of Model Development
- Validation
- Uncertainty Analysis in Exposure Assessment
- Variability and Uncertainty Method Analysis
- Data and Resource Requirements
- Use of Uncertainty Analysis in Evaluation and Validation
- Discussion and Conclusions

2.1 Welding Emission

Approximately 0.5-1% of welding consumable are transformed into fumes, dust, and pollutant gases. According to the data, in the UK, there are welding pollutants around 700 tons emitted per year and 70,000 tons of welding consumables [1].

The main pollutants generated during welding operations are particulate matter and particulate phase hazardous air pollutants [2]. The quantity of emissions released depends on the type of welding process and its operating conditions, type of electrode and its diameter and composition. The work piece composition has a direct impact on the quantity of fume released. For instance, galvanized coatings, cleaners, oils, and paints generate organic and metallic fumes. Furthermore, fume emission is also affected by operating conditions such as air speed over the arc, voltage and current of the welding process, arc length, polarity, welding position, electrode angle and deposition rate.

There are three important factors contributing to emission of welding fumes, which are: 1) particle size, 2) composition and 3) emission volume. There is a variety of particle size range. Some particles are inhalable and they may remain airborne for a long time [1].

This study aims to create an empirical model that can point out the relationship between process behaviour and the resulting welding fume emissions [3]. The welding parameter settings can assist in predicting emission rates while adjustments can be specified under the emission rate limit requirements [3].

Normally, welders would use one of three welding positions depending on the work situation [4], namely: flat horizontal downhand), vertical and overhead. The downhand position is a common position often used in arc welding as this position can help minimize the fume exposure for welders by allowing them to position their head out of the fume plume. The posture of the welder is related to the welding position. There are three welding positions namely crouching, standing and sitting. When considering welding position with the highest risk of getting fume exposure to the lowest, it has been found that crouching allows the welder to be exposed to the highest fume exposure level, followed by standing and then sitting, respectively [4]. However, the amount of fume exposure may also differ from the above depending on the distance between the welders' head and the position of the fume plume and any control measures implemented. For example, if a welder is in the sitting position but his head is directly in the position of the fume plume, the welder would be exposed to higher fume exposure than if they were in the standing position, but their head was not in the vicinity of the fume plume. Therefore, having the right understanding, skill, and experience of these principles allows a welder to reduce the risk of being exposed to fume. The above variables are factors affecting the amount of fume produced while welding [4] and the extent of direct contact with fume in the welding plume.

The fundamental information for creating a model is the determination of process-specific emission rates, which can be acquired through the experimental welding fume emission measurements using a fume-box or chamber. The model should include information relating to dependency and influencing factors, such as welding process (emission rate), welding parameters - which modify emission rate (e.g., current and voltage), arc time or more detailed data on times welding, time welder spends with head in plume, local ventilation, room size and ventilation rate, and interzone flow rates.

2.2 Exposure Assessment

There are three basic methods which are the fundamental process of exposure assessment such as 1) individual estimation based on professional judgment, 2) direct measurement of environmental exposure and 3) prediction of exposure using mathematical modelling [9]. Direct measurements can provide evidence as to the magnitude of exposure for a specific situation, but the process is time consuming and can be expensive. Consequently, subjective judgments, which are often made with relatively low transparency, form the basis of most exposure assessments. The most neglected area or exposure assessment is exposure modelling, which has been less supported by governmental research funding agencies. However, these circumstances have changed in recent years because of regulatory developments such as the REACH (Registration, Evaluation, Authorisation & Restriction of Chemicals) Regulations in the European Union, which require risk assessments in a variety of exposure scenarios where it is not feasible to undertake monitoring [9].

The definition of “exposure assessment” means the determination of parameters representing the distributions of contaminant (or its products) in environmental and/or biological levels across exposed population, along with attendant statistical evaluations and interpretations of such estimated parameter [10]. Exposure assessment provides information on the contaminant exposure pathways as well as the individuals who are exposed [11]. Therefore, exposure assessment, including the uncertainties involved, is an important element of reliable risk assessment.

Exposure assessment is a complex process that involves quantitative and qualitative characterisation of different uncertainties. Many factors need to be considered to accurately assess exposure, including the types of origin of contaminant exposure, the physical, chemical and biological characteristics of compounds that affect the dispersion in the environment and their absorption, individual mobility and behaviours, and different exposure directions and pathways [11]. Therefore, it is important to consider these factors and their complex interactions when building a conceptual model to mathematically and statistically assess exposure.

2.2.1 Gravimetric and Chemical Analysis Methods

The Health and Safety Executive (HSE) has published a series of validated methods called Methods for Determination of Hazardous Substances (MDHS) for air collection and analysis. The series encompasses a range from general methods for gravimetrically analysing respirable, thoracic and inhalable aerosols (MDHS14/4) to sampling and analysing welding fume (BS EN ISO 10882-1:2011) [12] [13]. Air collection and analysis can involve the use of a 25 or 37 mm sampler positioned behind the welding visor [14]. Even though, direct monitoring is perceived as an effective measure, there are two restrictions. For example, many safety and health practitioners fail to appreciate the exposure variability and documentation of exposure determinants. If these factors are not determined, the result if exposure data collected will less useful.

The first step is to consider the 8-hour TWA exposure level. The average exposure level for each worker may vary widely, even though they perform similar tasks. The notion expressed by Kromhout *et al*. [54], that environmental and production factors were shown to have distinct influences on the within-worker variability, but not on the between-worker variability. Mobile workers working with an intermittent process and those where the source of contamination was either local or mobile also showed great day-to-day variability. In addition, if only one or two exposure measurements are made for a single worker, there is considerable uncertainty in the exposure level for individuals (or groups). A randomized sampling process should be applied to choosing the time periods or subjects monitored. Provision of confidence intervals for summary exposure measures is a common tool used to estimate uncertainty and variability in the value of the average (typical) exposure level. However, in order to establish a confidence interval, it needs at least two exposure values, ideally more, so that the standard deviation can be estimated [15]. Although certain inferences can be made about exposure by considering the length of time a worker is in the area, the best indicator of a person's actual exposure comes from personal sampling since the sample is collected by equipment that is actually worn by the worker during the workday. Breathing zone samples are collected at the worker's nose and mouth. Breathing zone samples provide the best indication of the concentration of contaminants in the air the worker is actually breathing.

The second step is the determination of factors in physical exposure level during the monitoring period. These factors should be recorded together with the strategies adopted by workers and the monitoring periods. The air sampling method and analysis also require to be documented. Without this information it is impossible to extrapolate the measurements to reasonably represent the exposure intensity for the tested subjects or for other workers working the same tasks [15].

As small sets of measurement data can lead to false conclusions, organizations undertaking monitoring should therefore install a program to periodically review risks as well as to make good documentation and ensure records of the information are retained. False conclusions may cause practical problems for organizations and could possibly lead to unexpected regulatory or legal action. Exposure monitoring can be carried out in the existing processes, but this approach is less suitable for future processes, or for developing an emergency response plan against unintended release. Since it is not possible to perform a *de facto* exposure monitoring in such circumstances, other estimation methods for exposure intensity must be adopted. This is a further impetus for mathematical modelling [15].

Welding fume exposure measurement can be performed to evaluate fume exposure risk of welder by air sampling to analyse the fume concentration and compare the results with the standard or occupational exposure limits (OELs). The objectives of such an exercise are to determine whether the fume exposure level experienced by welders is appropriate and will not affecting their health, as well as to analyze whether the applied engineering controls are appropriate or not.

2.2.2 Welding Fumes Exposure Measurement

Low welding fume concentrations have been measured in situations where there is good ventilation. For example, Castner and Null [16] studied the working behavior of welders who used SMAW technique in the open area of a shipyard. The study results showed that the average 8-hour TWA concentration measured at the breathing zone of welders has total fume concentration range of 0.13 - 0.46 mg/m^3.

Medium concentrations of welding fume have been found in more confined spaces. Boelter *et al*. [17] collected samples to assess total particulate concentrations and make comparison with the concentrations obtained from a model. Samples were collected from workers using SMAW welding in a breezeway and boiler room. There was no perceptible air movement in the boiler room and it was judged to be still air. The study found that the average total particulate concentrations in the breezeway and boiler room areas were in the ranges of 2.89 – 4.38 mg/m^3 and 4.73 – 5.90 mg/m^3, respectively.

High concentrations have been measured in situations where intensive welding using processes that emit greater amounts of fume in enclosed environments. Balkhyour and Goknil [18] assessed total fume concentration for 163 welders who work with MMAW from six factories in Jeddah, Saudi Arabia. It was found that total fume concentration (8-hour TWA) was in the ranges of 3.0 – 11.3 mg/m^3. Natural air ventilation helped to reduce these levels but the exposures were not considered to be controlled.

Measurement data can also be used to calibrate exposure models or to validate models that have been previously produced. During the model calibration process of this study, air sampling was conducted in the welding area to assess the fume concentrations in the form of total particulate. In such circumstances it is particularly important that the parameters used in the model, e.g., ventilation rates, worker behaviour and welding process parameters, are collected alongside the measurement data. The details will be further described in Chapter 4. Data gathered from research and reports on fume measurement can also be used for calibration, but often these lack details of the model parameters making such data unsuitable for calibration. However, such data can still be useful in verification exercises. This research has tried to identify total particulate concentration welding fume data covering low, medium and high concentrations, along with whatever model parameters are known, to be used in verification of the developed weldART. Details of this exercise are given in Chapter 6.

2.3 Welding Fume Buoyant Plume

In order to comprehend the level of concentrations within a workplace breathing environment are affected by the contaminants, the dispersion is important factor. Meanwhile, the fume plume movement can be described in three important steps as follows: 1) the fume disperses from the original source, 2) the general rise of plume and 3) the extraction rate required to regulate the concentration within the working environment [7].

According to what Slater [7] the fume will travel towards that ceiling up to a height of 1.15 metres above the source. As the environment is generally confined, e.g., within a closed room, the dispersal height is limited.

The definition of plume is the occurrence of a turbulent convective air current from a finite heated source producing a steady continuous release of buoyancy, mass or momentum. A heat emission source, such as welding, tends to decrease the density in the released fluid and the difference in density relative to the surrounding environment generates a buoyant fluid that accelerates vertically [7].

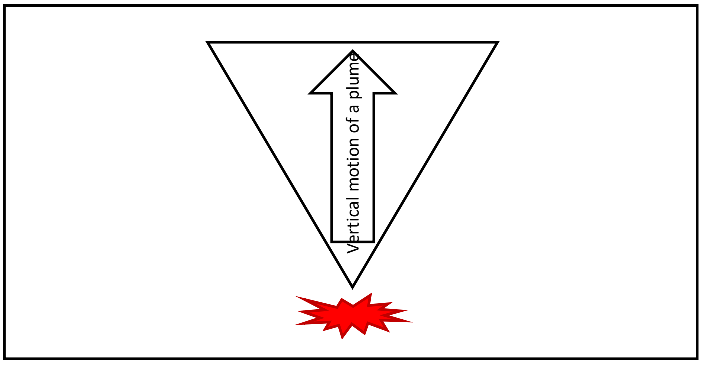

Figure 3 A 2D depiction of turbulent plume flow from a source of welding fume.

The vertical motion of the plume exhibits several different flow mechanisms in a calm environment. Laminar flow is the primary initial flow characteristics of a plume. The laminar flow changes into a turbulent flow within a small distance from the source point, which creates a turbulent plume mixing with the surrounding are throughout its vertical movement and expanding in size and slowing at the same time (Figure 3). In some quiescent environments such as large workshops, welding fumes tend to reach maximum plume height and spread out to surroundings. If there is no precaution imposed, this can create an accumulation of contaminant fume within the working environment [7]. This layer is called the first front. The plume's turbulent nature fades away, creating a uniform non-turbulent environment. New fluid passes through the boundary layer as the plume continues. It will be surrounded by the lighter stratified environment and reach the ceiling as it becomes more buoyant than it was initially. Then, the first layer will be pushed down to the new layer of lighter fluid. This formation process occurs repeatedly to produce a new, lighter front, where the natural convection creates a stratified density. All of the process is called the principle of the filling box model [7]. Slater [7] stated that the welding process generates the fumes' highly buoyant nature, passing through the breathing zone of workers moving up to the ceiling. This occurs when a buoyant contaminant floats in a limited space.

The plume generated by the welding fume does not generally last for a long period but will be maintained for the duration of the welding activity. Therefore, it is only a continuous process during its operation. The primary stage of the plume formation takes only a few seconds. The formation of drops of molten metal occurs when materials are transferred from the electrode to the base material. The melting rates are diverse, depending on type of electrode, current, and material. It is expected that fumes are produced when vaporized metal condenses on the outside of the arc or when some droplets become exposed to air. Moreover, fume can also be generated when the droplets contact with the base material and the melted filler or when the surrounding gas shield is touched by base material splashes [8].

The intensive turbulence created by the source of the welding plume may be explained by the high frequency of drop transport and the dynamics in fume generation. Olander [8] has investigated the particle flow and the number concentration within a welding fume buoyant plume. According to his study, the parameters needed to describe the concentration are the surrounding air temperature and the temperature gradient, the air entrainment coefficient, the initial radius of the plume and initial velocity of the air in the plume, the size distribution and/or number concentration at a specific plume level, the initial plume temperature or heat flow, total source mass flow, particle component of the total source mass flow, and the coagulation coefficient. However, the initial radius, the initial velocity, and the initial temperature or heat flow from a welding process cannot easily be determined, making the quantification of emissions from welding processes based on scientific principles problematic.

2.4 Fume Formation Rates

Fume formation rate (FFR) is the welding fume generation rate; and this is similar to the intrinsic emission potential of a substance in the ART model. The two measurement units used for fume formation rates are intensity of evolution (g/min) and the total evolution per unit of melted metal or melted electrode (g/kg). Fume formation rates can be measured experimentally. However, during the process of welding, there are multiple factors that can influence the gaseous and particulate fume levels which can be summarized as follows [7]:

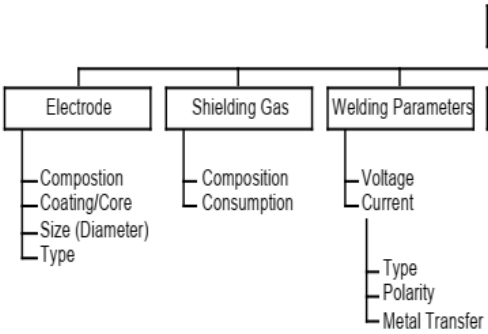

Figure 4 Factors that influence the formation of welding fume.

The importance of each factor is hard to determine due to the complex interrelationships among them. The welding process affects the amount of formation of welding fumes. However, surface coatings and impurities play a role. In addition, there are other factors that must be considered [55], e.g.,

Current and voltage: the higher the values are for the welding current and welding voltage, the higher is the amount of welding fumes.

Type of current: using alternating current results in higher emissions than DC.

Electrodes circumference: the larger the diameter of the electrode used, the higher the amount of welding fumes.

Enclosure type: the substance with which the electrode is sheathed affects the welding fumes: Rutile coated electrodes develop the lowest amount of welding fumes, while the highest amount of harmful substance emissions are produced with cellulose coated electrodes.

Electrode pitch: if the electrode pitch is flat, only small amounts of welding fumes are created than with steeper angles of attack.

Type of weld: if variations of build-up welding is used, higher pollutant emissions occur. With joint welding, the amount, however, is significantly lower.

2.5 Exposure Modelling and the ART Model

The term "model" in an exposure study refers to a representation, whether it be conceptual or mathematical, of an exposure process that is used as a basis to quantify exposure [11]. Therefore, exposure models include conceptual and mathematical description of exposure processes and take into account the circumstances, scenarios and their mathematical expressions.

There are certain advantages of building statistical and mathematical models over using direct air monitoring data in some situations, such as making retrospective assessment of exposure in case there is lack of historical data; predicting present and future exposure in the absence of processes or operations and approximating the exposure with a very few air samples which may have high variability. Nicas and Jayjock [19] indicated that modelling may give estimation of exposure with better accuracy than measurement datasets with a few data points. Formal modelling has become an indispensable tool in the occupational health arsenal when it is applied with advances in computing methods and the use of affordable software [9].

The construction of a human exposure model is relatively simple and can require a limited number of parameters including source, generation and control of contaminant. The model may also consists of key predictors to gauge the exposure and assess the effects of contaminants. The developed model can be used to improve the experience, harness more knowledge and simulate changes in the real exposure circumstances [20]. The characteristics of the models depends on their scope and complexity, subject to different experimental settings and the applied assumptions. For example, the assumptions about the transport pattern of pollutants range from completely instantaneous mixing throughout the room to two well-mixed zones within one chamber. This results in a continuous concentration gradient over time and area [19].

Exposure assessment models aim to estimate accurate and precise concentrations of contaminants and determine the nature of exposure. Moreover, models are also used to predict the impact of contaminants and guide risk assessment and management of contaminant concentrations and emissions. The main advantage of using models is the speed with which data are obtained, compared to the actual monitoring of the risk.

Furthermore, they can provide the correlation and information that can explain the relationship between the hazardous contaminants and working environment [21]. These data can be derived to create verifiable hypotheses to enhance the basic understanding and more accurately estimate the exposure [20]. Under the influence of REACH, various models have been created although the validation of these models have usually been performed only after the model release [22].

The tighter regulations demanded by the European Union, for example the REACH and The European Chemicals Agency (ECHA) actions, have increased the number of occupational exposure models available [20]. ECHA, in particular, approached these regulations with a tier system. A Tier 1 approach uses a basic model and is often conservative in its estimation of exposure (i.e., it should always overestimate). Due to the nature of the model, only a limited range of data is required. Various screening models can be applied to satisfy the initial Tier 1 approach within REACH, such as Stoffenmanager®, European Centre for Ecotoxicology and Toxicology of Chemicals' Targeted Risk Assessment (ECETOC TRA) tool, and the EMKG-Expo-Tool (Einfaches Maßnahmenkonzept für Gefahrstoffe Exposure Tool) [23]. A Tier 2 approach is needed when the Tier 1 strategy is unable to substantiate that there is a sufficient protection. As advised by ECHA, Tier 2 requires a more extensive data input to limit uncertainty, and therefore is designed to assess well-defined exposure [24]. Any proper method that is precisely and accurately validated can be utilised to assess at Tier 2 [23]. However, ECHA recognises the Advanced REACH Tool (ART) as the only higher tier model for determining inhalation exposure [23]. The tool takes advantage of a Bayesian methodology, where the mechanistic model output is adjusted through more data input and measurements [25]. Nevertheless, none of these models cover welding processes within their scope.

Statistical models have the ability to provide an assessment of workplace situations and their hygiene. For example, analysts have applied multiple linear regression models to assess chemical exposure to curing fumes in rubber-manufacturing plants [26]. However, the model still has many limitations such as inconsistency and a large error margin. These limitations stem from differences in work pattern and task content as well as the lack of frequency in the tasks performed. While statistical models include many modifying factors that are included in physically based deterministic models they do not do this is a physically realistic way, which makes generalisation of this type of model more uncertain.

The two-zone model has been used to model welding fume behaviour by applying the concept of breathing zone (near-field or NF) and area (far-field or FF) of fume concentration [27]. However, the model still has some limitations because it was not originally intended to assess fume formation rate and therefore corrections had to be applied. For instance, elevated working temperature and the small and localized source of heat will have to be taken into account to adjust for the concentration of fume in the NF and FF zones [28]. Therefore, further investigations should be conducted to optimise the model.

A statistical model to assess welding fume exposure, which takes into account the exposure parameters and related factors, such as sampling year, welding process, type of ventilation, degree of enclosure of the working area, base metal and sampling location, was developed and validated [29]. After cross-validation, the model could produce the exposure model to welding particulates based on measurements gathered from published literature. Furthermore, the model efficiency could be enhanced by adding details of exposure determinants.

The ART algorithm estimates the contribution from NF sources [equation (2.1)] and FF sources [equation (2.2)]. Welder's exposure from a near-field source (C_{nf}) is a multiplicative function of substance emission potential (E; e.g., welding process, consumables, shielding gas), and activity emission potential (H; i.e., power supply), localized control (LC), and dispersion (D). The algorithm for a far-field source (C_{ff}) includes segregation (Seg) and personal enclosure or separation (Sep).

$$C_{nf} = (E_{nf} \cdot H_{nf} \cdot LC_{nf}) \cdot D_{nf} \qquad (2.1)$$

$$C_{ff} = (E_{ff} \cdot H_{ff} \cdot LC_{ff} \cdot Seg_{ff}) \cdot D_{ff} \cdot Sep \qquad (2.2)$$

Then, the overall exposure is estimated by algorithm equation (2.3):

$$C_t = \frac{1}{t_{total}} \sum_{tasks} \left[t_{exp} \cdot (C_{nf} \cdot C_{ff}) \right] + t_{non-exp} \cdot 0 \qquad (2.3)$$

The algorithm takes into account various activities [and exposure time (t_{exp})] within an 8-hour work shift (t_{total}) and also allows periods with assumingly zero exposure ($t_{non-exp}$).

2.5.1 Box Model

A single box model or general ventilation model is one of air quality modelling algorithms that is commonly used in inhalation exposure modelling. The box model applies basic principles of mass conservation and is based on the assumption that contaminants are emitted to the air in the working area in a manner of uniformly mixed into the air volume. Thus, this emission characteristics is referred to as a "box" [5]. The model simulates air concentration similar to a box with homogeneous inner air concentration which can be expressed using the following equation [6]:

$$\frac{dCV}{dt} = QA + uC_{in}WH - uCWH \tag{2.4}$$

Where;

C	=	Concentration of pollutant throughout the box, µg/m^3
C_{in}	=	Pollutant concentration entering the box, µg/m^3
Q	=	Pollutant emission rate from source per unit area, µg/m^2 · s
V	=	Volume of the box, m^3
A	=	Horizontal area (box width x box length), m^2
W	=	Box width, m
H	=	Box height (mixing height), m
u	=	Wind speed normal to the box, m/s

The box size is subject to average wind speeds, physical aspects of the surroundings, source of contaminant and inversion heights (outdoor situations) [5]. Box model characterizes the homogenously dispersion of a single chemical inside and calculates air exposure concentrations (mg/m^3).

Box models offer the opportunity to investigate the pattern of potential exposure, particularly the temporal variation, of air pollutants in a simple system.

2.5.2 Two-box Model

Two-box models used in occupational health are based on simple assumptions about airflow and transmission patterns. According to the research of Nicas [30], a two-zone model can be adopted to describe concentrations in the "near field" in the vicinity of the source and the "distant field", which is far away from the source. Although these models are increasingly used in the occupational environments [19], they have not been validated in occupational surroundings analytically. Experimental research has been performed to assess the parameters applied in the model and the performance of the model. For instance, in a two-zone model, there is often insufficient understanding on the airflow rate parameter between the near field and the far field. The methods available to estimate this parameter neglect other related influencing factors such as body movements, body temperature, and the presence of the human body which can affect the average wind speed within the zone near the field [19]. Furthermore, the study of Cherrie [31] has examined the effects of common ventilation conditions and various room sizes in a simulated circumstance in the study, assuming that there are uncertainties of model parameters in most settings.

Emissions in a workspace can be described using indoor air quality models [32]. These models take into account a source (such as welding) and airflow patterns and dispersion, which are important factors in choosing the correct model to assess a workplace. A well-mixed room model can sufficiently assess the exposure intensity for individuals within the three-metre vicinity from the contaminant emission source, although the exposure intensity is usually underestimated [32]. This is because the well-mixed room model assumes that contaminant would be evenly dispersed throughout the room. On the other hand, the air monitoring data suggest that the contaminant concentration is higher near the source. In other words, the well-mixed room model is analogous to a single box. To account for the spatial variation of contaminant in a room, a two-box model could be used. The two-box model spatially divides the room into two zones – one containing the emission source and around the welder (near-field) and the other is the entirety of the room (far-field).

2.5.3 The ART

The ART mechanistic model is a method to estimate the inhalation exposure of hazardous substances. Even though it was originally intended to assess exposure for the REACH Regulations, it has been shown to be compatible with exposure assessment in other areas [33]. The model applies the “transmission” model of contaminant from the source (e.g., welding arc) to the receptor (the worker). The independent principal modifying factors (MFs) are adopted in a multiplicative model to modify the exposure estimate. MFs include factors related to the source, compartments of transmission and the receptor [34]. Furthermore, the model utilises MFs to explain exposure in a specific situation (e.g., substance emission potential, activity emission potential, localized controls, dispersion, personal enclosure, segregation, and surface contamination) [23]. The model's output is exposure score that gives a relative ranking of geometric mean (GM) exposure level for different exposure situations. However, the model has been calibrated so that the exposure score can be made to correspond to a quantitative level of exposure in terms of concentration in mg/m^3.

The ART mechanistic model normally estimates inhalation exposure without the exposure data. However, relevant exposure data can be integrated via a Bayesian updating process to enhance the model reliability. The Bayesian methodology enables an updating of the model estimation of exposure, which in turns improves the precision of the exposure estimate. Accuracy can be enhanced depending on the degree of similarity between the data and the modelled scenario, the amount of available measurements (number of measured companies, number of measured workers, and repeated measurements), and the variability level of exposure in the measurements applied in the Bayesian update [35]. In addition, the reliability of the ART model could be enhanced through guideline for assessors, application of consensus procedures, and improvement of training methods. However, the model has some limitations in the variability in the estimation of the levels of exposure for a given scenario and that the calibration is done separately for vapours, mists, and dusts and gases, fibres, and fumes are not included [33], [36]. It should be noted that a model that includes the estimation of gases, fibres, and fumes as well as the risk of welding fume inhalation is still not implemented.

2.5.4 Characterization of Principal Exposure Modifying Factors

The ART model is associated with and can be adjusted by MFs. Useful MFs have to be distinctly identifiable, observable, quantifiable and can be adopted in various assumed exposure scenarios [37].

Activity Emission Potential (H)

The MF 'activity emission potential' elaborates the possibilities of the activity to produce contaminants (e.g., types of welding processes) taking into account of the following characteristics: type and amount of energy transmission, scale (e.g., amount of product used) and product-to-air interface (e.g., level of containment).

Substance Emission Potential (E)

The MF 'substance emission potential' is used to estimate the intrinsic emission potential of a substance, i.e., amount of particulate agents and volatility for liquids.

Localized Control (LC)

The MF 'localized control' is applied as controlling measures in close proximity to the source that are desired to eliminate emissions, e.g., local exhaust ventilation, airborne capture sprays, suppression techniques, containment of the source.

Segregation (Seg)

The MF 'segregation' defines the performance of source isolation measure from the work environment.

Dilution (D)

The MF 'dilution' defines the effect of mechanical and natural room ventilation and room size on the concentration in the NF or FF compartments.

Personal Behaviour (P)

The MF 'personal behaviour' takes into account the influence of workers movement and their body orientation relative to work piece, distance between worker and the source and other factors causing deviations from a completely mixed concentration in the NF.

Separation (Sep)

The MF 'separation' elaborates how the concentration potential in the personal enclosure compartments is reduced relative to the FF in which it is embedded. Moreover, it was observed that a personal barrier (if any) encapsulates the person and could thus be taken as the NF zone.

Surface Contamination (Su)

The MF 'surface contamination' explains the emission associated with release of deposited contaminants on surrounding surfaces (including worker clothing) due to natural means or general workplace activities (e.g., moving equipment/vehicles).

Respiratory Protective Equipment (RPE)

The MF 'respiratory protective equipment' elaborated the potential of RPE in protecting the wearer from inhaling airborne substances. However, RPE is not considered in the ART.

2.6 Procedure of Model Development

A model is an arithmetic algorithm that reflects a natural phenomena. When a model is implemented in a practical way, for example as computer code, it is generally referred to as a model tool. Moreover, a model tool is the association of control language, numerical techniques, and bookkeeping, representing the model from inputting data, through a series of instructions, until giving output. Technically, the numbers included in computer code are defined as algorithms [38].

The appropriate model development process can be broken down into two sections: which can be performed without referring to any field data and hereinafter are referred to as the subject of the appropriate model development process called "Synthesis", which is based on available information and the analysts' cognitive skill; and "Analysis", which refers to what needs to be done regarding the quantitative definition of the system. "Quantitative definitions of system behaviour" and "The analyst's knowledge and imagination" should, as much as possible, be independent from one another when entering into the components of the model [38].

2.6.1 Synthesis

The model developer has to search from multifarious knowledge sources in assembling in a mathematical model (for example, the outcomes of the previous model and field studies micro-level experiments). The first two phases of the model's development are accomplished by validating the code. Code validation is done by examining numerical techniques in computer code to ensure that it accurately characterizes a thought model and that there are no inherent numerical problems when determining solutions. Generic models occur when numerical algorithms have been entered into computer code to solve one or more partial differential equations [39].

From Beck *et al*. [38], they have inspected that, therefore, a model is created and the validity of the composition was determined regardless of whether a calibration or analysis of any subsequent uncertainties has to be performed. The assumptions (or disparity) of the constituent hypotheses in the model. The relative strengths and weaknesses of factors can be measured, identified and possibly quantified for the measurement of the overall model accuracy.

2.6.2 Analysis

Calibration is a simulated test containing acknowledged input and output data used to adapt or approximate the no-data factors [38]. The objective of the calibration is to adjust the configurations in the assessment model to ensure reliability and accuracy. The model may not be reliable straight away due to some parameters may not have been assigned a "correct" value as a result of incorrect assignment of parameters. As the "factors" mentioned are the model's coefficient or the calibration parameters. Calibration often means the estimation of the parameters contrary to the above definition of the generic model [38]. When generic model parameters are set to represent a computer program, the result is a site-specific model.

The model may be partly shown to be inappropriate at this stage if there are errors in the expression of some relationships, that is, the constituent hypothesis. Therefore, the encoded model can be affected by what is known as conceptual errors, structural errors, or uncertainties in the notional model, or model errors [38].

2.7 Validation

After the calibration process, analysts should determine a set of relationships numerical problem-solving steps, and values for all intrinsic parameters of the model are provided by the model development process. This will be adequate for the model to make the predictions that comprise the performance validity test without further modifications to the internal settings of the involved tool. The model's results should be compared with the data (or conditions) that are inferred from facts and independent of the data that was used to create the model; this is at the heart of what the American Society for Testing and Materials (ASTM) standard defines as “validation” [38].

This assessment may be performed [38], with four main elements as follows:

(1) The “raw” data

Some measurements of the consistency between model performance and the performance included in the current task requirements must eventually be calculated to inform a judgment on the validity of the model. Basically, the order of the observed (system) output responses, the outputs of the model, and the deviations between these two sequences can be regarded as the raw “data” available for administration in the validation process.

(2) Summarize the “attributes” of the raw data.

It can be very useful to calculate the “attributes” of these raw data. As a result, the attributes of their data content can be succinctly expressed, with a degree of impartiality against the false influence of random mistakes and situations recorded in the raw data. Such “attributes” incorporates the moments of probability distributions (e.g., means), statistical distribution functions, and the set of coefficients that appear in the correlation functions and the regression correlations. Statistically, calculating these “attributes” from the raw data is called an approximation or estimation.

(3) The “decision”

Both the raw data and the summarising attributes are concerning information for the fundamental “decision”: to determine whether the model is reliable and accurate prediction tool or not (under conditions which are normally to be expected to not be the same as the past circumstances). Nonetheless, the calculation of summarising properties does not disclaim the primary raw data congruity, even if it is subjective to decision-making. When many of the summarising properties are objectively calculated, this is often the event, the common use of notifying “decision” almost inevitably involves a personal balancing of the relative emphasis of each component. However, various summarising attributes may be comprehended companionably to inform in. Furthermore, as with all decisions, it is best to look at as much relevant information as possible based on the decision rules or the viewpoint of a particular decision maker.

(4) The “statistical” decisions

Many course selections require the use of rules outlining our preferences, taking into account the probability of incurred circumstance and the costs (benefits) associated with the chosen course amalgamation of action and the event outcomes (random events). Binary is the method of the process of the choice validation. It determines whether the model is reliable and a valid prediction tool. In addition, the outcome of random events is also binary, in which case the model may prove. It can be “true” or “false” reality, with consequences (in monetary) different for each possible combination of the course of action and the outcome of the event. In terms of these consequences, consistent, or automatic, rules that define the intended process that are considered the most popular can be used. This is not necessarily because analysts can process information relevant to subjective decisions to choose intended process without having to explicitly declare any rules. However, the key forms of more separate decision-making criteria are those that are guided by some “statistical” calculations (such as chi-squared test, Student’s t-distribution, Kolmogorov-Smirnov test, etc.) and these are the familiar rules used in statistical hypothesis test. The rules are encapsulated to such a degree that some statistic values calculated from raw data differ from reference values with a risk component (from wrong decisions), which is included in the allowable tolerance range for agreeable deviations. Practically, it tends to be compatible with the null hypothesis of “there was no significant difference between the model and the observations” and create an error in case the model is not rejected.

In the event that additional relevant datasets are obtainable, additional model performance testing may be performed. If all evidence from such assessments has been collected, then all assessments of the model’s reliability, both composition and execution, and all tests will be done. By way of explanation, the model’s reliability is resolved because it is a predictive tool. However, it does not include current task requirements. The reliability for the current task can be measured only to the extent that we believe the approximate characteristics of the present assignment, the characteristics found in the previous events, including this prospect (or expectation) may be proved to be surprisingly false in this case. There does not seem to be any formality: a method of modifying any quantitative computation of component validity and efficiency by the “degree of similarity” is expected between present and previous assignment requirements. However, there may be expert qualitative opinions (or a peer group) about it and there is no doubt that similar subjective approach is required for linking the quantitative results of all objective tests of the model conformity or the model reliability into a single index validation process. If one such index could quantify, it would be impossible to say that the valid model should score quite high on this index.

2.8 Uncertainty Analysis in Exposure Assessment

Other designs of analysis that could be considered part of the model development process are also validated for validation purposes [38].

It is irrational to expect uncertainty not to be tied to the generated model and forecasts. The analysis of such uncertainty has two aspects which are the reflection of the intrinsic and extrinsic parameters and the efficiency of the model, respectively. They can be characterized as follows [11]:

(1) Description of the range (or distributions) of the values that can be appointed to model parameters, which may be evaluated between them subject to model calibration as performance of the sources of the specified uncertainties relating to the data applied in this test.

(2) Range evaluations (or distributions) of datasets that are relevant to the model output variable predictions as a function, representing the ambiguity in the model's parameters.

The assessment can be used to establish the validity of the model's components in respect to the individual parameters in the model. Such measurements will illuminate the cumulative success (or failure) in the model's predictions in regard to any dataset applied in the development process. Its renditions can be applied to expand and certify professional recommendations in peer group model reviews. The latter, item allows alternative testing of the validity of the previous model's performance. The model's reliability can be simply comprehended as "inverse" based on the uncertainty of the forecasts. Analysts may carry out tests under the new terms of the present task requirements, providing simulations for those circumstances that may arise in a contaminant discharge, including quantitative measurements of the subjective probability that a specific circumstance will occur. Sensitivity analysis is the easier subsection of uncertainty analysis which can be defined as the level to which model results are affected by variations in the chosen input parameters.

There is probability that the incorrect datasets applied to the model parameter may be accepted. However, the error magnitude is not examined in the sensitivity analysis. It is usually assumed to be at the standard 1% or 10%, i.e., the closest evaluated results of the provided parameter or it may test the performance of the model at the mean, minimum and maximum values of the parameters. Model sensitivity analysis does not directly identify the model performance. Nonetheless, it is a predictive model. Significant differences as a result of small changes in the parameters suggests the model reliability may be suspect, in particular in case the "incorrect" parameters are completely new to the model or learnt from prior experience, which is quite challenging to be correctly assessed. Similarly, the model's reliability may also be questioned given that it only has a few parameters that match the task definitions. However, they are not commonly used (as in the previous discussion on the concept of relevance).

There are three sources deriving the errors in the model predictions as follows [11]:

(1) The approximated initial state of the system at the beginning of the forecasting;
(2) The presumed patterns of future changes in the system's input disruptions (generally, such as contaminant discharge rate or precipitation);
(3) A model in which the action of the inputs is transmitted through the evolution of the system output response (commonly, the concentration results of the contaminants that occur at the receiving end in some parts of the environment)

Where further uncertainty analysis is carried out, sufficient knowledge is provided to quantify the source of these uncertainties. There are various methods used for such analysis such as [11]: i) a first order error analysis (also known as a difference analysis or minor disturbance analysis), ii) Monte Carlo simulations which may have a more reliable sampling strategy and iii) a response surface analysis method which should also be applied to construct among components of the mentioned uncertainty sources, in which most contribute to the predictive ambiguity of the model. For instance, condemning a model as "invalid" would be inappropriate for forecasts with too many undetermined factors. However, the root cause of this ambiguity is due to insufficient data of input disruptions.

Undetermined factors in the model may be caused by ambiguity related to the model parameters. In addition, assessment of the uncertainty in the earlier stage may be identified in other research or documentation [11]. Typically, the upper and lower bounds of the possible values ("realistic") of the model compositions are present and may be applied to determine unknown factors in the respective parameters. However, it is relatively less straightforward. Quantifying the model uncertainty may be achieved by using an advanced model calibration scheme, although this is rarely practiced. This can be said that hypothetical relationships of uncertainty can be expressed arithmetically.

Planning for uncertainty is important for exposure assessment analysis of magnitude and exposure scenarios [11]. The aims of the uncertainty analysis encompass whole and individual characterisation and quantification of each step of exposure that would lead to accurate prediction of uncertainties. In order to evaluate ambiguity, analysts would normally conduct quantitatively assessment on the main sources of uncertainties using a tiered approach.

A tiered approach is a process pertaining a systematic assessment that proceed from a rather less complex to higher complicated exposure [11]. The main strength of this approach is that uncertainties within an exposure assessment could be adjusted in successive iterations. The tiered approach contains three tiers – Tier 1, 2 and 3. Tier 1 is the simplest screening-level analysis which adopts conservative and/or default exposure assumptions. The purpose of Tier 1 is estimate risk and analyse the sensitivity [40]. The more intermediate analysis is Tier 2 which involves more realistic exposure assumptions and higher level of complicated quantitative or qualitative uncertainty analysis. It is characterised by performing a one-dimensional Monte Carlo analysis at the same time with probabilistic sensitivity analysis. Tier 3 is the most advanced and integrates full quantitative assessment of variability and uncertainty such as more advanced one- or two-dimensional Monte Carlo analysis methods, micro-environmental exposure simulation or Bayesian methodologies. Moreover, Tiers 2 and 3 encompasses site- or population-specific inputs for assessment of exposure and uncertainty.

2.9 Variability and Uncertainty Method Analysis

Variability refers to the inherent heterogeneity or diversity of data in an assessment. Uncertainty refers to the lack of data or the complexity of the data in an assessment. Uncertainty can be either quantitative or qualitative. Monte Carlo simulation is one of the most commonly used numerical simulation methods for quantifying variability and/or uncertainty [11]. This method depends on the pseudo-random numbers formulated for each parameter of probabilistic model. Moreover, pseudo-random numbers are independent from realisations and samples from a uniform distribution, should not be serial correlation nor involved in series or periodicity of the simulated numbers. An effective number generator should be capable of produce millions of numbers before the next cycle starts and the number sequences should be random. Moreover, it should be able to reproduce the same sequence by determining similar seed values for the pseudo-random number each time. This allows for the reproducibility of the same Monte Carlo simulation at any period or the comparison of datasets between two options or risk assessment.

Monte Carlo simulation uses various alternatives to formulate random datasets from the probability distribution of each model parameter from a pseudo-random number generator. The inverse cumulative distribution function (CDF) method is the simplest alternative in terms of concept as each pseudo-random number signifies a CDF percentile of the model input. Analysts would determine fractal (the corresponding numerical value of the model input) and include the fractal into the model for one round of analysis. Subsequently, one random value is determined in a similar manner for all probabilistic inputs to the model for each model iteration. For instance, one random sample will be drawn from ten input with probability distributions to make predicted outcome of the model. Analysts then reiterates the step multiple times to generate estimates, which are used to elaborate an empirical CDF of the model outcome. Any statistic of interest can be calculated using the empirical CDF including particular fractal, the mean, the variance. Although the inverse CDF method is applied by Monte Carlo simulation software to create samples from model inputs, the details of how random numbers are generated are usually contained within the chosen Monte Carlo simulation software and, are not normally, selected by the user.

Utilisation of frequentist statistical methods to estimate confidence intervals is possible because Monte Carlo simulation is subject to random sampling technique. The methods simulate mean of a model output based on sample variance and size. Therefore, it is common to determine criteria for suitable sample amount to represent the frequentist methods. For example, if the mean of the precise model output is estimated, the Monte Carlo simulation can repeatedly construct numbers until the convergence is achieved with the target precision. Alternatively, analysts may conduct an initial run of an arbitrary sample size and statistical assessment of the outcome given sufficient runs. If not, additional runs with data from the first set of runs are combined to produce a large sample size in order to allow the model to obtain the intended degree of precision.

The Monte Carlo simulation is not without a disadvantage as the emphasis could easily be given to obtain high level of accuracy for numerical simulation regardless of the quality of input data. For instance, if there are key data quality limitations on model input assumptions, it would not be most logical to perform millions of iterations to obtain accurate numerical estimate of the model outcome. Therefore, analysts should decide whether it is effective to exert their time and effort to ensure precision for the 99.9th percentile model while a high degree of confidence of the shape and parameters of the model input distributions are unclear.

2.10 Data and Resource Requirements

Various factors have to be considered when assessing human exposure and producing models. We have outlined five relationships between human exposure and environmental emissions necessary to obtain data on structure and numerical values.

(1) The magnitude of the source medium concentration, which is the extent which contaminant is being emitted to indoor and outdoor air, or the estimated emission level of contamination in the environment.
(2) The contaminant concentration ratio, which takes into account transformation of source of medium concentration as it moves through environmental media before being exposed to human.
(3) The level of human exposure, which elaborates potential contaminated exposure as well as the frequency (days per year, minutes per day, etc.) and magnitude (cubic metres of inhaling air per hour).
(4) The duration of potential contact, which describes the duration in a person's life that is exposed to contaminants.
(5) The average duration for the type of impact on health under consideration, which takes into account average duration for the cumulative time under exposure i.e., whether it be a human lifetime span or a shorter time span.

These factors determine products or outcome required for a distribution of population or individual exposure. Moreover, the accuracy and quantity of these five factors and associated data determine the reliability of population exposure estimates.

2.11 Use of Uncertainty Analysis in Evaluation and Validation

In exposure assessments approaches, uncertainties are the deviations between the predicted exposure and actual exposure levels [32]. The level of uncertainty depends on the accuracy and reliability of the exposure model. Accuracy in exposure assessment is how close the estimates produced by the model are to the measured data. Reliability is the measurement of consistency or the ability to repeatedly reach the same conclusions after multiple assessments.

To test the reliability of an approach, a validation process is performed. A useful form of validation encompasses the comparison of the assessment outcomes with independent data or information (e.g., comparison of estimated exposure with biomarker measurements or epidemiological studies). However, it is important to note that both items subject to comparison also contain uncertainty and therefore methods elaborated in this study should be applied to independent data to provide an objective comparison.

All aspects of uncertainty analysis should be documented to ensure transparency of the exposure assessment. These aspects include details that would allow for independent replication of results as well as qualitative and quantitative descriptions of data, scenarios, methods, inputs, models, outputs, sensitivity analysis and interpretation of results.

2.12 Discussion and Conclusions

The ART model is a widely used knowledge-based exposure model that produces qualitative exposure estimates. However, fumes are not included in the calibration of the ART and were not assessed in the conceptual evaluation that the model is based upon. It is clear that without a detailed evaluation of the suitability of the ART it should not be used for welding fume exposure assessment. Moreover, there are no generic models to assess exposure to welding fumes. This review has shown that the source-receptor conception and the ART model provides a sound basis for this type of model, but it will require adaption to make it suitable to assess exposure to welding fume.

Identifying the magnitude of the emission from a welding source is a critical step required to formulate a practical welding fume model. The review of the welding fume emission mechanisms has identified that welding process type, input power level, shielding gas, and welding electrodes affect fume formation rates and should ideally be incorporated in a weldART model. However, occupational hygienists have in the past not recognized the importance of collecting contextual data about these factors and so the availability of measurement data that could be used to calibrate a weldART model is limited. In most cases from the list of source factors above it is only welding process type that is consistently collected. Therefore, although it might be advantageous to include source factors such as welding current or voltage it may in practice be impractical.

Additionally, the potential interaction of the welder with the fume plume and local control measures needs to investigate to determine the numeric multiplier to be applied. Welding fume is highly localized in a strong convective airflow and the positioning of the welder's head in relation to the plume could importantly influence their exposure. Similarly, the location and effectiveness of a local and general ventilation are likely to be key factors in a weldART model. The existing ART has not considered the specific geometry of the emissions from welding and this needs to be included in any new model. The scientific literature, for example, work by Fransman *et al*. [41], Tielemans *et al*. [42], Marquart *et al*. [43] and Van Hemmen *et al.* [44] provides some guidance to derive the magnitude of model modifying factors, but it may also be necessary to rely on expert judgement and/or a trial-and-error method for some specific parameter values. For example, Semple *et al.* [45] studied the use of the aggregate assessments from multiple assessors to improve the quality of the exposure assessment when limited information exists. They assigned values on a logarithmic scale to the model parameters depending on the assessor's judgment, because of the limited scientific data available.

The ART model is based on a modified multiplicative conceptualization that are mainly based on derived categories that were selected by using an exposure taxonomy. The intrinsic emission is a unit of concentration for the substance emission potential that represents the concentration generated in a standardized task without local ventilation. Further information or scientific justification for this selection is not clearly provide by the ART developers. The multipliers have mainly discrete values given in natural logarithm steps that were allocated by expert judgement. The scientific reasoning or linkage to physical quantities is not reported. The models calculate a subjective exposure score, which is then translated to an exposure level (mg/m^3) by using a calibration factor. The calibration factor is assigned by comparing the measured personal exposure levels with the exposure score that is calculated for the respective exposure scenarios.

Box models provide a clearer conceptual framework on which to develop a more realistic physical-based system. However, in most situations the details necessary to parameterize the model are unavailable, e.g., the magnitude of air flow between model compartments. However, it is possible that some approach to exposure modelling, incorporating elements of multiplicative model structure and box modelling could be applied. For example, using the box model approach to account for dispersion within the workroom and the multiplicative structure to account for factors such as the effectiveness of local ventilation. From the scientific literature about welding fume emission, as described earlier, the amount of fume exposure depends on the distance between the welders' head, the source of the fume plume and the control measures implemented. If the box model concept is applied in the weldART model then the fume plume movement and dispersion are the key variables that may affect the time of emission, emission rate and ventilation rate. Therefore, these parameters should be assigned into the weldART model.

Due to the lack of welding environment data, it is important to consider the uncertainty of any model estimates and so the use of Monte Carlo techniques could be used to generate parameter distributions such as for air velocity, room volumes, time of emission, emission rate and ventilation rate where these are not accurately known. In addition, some exposure modifying factors i.e., the positioning of the welder’s head and the localised control could be replaced with multipliers. The multiplier for localised control could adopt similar values to that of the ART model. The details of adapting the model to account for parameter uncertainty are described further in the validation process (Chapter 6).

CHAPTER 3
THE WELDART

3.1 Introduction

A mathematical model could reliably predict welding fume exposure, but currently a validated and widely accepted model is yet to be developed. A few models, developed by the European Centre for Ecotoxicology and Toxicology of Chemicals' Targeted Risk Assessment (ECETOC TRA), and the Stoffenmanager® and Advanced REACH Tool (ART), are used to assess airborne chemical contaminant exposure for regulatory purposes. Nonetheless, these models are not specifically designed for evaluation of welding fume [56].

Exposure to mixed contaminants of welding fume is an occupational hazard. Assessing welding fume could be accomplished by using methods such as the multivariate probability distribution to produce an exposure model [7]. The Near-Field/Far-Field model (also known as the two-zone model) is a type of multivariate probability distribution applied in the exposure assessment of airborne contaminants including welding fumes [57]–[59]. The model divides the room into the near-field (NF), which is the area around the welders, and the far-field (FF), which is the remaining room area. The model shows the compatibility in describing contaminant being transmitted and dissipated in indoor area. This model is also the basis of the Advanced REACH Tool (ART), which is multiplicatively optimised by modifying factors (MFs) to improve the model accuracy [60]–[62]. Although the ART model has been used to estimate hazardous chemical exposure, it was not originally designed to estimate fume concentration. However, the further modification through key MFs including type of welding process, electrical input power, shield gas composition and welding electrode type could be added to estimate welding fume concentration [63]. Furthermore, an additional spatial component, the welding fume plume (WP), could be added to the model framework [64]. Additional compartments could also be added to the model structure to reflect greater complexity in the workplace being modelled, e.g., for larger or more complex geometries.

The objectives of this chapter are to describe a multi-compartment mass-balance model as the basis for a deterministic model for prediction of welding fume exposure (The Welding Advanced REACH Tool or weldART). The model described is a hybrid of a multiplicative and box modelling approach.

3.2 Model Development

An exposure assessment according to weldART is a process that estimates or quantify the magnitude, frequency, exposure duration and characteristics of exposure. The process is based on three components, namely scenario, model and parameter. An exposure scenario is applied as a basis for an algorithm or a arithmetical model [65].

During the weldART development, it was necessary to review some of the ART MFs namely emission potential of the activity, localized controls and dissipation to allow the developed model to be applicable to exposure scenarios from a welding process [66]. The ART model could be further improved by MFs based on other models. For instance, the multivariate Johnson system of probability distributions model that adopts the normal and lognormal distributions, indicated high degree of correlation between manganese and total welding fume exposure [7]. This model also showed that the welding fume production rates were proportional to the process arc time, and welding process. Furthermore, the impact of fume formation and generation rates have been shown to be factors that affect the reliability of the model [7]. However, there are still other parameters that cannot be objectively quantified (e.g., type of current, electrodes circumference, enclosure type, electrode pitch, type of weld) and therefore cannot be applied in the mechanistic model [60]. Nevertheless, all of these parameters could be considered as MFs to enhance the accuracy of the model.

The generation rates of welding fume (fume formation rate or FFR) have been extensively studied and it has been found that there was a strong correlation between total fume concentration and input electrical power [61], [71]. This concept was demonstrated in studies of stainless steel welding using flux-cored arc welding or shielded metal arc welding with CO_2 or inert gas shielding that produced chromium and hexavalent chromium [25], [67]–[70].

Models have been developed to forecast fume production rates during welding. However, these models generally do not investigate all factors at the same time. For example, Dennis *et al*. [72] developed a model which used electrical current, wire velocity and droplet transmission frequency as variables. The model is applicable to optimal and high current modes. Nonetheless it has limitations in a low current mode and it is relatively unresponsive to droplet transmission frequency and subject to the current to wire velocity ratio. Moreover, it was found that shield gas element and oxygen level in the shield gas and ambient environment could influence the fume production rates. In particular, the type of gas in the shielding gas affects the fume concentration. For instance, helium and helium mixture produced FFR higher than argon based mixtures and active gas CO_2 increased the FFR [13], [22], [73]. The model developed by Liu *et al.* [74] was based on multivariable linear regression models and linear mixed models to estimate the total amount of released particulate matter and manganese. The linear mixed models accounted for fixed effects such as specific characteristics of each country where the data were obtained, industry and trade category, attributes of welding process and the sampling criteria. The model showed that key factors such as sampling area, ventilation type, consumables of welding and welding process type had the most impact on welding fume exposure. The model also suggested that controlling fixed effects, specific components in different workplaces and individual workers in a workplace decreased the total particulate and manganese concentrations.

Lines of evidence indicated that input power level, type of welding process, shield gas, and welding consumable have material effects on fume formation and generation rates. Therefore, these parameters should ideally be included as principle MFs when developing the source-receptor predictive exposure model ART in modelling fume behaviour, although as noted earlier in practice occupation exposure measurements seldom document such details and so there may be practical limitations on how these parameters could be included in a model.

MFs related to fume composition and production rates (i.e., type of welding process, input electrical power, shielding gas, and welding consumables), the airflow circulation causes the dissipation of fumes from the source and the welder's exposure with the fume plume. Therefore, the ART model for welding fume should consider whether these could also be incorporated as modifying factors.

Welding Process

Type of welding process is a main determinant of FFR. In addition, different processes may produce FFR that vary by as much as two orders of magnitude. A comparative study has found that FCAW had higher FFR than GMAW (750-2,502 mg/min vs 36-372 mg/min) [17]. The manganese concentrations were also different for GMAW (0.45x), GTAW (1.20x) and FCAW (1.24x) relative to SMAW [41]. Besides being different processes, factors within the process including electrical current, type of electrode and shielding gas formation also affect FFR. Overall, higher electrical current resulted in higher FFR, although it could also be mitigated by using a different shielding gas such as argon [22], [72].

Current and Voltage

Welding fume generation is affected by the electrical current and voltage applied in welding processes for FCAW [71] and GMAW [75], [76]. It is because higher current increases fume rates. Moreover, the amount of flux stimulates fume rates for a specified current [30]. This is because current and voltage have a direct correlation with temperature of the electrode tip, heat transmission to the electrode and type of electrical current, i.e., alternating current (AC) and direct current (DC). Elevated temperature at the electrode tip produces higher FFR due to the higher evaporation rate and melting rate of the electrode, enabling easier transmission of electrode material through the arc [13]. The metal transfer mode in GMAW can be classified into five types - short-circuit transfer (most common mode), globular transfer, spray transfer, pulse-spray transfer, and rotating transfer [77], [78]. Each mode has a specific metal transfer capability and has different electrical current and voltage requirements, resulting in different FFRs [13]. Globular transfer mode at 23.5 V with pulsed current and 26.5 V with steady current produced the highest FFR [26], [79]. Lowering the voltage from 23.5 V to 16 V significantly decreased the particle mass concentration in welding fume [80]. Similarly, decreasing the voltage from 25 V to 17 V in the short-circuit transfer mode in GMAW decrease the FFR five times [78].

The welding current can be divided into three categories - alternating current (AC), direct current electrode positive (DCEP) and direct current electrode negative (DCEN). These different types of current configuration contribute to the variation in FFRs. For instance, in the SMAW process, the difference between DCEP and DCEN is as much as 30% in FFR [13]. In GMAW, AC emitted the similar level of fume as DCEN. The different current types result in different electrode tip temperature, and therefore differences in FFRs.

Elevated current and input power (i.e., current x voltage) in FCAW would result in higher fume production rate with an exponent of 1.75 and 1.19 respectively (equations 3.1 and 3.2 below) [71].

$$\text{FFR} = 6.2\text{E} - 2(\text{Current}^{1.75}), r^2 = 0.86 \quad (3.1)$$

$$\text{FFR} = 7.1\text{E} - 1(\text{Input Power}^{1.19}), r^2 = 0.86 \quad (3.2)$$

Overall, an increase in the electrical current requires higher voltage [13]. For example, a 1-5% increase in voltage can result in up to 20% increase in the FFR [22].

In SMAW, when the current rose from 90 A to 120 A, value of FFR can be described by the following equations [81]:

$$\text{FFR}_{\text{DC}} = (0.0218 \cdot \text{Current})^{1.94} \quad (3.3)$$

$$\text{FFR}_{\text{AC}} = (0.0128 \cdot \text{Current})^{1.94} \quad (3.4)$$

In equations (3.3-3.4), the units of FFR for direct current (FFR_{DC}) and the FFR of the alternating current (FFR_{AC}) is mg/min, and the unit of electrical current is ampere (A).

In GMAW under equal electrical current, as wire diameter gets smaller, FFR will increase, as elaborated in the following equations [81]:

$$\text{FFR}_{0.8\text{ mm}} = 0.019\text{e}^{0.0102(\text{Current})} \quad (3.5)$$

$$\text{FFR}_{1.0\text{ mm}} = 0.0268\text{e}^{0.0057(\text{Current})} \quad (3.6)$$

$$\text{FFR}_{1.6\text{ mm}} = 0.0164\text{e}^{0.0051(\text{Current})} \quad (3.7)$$

Based on previous studies, we conclude that i) the type of current influences FFR, ii) increase current leads to elevated FFR and iii) adjustment of current requires respective change in voltage and the two factors are dependent. Therefore, current should be considered as the main MF for modelling welding fume exposure.

Electrode Type

The electrode or the welding rod, considered as the “consumable”, is the main source of welding fume in arc welding [82], [83]. Normally, the electrode used is of similar composition to the base material and the fume is usually generated from inner flux and tubular wire [84]. Mild steel is the most common metal for electrodes and some steels contain additional metals such as Cr and Ni. High-manganese hardfacing electrodes, for instance, contains 14% Mn and high-chromium hardfacing electrodes contain Cr up to 30% [85].

Shielding Gas

Shielding gas and its composition directly influences the generation of fume and FFR [75], [76]. It is found that as O_2 and CO_2 increases inside the shielding gas, FFR also increases [22], [79]. For instance, increasing CO_2 from 2% to 25% in an Ar shielding gas increased the maximum FFR by two fold [18], [85]. In GMAW, the effect of shielding with CO_2 has a greater effect on FFR than O_2, in particular, with O_2 below or equal to 2% [75], [79]. However, using more than 2% O_2 is often not practiced because it has an adverse impact on the welded joint [86]. FFR rose from 162 to 270 mg/min when Ar+5% CO_2+2% O_2 was changed to Ar+20% CO_2+2% O_2 shielding gas. However, some shielding gases, such as He-based mixtures, was not significantly affected by the addition of O_2 and CO_2 [75]. Moreover, the shielding gas also interplays with current and voltage in GMAW [22]. In an Ar+5% O_2 versus CO_2 shielding gas, FFR for CO_2 increased continuously with both current and voltage while FFR declined to minimum level and then rose again, separately for both increasing voltage and current for O_2. Based on these studies, we conclude that as the current and CO_2 concentration in the shielding gas increase, FFR will also increase.

Overall Assessment

Overall, it is judged that the primary determinant of fume emission is the welding process. Other factors such as current and voltage or shield gas are often associated with the process and for many practical welding situations these specific welding parameters are either defined by the process or are generally within a narrower range than has been explored in the experimental studies. Therefore, for practical model development it has been concluded that welding process should be the main determinant of fume emission. In a multiplicative conception the MF could be assigned based on the typical FFR associated with the process or in a box-model conception the FFR data could be used directly. However, occupational hygienists should collect more comprehensive data on factors such as welding current/voltage and shield gas composition when measuring welding fume exposure so that in the future these parameters can be incorporated into modelling initiatives.

3.3 Adapting the ART for Welding Fumes

The proposed conceptual model for welding fume comprises three scenarios that account for the welder's exposure to the welding fume plume (WP). The first scenario illustrates the possibilities of fellow worker being exposed to fume in the FF (Figure 5). The second diagram illustrates the chance of fume exposure to a welder in the NF (Figure 6). And the third illustrates the chance of fume exposure to a welder in case NF and the fume plume (WP) are situated in the same area (Figure 7).

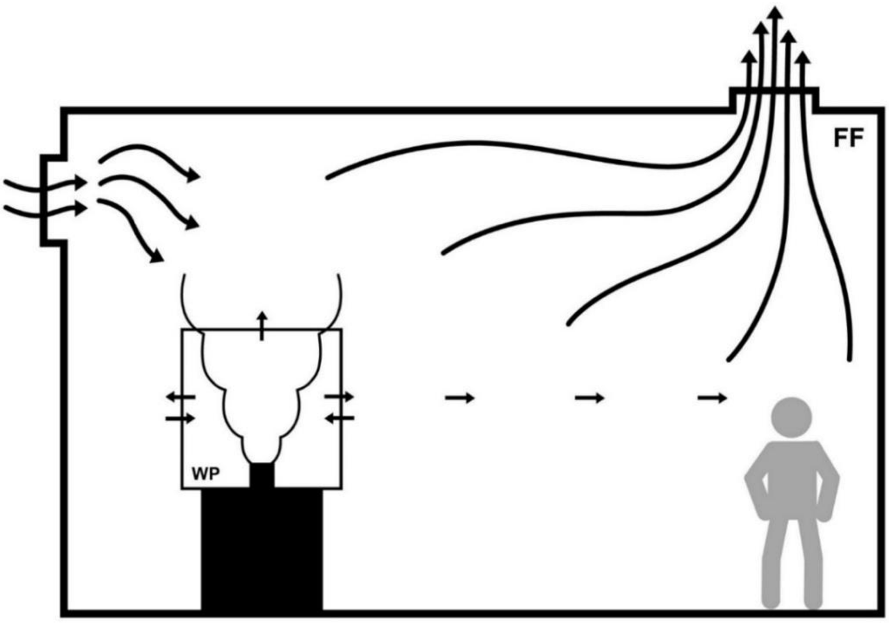

Figure 5 A schematic representation of the first scenario where a colleague is exposed to fume in the FF.

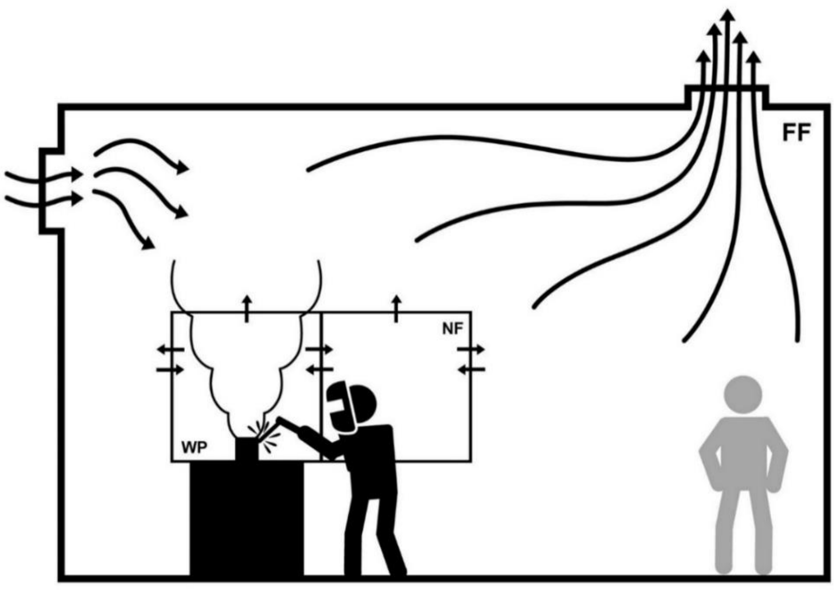

Figure 6 A schematic representation of the second scenario where a welder is exposed to fume in the NF.

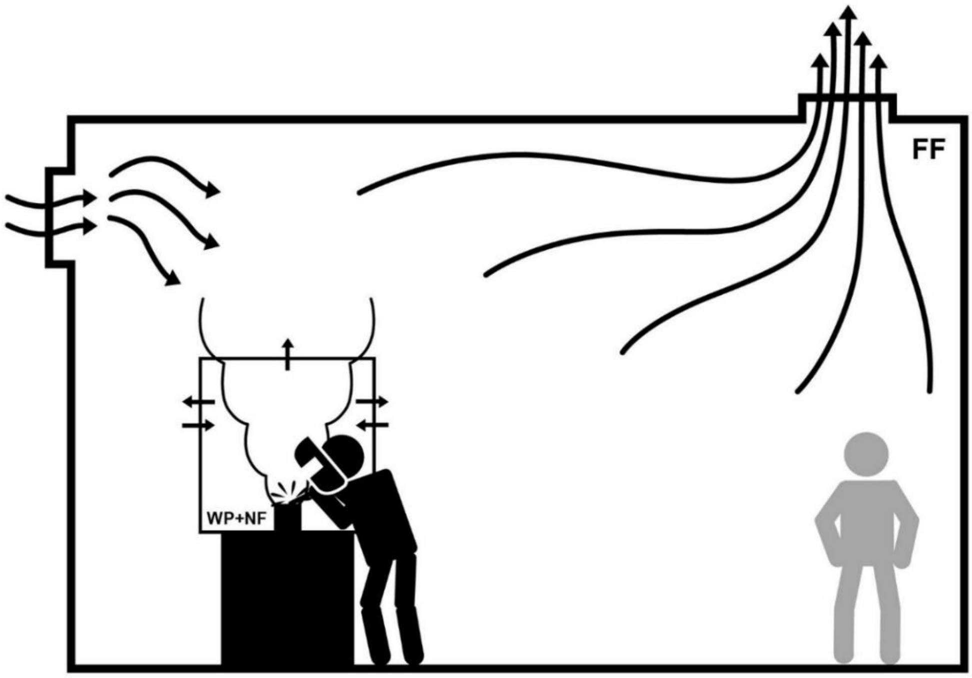

Figure 7 A schematic representation of the third scenario where a welder is exposed to fume when NF and WP are situated in the same area.

It is possible to construct these scenarios in a multi-compartment mass-balance model of the welding process, as elaborated in the study of Sailabaht *et al.* [63]. The model described three spatial compartments – NF, FF and WP as shown in the weldART model (Figure 8). The WP contains the welding fume emission source (E_{WP}). The breathing zone of the individual whose exposure is to be estimated is either the WP or NF compartment, depending on their head location (defined by the MicroPEM monitoring data and/or video record as described in Chapter 4). During single welding tasks, however, most welders work some time in both the WP and the NF, and the personal exposure concentrations (C_{exp}) can be calculated as a time-weighted average concentration between those two compartments. The FF represents the remainder of the room. β coefficients (m^3/s) symbolizes airflow between compartments. The weldART model consists of three simultaneous differential equations as follows:

$$\frac{dC_{NF}}{dt} \cdot V_{NF} = \left(C_{WP} \cdot \beta_1\right) + \left(C_{FF} \cdot \beta_3'\right) - \left(C_{NF} \cdot \beta_1'\right) - \left(C_{NF} \cdot \beta_3\right) \quad (3.8)$$

$$\frac{dC_{FF}}{dt} \cdot V_{FF} = \left(C_{WP} \cdot \beta_2\right) + \left(C_{NF} \cdot \beta_3\right) - \left(C_{FF} \cdot \beta_2'\right) - \left(C_{FF} \cdot \beta_3'\right) - \left(C_{FF} \cdot Q_{FF}\right) \quad (3.9)$$

$$\frac{dC_{WP}}{dt} \cdot V_{WP} = E_{WP} + \left(C_{NF} \cdot \beta_1'\right) - \left(C_{WP} \cdot \beta_1\right) + \left(C_{FF} \cdot \beta_2'\right) - \left(C_{WP} \cdot \beta_2\right) \quad (3.10)$$

Where;

C_{WP}, C_{NF} and C_{FF} are the fume concentration in the WP, NF and FF, respectively (mg/m^3)

E_{WP} is a fume emission rate in the WP (mg/s)

V_{WP}, V_{NF} and V_{FF} are compartment volume in the WP, NF and FF, respectively (m^3)

β_x and β'_x are the airflow between compartments (m^3/s)

Q'_{FF} and Q_{FF} are volume airflow flowing in and out of the FF, respectively (m^3/s)

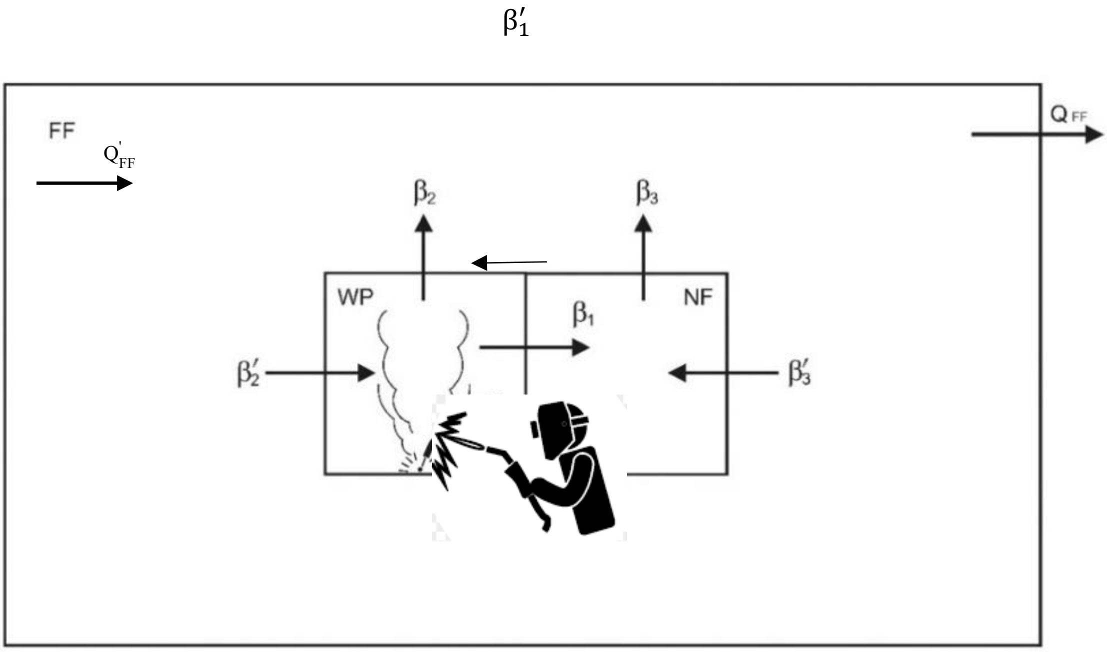

Figure 8 A conceptual diagram of the weldART model with three compartments when evaluate the fume concentration of welder who work in the NF that related with the equation $\frac{dC_{NF}}{dt} \cdot V_{NF} = (C_{WP} \cdot \beta_1) + (C_{FF} \cdot \beta'_3) - (C_{NF} \cdot \beta'_1) - (C_{NF} \cdot \beta_3)$

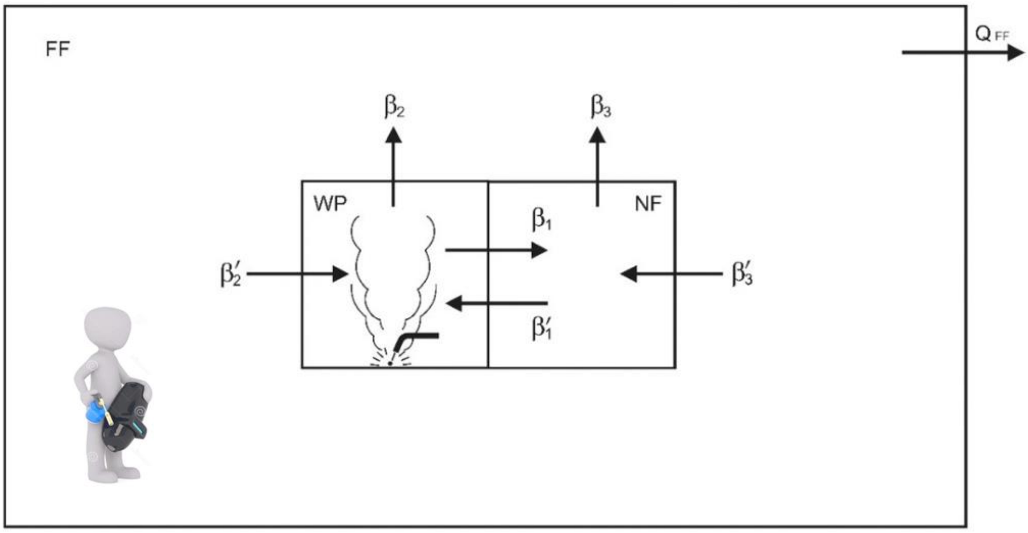

Figure 9 A conceptual diagram of the weldART model with three compartments when evaluate the fume concentration of the welder's colleague who work in the FF that related with the equation $\frac{dC_{FF}}{dt} \cdot V_{FF} = (C_{WP} \cdot \beta_2) + (C_{NF} \cdot \beta_3) - (C_{FF} \cdot \beta_2') - (C_{FF} \cdot \beta_3') - (C_{FF} \cdot Q_{FF})$

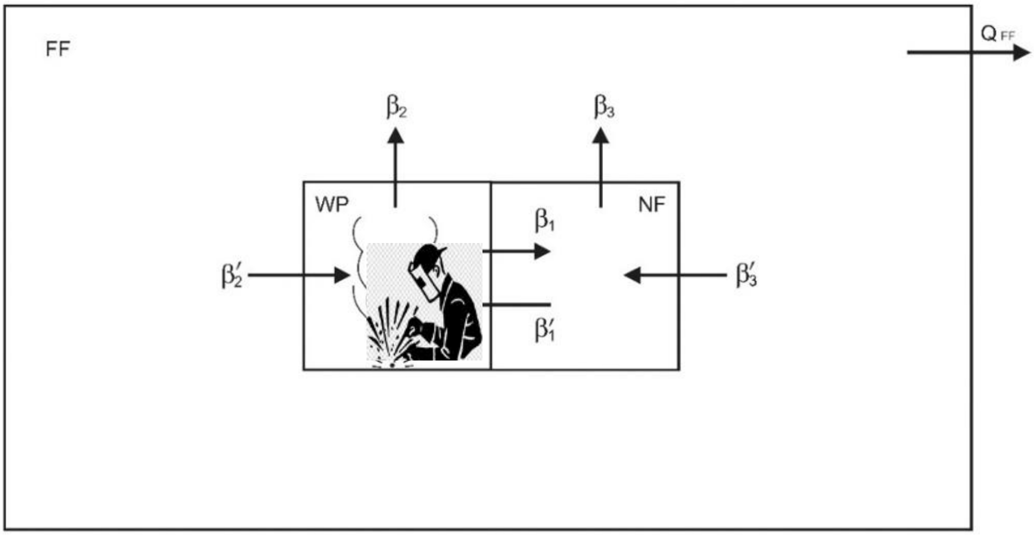

Figure 10 A conceptual diagram of the weldART model with three compartments when evaluate the fume concentration of the welder who work in the WP that related with the equation $\frac{dC_{WP}}{dt} \cdot V_{WP} = E_{WP} + (C_{NF} \cdot \beta_1') - (C_{WP} \cdot \beta_1) + (C_{FF} \cdot \beta_2') - (C_{WP} \cdot \beta_2)$

Often, a building with welding work is a large open-air building, sometimes the room size of the workspace is more than 3,000 m^3. In such situations the very large space is poorly modelled by a single FF compartment because it is assumed the released fume quickly mixing into the FF, i.e., the assumption of instantaneous mixing throughout the space. In case of the very large workspaces, therefore, the model was modified to consist of four compartments with the FF as intermediate zone and an additional residual room zone (RM) (Figure 11). The NF in this scenario is the same definition in the three compartments scenario that is distance from the welding source around 0.3 to 1 metre. Meanwhile, the FF is the area between NF and RM, with a distance of approximately 3 meters from NF. Preliminary exploration of this modelling structure showed that the introduction of two zones representing the FF and RM made little effect on the WP and NF concentrations but provide a more realistic simulation of measures FF concentration.

These changes led to a fourth differential equation as follows:

$$\frac{dC_{RM}}{dt} \cdot V_{RM} = \left(C_{FF} \cdot Q_{FF}\right) - \left(C_{RM} \cdot Q_{FF}^{'}\right) - \left(C_{RM} \cdot Q_{RM}\right) \tag{3.11}$$

Where;

C_{RM} is the air concentration in the RM (mg/m^3)

V_{RM} is compartment volume in the RM (m^3)

Q'_{RM} and Q_{RM} are volume airflow flowing in and out of the RM, respectively (m^3/s)

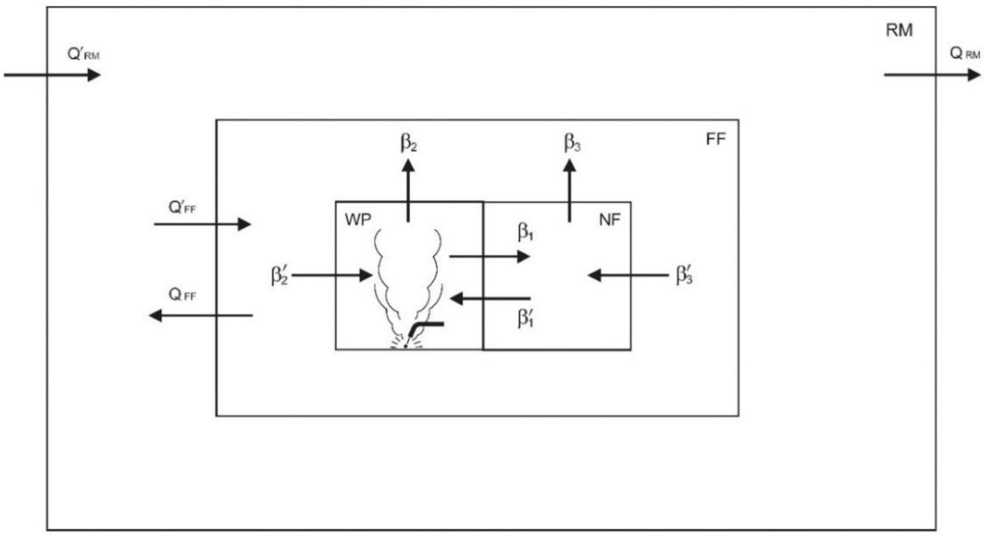

Figure 11 A conceptual diagram of the weldART model with four compartments.

3.4 weldART Exposure Model

The weldART model assumes one source of WP but this can be altered to incorporate additional sources in other subdivisions. The simulation is based on assumption that the fume concentration starts at zero and that air within individual compartments would immediately mix at each successive time iteration of the model. The weldART model parameters are shown in Table 5 and an R script was used to solve the equations [87]. Note that this is a box-model formulation of a model and so most of the parameters are physical values, e.g., emission is in terms of mg/s rather than as a dimensionless MFs.

The initial values in Table 5 can be explained as following: the air flow behaviour also affects the estimation of the model. A study found that when a fume plume travelled vertically to a height of 1.15 m above ground level (with the volumetric flowrate of 0.045 m^3/s), the welding plume would stop flowing upward and started to spread laterally [13]. The lateral dispersion, besides dissipation out of the compartment due to room draughts, occurred at the top of the WP compartment when welding took place at the bottom of the compartment. Airflows (β) in WF and NF were estimated using the following assumptions: i) air velocity was 0.05 m/s; ii) β_2 (based on assumption that the lateral dispersion was 0.5 m x 1.15 m x 0.05 m/s) was set at 0.0738 m^3/s; iii) β'_2, the dissipation from the fume plume area, was 0.0575 m^3/s (i.e. 0.5 m x 1.15 m x 2 sides x 0.05 m/s); iv) one side of the WP and NF has airflow rate of 0.05 m/s and β'_1 was 0.0288 m^3/s (0.5 m x 1.15 m x 0.05 m/s), β_1 was found to be 0.0125 m^3/s when β_1 was evaluated to stabilize the incoming and outgoing airflow of the WP ($\beta_1 = (\beta'_1 + \beta'_2) - \beta_2$) [88], [89]. Another study by Mahyuddin *et al.* [89] assumed that β_3 was 0.03 m^3/s (i.e., 0.5 m x 0.5 m x 0.12 m/s) with the upward airflow speed above the human head being 0.12 m/s [89]. In addition, β'_3 was evaluated to balance ($\beta'_3 = (\beta'_1 + \beta_3) - \beta_1$), i.e., β'_3 was set at 0.0463 m^3/s. Airflows into and out of the FF at the rate Q (m^3/s) depended on the room size and general circulation or air change per hour (ACH). The study assumed that Q_{FF} was designated at 22 m^3/s subject to an evaluated air exchange of 2.25 ACH which was obtained by estimating the room volume equal to 35,200 m^3 and ventilation rate equal to 22 m^3/s.

Fume formation rate (FFR) relies on several factors including type of welding electrode, electrode angle, electrode diameter, base metal, electrical input power, workpiece composition, shielding gas mixture and flow rate, arc length, polarity, welding position and welding speed [76], [90]. These factors are necessary to evaluate the dispersion and transport of contaminants, yet no data were available. Therefore, it is challenging to quantify the FFR in the model. Sailabaht *et al.*' study [63] has illustrated that the material factor that affected the FFR was the welding process and assigned welding process numeric values (multipliers) for FCAW (1.0), SMAW (0.8) and GTAW (0.03). However, inputting these values resulted in unrealistic concentrations of fume and therefore FFRs were modified based on the Monte Carlo technique. R programme was used to generate values by using the function "rtri" to generate pseudo-random numbers from a symmetric triangular distribution. The syntax for function "rtri" is:

rtri <- function (n, min, max, mode)

Arguments;

n = sample size. If length (n) is larger than 1, then length (n) random values are returned. For this study, the value is n = 100,000.

min = vector of minimum values of the distribution of the random variable. The default value is min = 0.

max = vector of maximum values of the distribution of the random variable. The default value is max = 1.

mode = vector of modes of the random variable. The default value is mode = (max-min)/2.

Meanwhile, using the emission rates from the report of technical rules for hazardous substances (TRGS) (Table 3) [91] as the minimum and maximum values to identify realistic fume concentrations and calculate the average of the generated values. The optimised FFR factors for the weldART model were 2.6 (FCAW), 2.0 (SMAW), and 1.6 (GTAW), corresponding increase in emission originated from GTAW processes was observed.

Table 3 Assessment of the procedures with reference to emission rates, taking account of factors or effects specific to individual materials, assignment to hazard classes.

Procedure	**Emission Rate (mg/s)**	**Hazard Class of Procedures**		
		Substances that Place Strain on Respiratory Tract and Lungs	**Toxic or Toxic-Irritating Substances**	**Carcinogenic Substances**
Submerged arc	< 1	low	low	low
Gas welding (autogenous procedure)	< 1	low	low	-
TIG	< 1	low	medium	medium
Laser welding without filler metal	1 to 2	medium	high	high
MIG/MAG (low-energy gas-shielded welding)	1 to 4	low	medium	medium to high
Electric arc, MIG (general)	2 to 8	high	high	high
AG (solid wire), flux-cored wire welding with shield gas, laser welding with filler metal	6 to 25	high	high	high
MAG (flux-cored wire); flux-cored wire welding without shield gas	> 25	very high	very high	very high
Soldering	< 1 to 4	low	medium	medium
Autogenous flame cutting	> 25	very high	very high	very high
Electric arc spraying	> 25	very high	very high	very high

Further optimisation on the released fume quickly mixing into the FF was necessary in the large workspace. Therefore, the weldART model was modified to consist of four compartments with FF as intermediate zone and an additional residual room zone (RM) (Figure 11) because the assumption of instantaneous mixing throughout the large space. Also, the weldART model parameters are modified as shown in the column “Revised Values” in Table 4.

Table 4 The comparison of weldART model parameters between three compartments and four compartment models.

Parameters	Initial Values (Three Compartments)	Revised Values (Four Compartments)
Compartment Volume (m^3)		
V_{NF} and V_{WP} (W x L x H)	0.2875 (0.5 m x 0.5 m x 1.15 m)	0.2875 (0.5 m x 0.5 m x 1.15 m)
V_{FF} (W x L x H)	35,200 (20 m x 160 m x 11 m)	300 (10 m x 10 m x 3 m)
V_{RM} (W x L x H)	-	35,200 (20 m x 160 m x 11 m)
Fume Emission Rate in the WP (E_{WP}) (mg/s)		
FCAW	2.6	2.6
SMAW	2.0	2.0
GTAW	1.6	1.6
Airflow between Zones (m^3/s)		
β_1	0.0125	0.0125
β'_1	0.0288	0.0288
β_2	0.0738	0.0738
β'_2	0.0575	0.0575
β_3	0.0300	0.0300
β'_3	0.0463	0.0463
Volume Airflow Flowing In and Out of the FF (m^3/s)		
Q_{FF}	22	0.25
Q'_{FF}	0	0.25
Volume Airflow Flowing In and Out of the Room (m^3/s)		
Q_{RM}	-	22
Q'_{RM}	-	22

Parameters	Initial Values (Three Compartments)	Revised Values (Four Compartments)
Measured : Modelled Ratio		
Personal	1.2	1.3
NF	1.1	0.9
FF	87.3	1.0

In order to develop effective and probabilistic weldART model, variables, namely welder's head (WH) and localized control (LC) [92] were also taken into consideration. Multiplier of WH will be considered according to distance from welding fume plume. Meanwhile, multiplier of LC would adopt similar criteria of ART model. The weldART model concentrations subject to a time-weighted average of the WP and NF concentration. The adjusted model concentrations were calculated by using equation 3.12. Further details are described in Chapter 6.

$$\frac{(C_S \cdot T_S) + (C_{NF} \cdot T_{NF})}{(T_S + T_{NF})} \tag{3.12}$$

Where;

C_S = Welding source concentration (mg/m^3)

T_S = Time of welder’s head at welding source (s)

C_{NF} = NF concentration (mg/m^3)

T_{NF} = Time of welder’s head at NF (s)

3.5 Discussion

The assumptions about the values of the parameters are crucial to the ability of the model to reliably predict welding fume exposure. In this study the best parameter values were selected based on the published literature, but a rich set of contextual data may not be available in all circumstances.

It was originally intended to develop a multiplicative deterministic model with similar structure as the ART tool with multipliers associated with definite model factors. However, a more complex multi-compartment mass balance model was developed because welding comprises a confined set of similar procedures and there was sufficient research to sustain selection of FFR for each of the main welding processes to parameterise a mechanistic mass-balance model. This model is specific to welding because inputs and MFs such as emission strengths, compartment airflow rates and other factors are required for more realistic modelling [93].

Dispersion of fume has a direct consequence on the correlation between the FFR and breathing zone exposure [16]. The concentration of fume is highest at the emission source and reduces vertically upward away from the source although the airflow can be difficult to characterise in real-life welding situations. Moreover, the ventilation system also plays a role in the flow characteristics of the fume plume. Welding fume and the metal components are present at a higher density in an enclosed or poorly ventilated area [7], [41], [52], [94], [95]. The current ART model considers the limited areas (i.e., small volume and/or low general circulation rate) although it is not validated for welding fume. Therefore, this factor should be further investigated when weldART is calibrated.

It is still necessary to incorporate MFs into the scheme because for some elements, e.g., inclusion of the effectiveness of local control measures, where the most appropriate way to deal with such interventions is using a MF to alter the emission strength in the box model.

3.6 Conclusions

A box-model conception was used for the weldART model accounting for welding-specific factors (type of welding process and plume dispersal). The approach is possible for welding because of the limited range of scenarios where welding may take place and the availability of data to parameterise the model. Inclusion of multiplicative MFs for local control are a necessary addition, although in the initial use of the model described in the following chapter there was no local control measures in place. It is proposed that the local ventilation MFs in the ART tool could be used in this way. Elaboration of the model to take account of variations in shield gas and electrode current and voltage were considered but it was concluded that while the published experimental research could provide some indication of how this could be done the absence of such data in real life monitoring datasets would make it difficult to calibrate the tool. Later it may be possible to include such elaborations. The model does not consider the effectiveness of personal protective equipment and therefore it is excluded from this study.

Calibration of the weldART model to ensure the estimates of welding fume exposure (mass unit per air volume unit) are reliable will be necessary. This could be accomplished by obtaining a variety of exposure measurements of dissimilar welding processes in various scenarios and work pattern. Hence, a large database with associated model parameters will need to be compiled. However, with the limitation that we cannot discover the database then we carried out with our measurement survey.

CHAPTER 4
WELDING FUME EXPOSURE MEASUREMENT STUDY

4.1 Introduction

The standard method of evaluating welding fume exposure depends on analysing air samples collected onto a filter via gravimetric or chemical methods to quantify the fume concentration. Developing the welding ART model requires measurements of fume concentration to be used in the calibration step. Therefore, Chapter 4 will describe the sampling process, sample analysis, effect of fume concentration, as well as comparison of fume concentrations from two sampling methods, namely a direct-reading measurement and gravimetric measurement. This chapter reports measurements of welding fume exposure that were collected along other contextual parameters necessary for modelling. The welding fume samples in this study were not analysed for metal components, but only expressed as total welding fume.

All sample collection activities involved in welding fume exposure measurement in this chapter have ethical approval from the Ethics Committee of the School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK, under the approval reference number 19/EA/JC/2. Each participant provided written informed consent before the sampling commenced.

4.2 Materials and Methods

4.2.1 Equipment

1) Filter cassettes, 37 mm (SKC)
2) Swinnex® sampling heads, 13 mm, lot no. T18D58550 (Merck Millipore)
3) MicroPEM™ version 3.2A with $PM_{2.5}$ impactor set (RTI International)
4) Glass fibre filters, 1.2 µm pore size, 37 mm, lot no. d891285, (ANOW®)
5) Glass fibre filters, 2 µm pore size, 13 mm, lot no. R9BA99023, (Merck Millipore)
6) PTFE (Polytetrafluoroethylene) membrane filters, 0.22 µm pore size, 25 mm, lot no. 20180929PQ24M (EZFlow®)
7) Support pads (cellulosic pads), 37 mm (SKC)
8) Personal sampling pumps, model 224-PCXR8, serial no. 917143 and 917644 (SKC)

9) Personal sampling pumps, model GilAir5, serial no. 20071201011, 20071201012, 20071201013, and 20071201014 (Gilian®)
10) Portable primary calibrator, model Bios Defender 510, serial no. 112114 (DryCal)
11) Filter microbalance, model MSA6.6S000DF, serial no. 33505850 (Sartorius)
12) Flexible tubing
13) Adhesive tape
14) Stopwatch
15) Anti-static tweezers
16) Glass marking pen

4.2.2 Participants

Prior to carrying out the first test the author asked the welders to complete a short data questionnaire relating to the process and work environment. Then they were asked to install an in-visor sampler (a MicroPEM monitor) inside the welding visor (Figure 15) in order use this data as an indication of their personal exposure. Two sample collection strategies were used; over approximately 15-60 minutes during the actual welding process on the sampling days. These monitoring techniques are widely used in occupational hygiene practice and are of minimal encumbrance for the welder (total weight of equipment <0.5 kg). The welders were asked if the researcher could collect photographs or video to the welding process - permission was previously obtained from the welders' employer. No personal identifying data was linked with the images, and they were held securely on an encrypted password-protected computer.

4.2.3 Measurement Strategy

Welding fume samples were collected from 17 welders in a large fabrication plant that constructs pipes, pressure vessels, heat exchangers and silos. These workers used three welding processes: FCAW, SMAW and GTAW, although most of the welding activities involved GTAW; SMAW and FCAW are practiced occasionally. During the operation, workers wore gloves and a welding visor.

The building used in this study was a very large spacious building. Because of this it was necessary to modify the weldART model to have four compartments (WP, NF, FF and RM) as described in Section 3.3. The volume of the workshop building was approximately 35,200 m^3 (20 m (width) x 160 m (length) x 11 m (height)) with an entrance and exit at the front and back of the building (Figure 12-13). The entrance and exit were open at all times. There were also openings on both sides of the top of the building walls connected to the roof. The building therefore had internal natural ventilation without mechanical ventilation. On the sampling dates, attempts were made to measure the air velocity in the air sampling area, but the anemometer was malfunctioning. However, it was observed that the wind speed at the air sampling area was not high because the welders were working in the middle of the building. They were not in an area exposed to strong airflow, such as at the entrance or exit. In addition, openings on both sides of the building walls were located high above the ground. The ambient temperature during the data collection was between 32 to 42 °C, measured at 17 monitoring points throughout the building.

All air sampling were performed during a single task of welding and not the whole shift using two techniques. In the first measurement technique, samples were collected using a 13 mm diameter Swinnex sampling head, which was linked to an individual sampling pump in compliance with BS EN ISO 10882-1:2011 sampling method for airborne particulates in welding and allied processes [96]. The second method was using a MicroPEM direct-reading aerosol monitor (https://www.rti.org/impact/micropem-sensor-measuring-exposure-air-pollution) with the inlet tube also located inside the welding visor.

Figure 12 The workshop building.

Figure 13 The inside workshop building.

MicroPEM provides a personal level of exposure information in very lightweight form that an individual can wear that can provide data on temporal changes in particulate concentration. The National Research Council (NRC) [97] encourages the application of personal exposure monitors to determine exposure characteristics, patterns and levels for their relationship to acute and chronic health effects. However, it can be troublesome to conduct personal exposure sampling. Analysts must identify periods when the monitor is not worn according to protocol to ensure representativeness of data [98]. The current version of the MicroPEM provides a full representation of the individual exposure by having both a built-in filter to collect the sampled aerosol, as well as a scattered light detector to record patterns of real-time exposure. William [97] reported that the response time of MicroPEM is 10 seconds and can provide real-time concentration estimates every 10 seconds. The MicroPEM was used as per manufacturer's calibration. The optional United States Environmental Protection Agency (US EPA) $PM_{2.5}$ or PM_{10} selector involves the collecting information regarding the target respiratory tract accumulation zones (deep lungs or thoracic, respectively) enabling the study of the link in health to adverse disease outcomes. In this study, only $PM_{2.5}$ was measured because it corresponds more closely to the size of the fumes [6], as elaborated in detail in Chapter 1.

Application of particulate matter (PM) sampling criteria of the US Environmental Protection Agency (US EPA) ensured acceptable MicroPEM accuracy, which is acquired if the D_{50} incoming intersection is within 0.5 m (for $PM_{2.5}$ or PM_{10}) and the calibration slope from arranged field sampling is within ±15% and interception is within ±10% according to the standard, target variance is ±15% in collocated measurements in the nominal concentration range.

4.2.4 Exposure Assessment

Three Swinnex samples were collected for each task. The first was placed inside the welding visor to measure personal exposure. Meanwhile, the second was placed about 50 cm from the welding area and 1.5 m above ground to measure fume concentration in the NF. Although, in some cases it was impractical to setup the sampler near the welder because it obstructed the welder's work. However, in these cases it was attempted to setup the NF sampler as close the welder as possible, as shown in Figure 14. Lastly, the third sampler was located about 200 cm away from the welding area and 1.5 m above the ground to collect fume concentration in the FF (Figure 14). Each Swinnex holder contained a 13 mm glass fibre filter with pore size of 2 µm. Air was drawn through the filter via the sampling system at a flow rate of 1 L/min. The airflow was measured before and after each sampling session using an airflow meter. The average flowrates at the start and the end of the sampling period of each individual sampling pump was then determined. After the process, the filters were then reweighed using a Sartorius filter microbalance (up to 0.001 mg scale) and the gravimetric concentration calculated. Samples were not analysed for component metals.

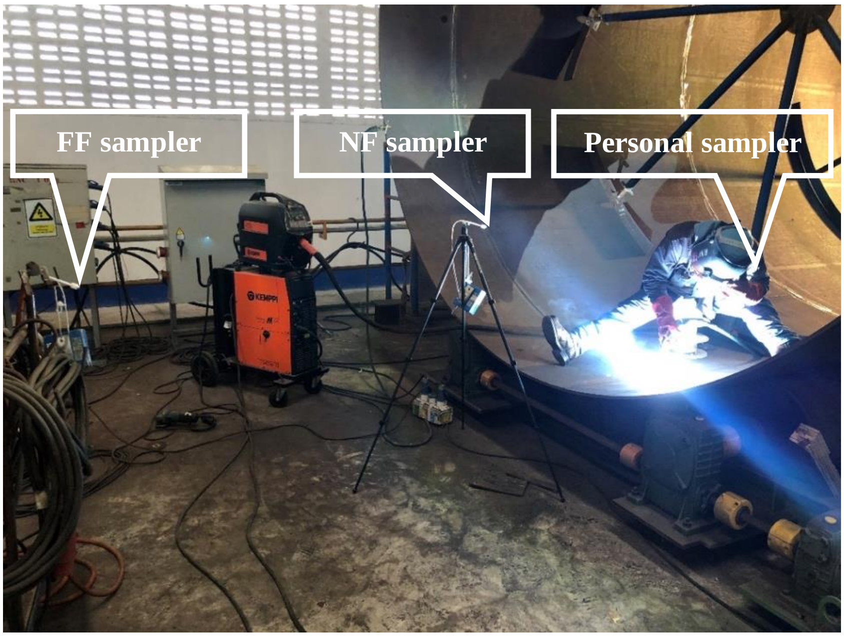

Figure 14 Three Swinnex samples were collected for WP, NF and FF location.

The pump for the Swinnex personal sample was located on a belt of welders. Sampling tube was then connected to draw air from inside the welding visor (Figure 15). According to the manufacturer's recommendation, the instrument's flowrate should be fixed at 0.5 L/min. In addition, the flowrate would be re-measured after the sampling period.

Figure 15 Swinnex and MicroPEM samplers attached to the welding visor band.

Ten blank filters exposed to the same conditions with no air drawn through were used as controls. The average change in mass incurred in the control samples was deducted from the corresponding samples' mass. In addition, the welders' head orientation in relation to the welding fume plume and the operation periods were obtained from a video recording during the evaluation. Ultimately, because of identified problems with the data from the MicroPEM, these data were not directly used in calibrating the weldART but was applied to identify the welding periods as evidenced by the video record. During the sampling, information about exposure determinants, i.e., process type, sampling time, arc time, working room volume, and shielding gas, were collected by observation.

4.3 Results

4.3.1 MicroPEM Monitoring

The data from the MicroPEMs monitors is indicative of real-time continuous $PM_{2.5}$ concentration. Comparison of data and the welding activities from the video record was made. The graph representing the time welders were engaged in welding (arc time) was plotted against the MicroPEM concentrations. Subsequently, the welding times in each welding task were summarised. These times were used to estimate personal exposure. An example of the plot $PM_{2.5}$ concentration over a period of time as identified by the video record is shown in Figure 16.

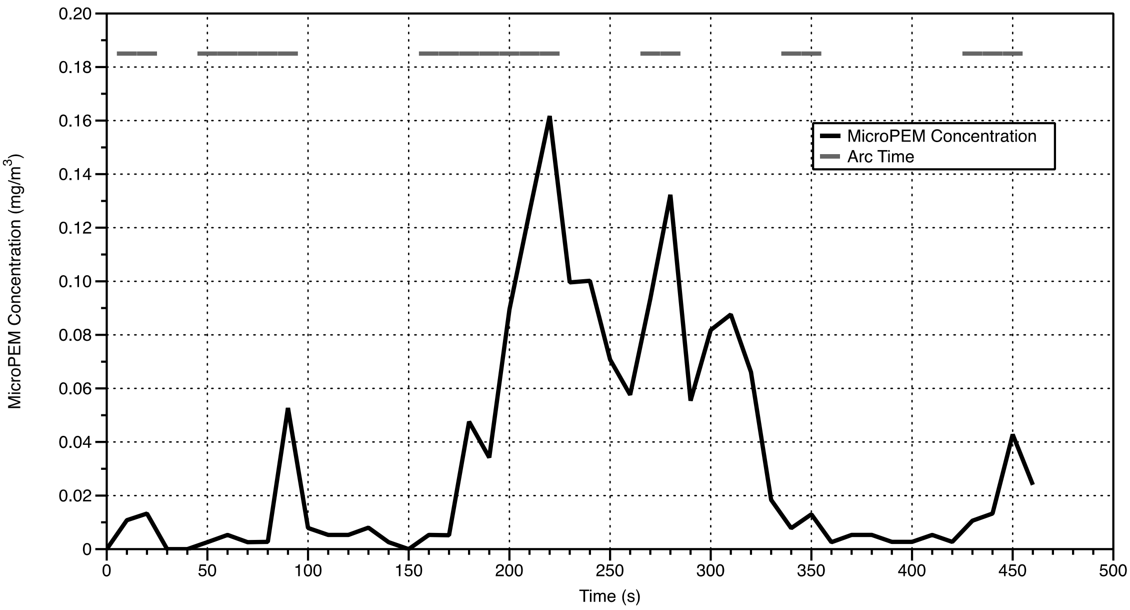

Figure 16 The example (Sample ID 2) of the MicroPEM concentration and the arc welding period.

4.3.2 Air Sampling Results

After collecting data on total particulate (TP) gravimetric concentrations and average $PM_{2.5}$ concentrations during the sampling period from the Swinnex samples and MicroPEM (Table 5), it was found that the geometric mean concentrations from the personal samples (WP) of FCAW, SMAW and GTAW were 24.54, 5.73 and 3.58 mg/m^3, respectively. Meanwhile, the geometric mean concentrations from the MicroPEM samples for FCAW, SMAW and GTAW were 0.80, 0.02 and 0.03 mg/m^3, respectively.

Sample ID 1 was excluded from subsequent analyses because it was an extreme outlier. This outlier is an atypical value in the dataset, and in a small dataset it could distort the statistical analyses. When analysing the FCAW process type, Sample ID 1 was considerably higher than Sample ID 2 and 3 (approximately 4-5 times). A likely reason for the higher value of Sample ID 1 was because it was taken while there were other welding activities ongoing close by. This may have caused the fume to be blown into the sampling area of Sample ID 1. It was concluded that the collection of Sample ID 1 may not have been a reliable measure of the conditions of the specific welding operation, and the outlying value should be excluded from the analysis. However, during other sampling operations, the working areas were quite far apart, and there was less chance for such incident to occur.

When considering relationship between MicroPEM monitors and gravimetric measurements of Sample ID 1-17, it was found that Pearson's correlation coefficient (r) was 0.93 (R^2 = 0.87).

Table 5 The results of total particulate concentrations from the Swinnex samplers and average $PM_{2.5}$ concentrations from the MicroPEMs during the sampling period.

Sample ID	Process Type	Sample Time (min)	Arc Time (min)	% Arc Time	Concentrations (mg/m^3)			
					Swinnex Sampler			MicroPEM
					Personal (WP)	NF	FF	
1	FCAW	21	11	52.4	75.0	5.2	1.8	5.25
2	FCAW	8	4	50.0	14.6	3.0	0.6	0.04
3	FCAW	19	7	36.8	13.5	4.6	1.5	2.43
4	SMAW	11	11	100.0	8.8	0.7	0.2	0.02
5	SMAW	21	19	90.5	5.5	0.5	0.2	0.01
6	SMAW	21	21	100.0	3.2	0.5	0.2	0.02
7	SMAW	12	10	83.3	7.1	0.7	0.2	0.02
8	GTAW	21	20	95.2	5.5	0.3	0.1	0.02
9	GTAW	19	9	47.4	5.0	1.7	0.5	0.01
10	GTAW	31	31	100.0	4.4	0.5	0.1	0.16
11	GTAW	41	39	95.1	4.0	0.3	0.1	0.03
12	GTAW	21	20	95.2	4.0	0.3	0.1	0.02
13	GTAW	31	31	100.0	3.9	0.3	0.1	0.02
14	GTAW	71	69	97.2	3.9	0.2	0.1	0.02
15	GTAW	41	38	92.7	2.8	0.3	0.1	0.05
16	GTAW	41	38	92.7	2.7	0.3	0.1	0.02
17	GTAW	54	50	92.6	1.5	0.3	0.1	0.04

Sampling period has positive correlation with arc time (R^2 = 0.96) and constitutes about 90% of the sampling period on each occasion. Even though this study had short sampling times for each measurement, it covered the most welding time. This study used gravimetric method that compared between before and after weighting which it has not the limit of detection (LOD). Arc time has inverse correlation with evaluated personal exposure concentrations (R^2 = 0.45) as well as having low correlation with the NF and

FF concentrations. However, arc time (and all parameters that go with it) is not a good parameter for predicting exposure (R^2 = 0.45).

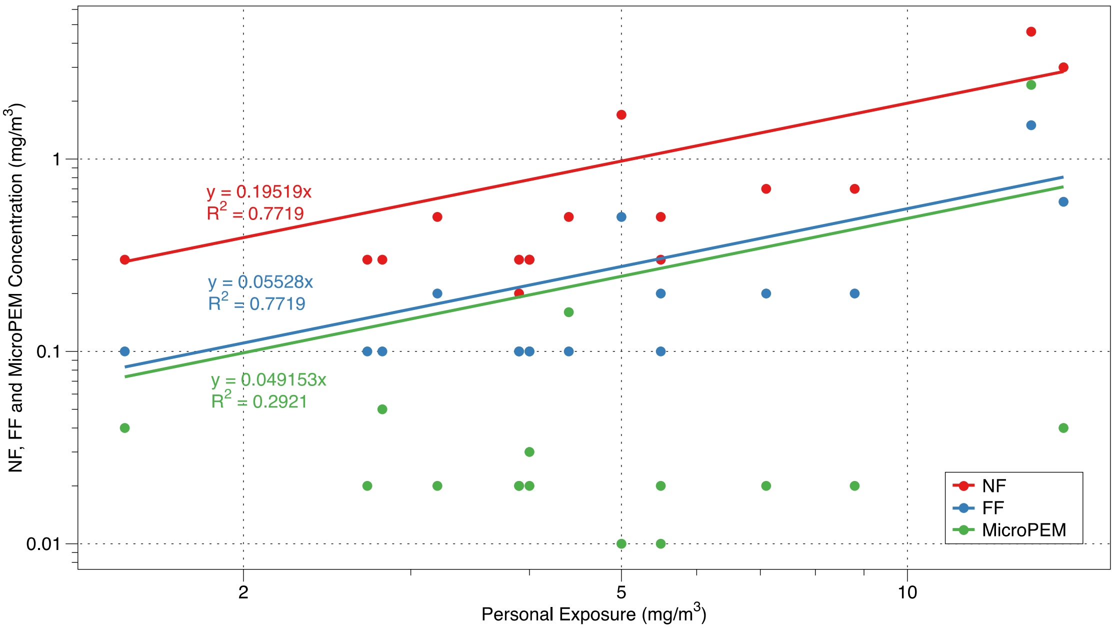

Figure 17 The relationship between personal exposure for total particulate concentrations from the Swinnex samplers and average concentrations from the NF, FF and MicroPEMs when Samples ID 1 was excluded (n=16).

Figure 17 shows relationship between personal exposure for total particulate concentrations and average concentrations from the NF, FF and MicroPEM. It was indicated that concentrations of NF, FF and MicroPEM equal to 20% (R^2 = 0.77), 6% (R^2 = 0.77) and 5% (R^2 = 0.29) of personal exposure.

Moreover, when excluded the Sample ID 1 (n=16), a strong positive correlation between personal exposure and NF and FF compartments (coefficient of correlation; r = 0.86 and 0.87, respectively) was also found. Meanwhile, a weak direct correlation between personal exposure and MicroPEM data (coefficient of correlation; r = 0.56) was found.

4.4 Discussion

The sampling area is a very large workspace and it was clear that the FF may not represent the whole work area. After reflecting on this, the weldART model was modified to include four compartments as described in Chapter 3, i.e., by subdividing the original FF into two separate spaces.

The MicroPEM monitors underestimated and had poor correlation with the gravimetric measurements. The underestimation was in part due to MicroPEM measuring $PM_{2.5}$ while welding fume particles ranges from a few nanometres to 20 µm [14]. The Swinnex samplers collect particles with larger size than the MicroPEMs [33], [99]. In addition, the MicroPEM monitors may have underestimated because of the placing position of the air inlet of sampling tube of MicroPEM was slightly higher than air inlet of the Swinnex sampler as well as being inserted deeper inside the welding visor, as shown in Figure 12. Further, and perhaps most importantly, it is probable that particles may deposit on the inside of the sampling tube due to the electrostatic deposition before the entering the aerosol sensor [100], which was located on the workers belt. For these reasons, particularly the possibility of particle deposition in the sampling tube, these MicroPEM data were not used for the model calibration although they were used to assist in the identifying welding periods.

The sampling periods ranged from 8 to 71 minutes, which were the actual working times of the welders per job task. Each welder had 4-5 tasks per day. Some welders took periodic breaks to change the filler wire or change welding posture. The arc times were between 4 - 69 minutes, representing 36.8 - 100% of the sampling period. Because the sampling periods were relatively short. The data could not be used to compare with the mean concentration standard over the operating period (time-weighted average; TWA).

In this study, samples were collected for 4 days with three types of welding, namely FCAW, SMAW and GTAW. On each day, welders did not work continuously throughout the day. In one day, a welder may have only worked in the morning. As a result, the number of sampling types did not cover all welding processes and there were only small number of samples collected. In the future there should be a study on other welding process types as well as to increase the number of samples along with the data necessary to parameterise the weldART model. This may provide more accurate study results in relation to assessing the possible risks for the workers.

4.5 Conclusions

It was found that FCAW process produced more welding fume particulate concentrations than SMAW and GTAW. The MicroPEM monitors underestimated the concentration measured with a gravimetric sampler and there was a poor correlation between these measures. It is presumed that the MicroPEM data were untrustworthy, most likely because of deposition in the sampling tube before the light scattering sensor. However, these real-time measurement data were used to identify welding periods, i.e., arc-time.

CHAPTER 5
THE WELDART MODEL CALIBRATION

5.1 Introduction

The objective of calibration is to determine the parameters to achieve the closest agreement between the model estimates and the actual exposures in a given situation. The parameters must provide a suitable level of independence to adapt the model's behaviour to suit arbitrary system behaviour [101]. However, this provides only a narrow insight into the model's behavior under never-before-seen conditions, i.e., the model is only reliably calibrated for the parameter domain available for the evaluation.

As the weldART model was developed from the ART model, it is important to understand calibration used for the ART model. The process consisted of three objectives. The first objective was to determine whether the mechanistic model scores can be precisely arranged in respect to exposure measurements. The second purpose was to allow the mechanistic model to assess actual exposure status rather than corresponding scores. The third was to initiate measure to quantify model uncertainty. The ART model was compared the original model predictions and measurements and then defined calibration factors that were used to convert the scores form the model to estimate the concentrations. Also, the ART model had different calibration domains, e.g., inhalable dust, vapours, and mists.

The ART calibration study results indicated that, after calibration, the ART model could evaluate geometric mean (GM) exposure levels with 90% confidence level in a specified circumstance subject to parameters between two and six of the measured GM depending upon the form of exposure [99].

This chapter aimed to calibrate the weldART by adopting exposure information of welding contaminants from Chapter 4.

5.2 Methods

The weldART model assumes that air within each compartment is instantaneously well mixed and concentration starts at zero. The model development is based on a multi-compartment mass-balance model of the welding process, with four spatial compartments – WP, NF, FF and RM as described in the Chapter 3. Then, the model calibration was performed using 16 sets of fume exposure measurements - personal exposure level (as shown in Table 5 in Chapter 4) evaluated inside the welding visor, NF and FF concentration and the weldART model estimation, along with the necessary contextual data.

Linear equations were used to fit the weldART model concentrations to the individual exposure (subject to a time-weighted average of the WP and NF concentration), the NF and the FF concentrations. The flowrate between the model compartments was adjusted to optimise the fit between the weldART simulated concentrations in the measurement data by trial-and-error approach (Table 4 in Chapter 3).

5.3 Results

Figure 18 shows the data from the initial model (model testing No. 1) estimates in relation to the measured data that the ratio between measurement and model concentrations model does not close to 1.0. The weldART model estimates following adjustment of the compartment flowrates (β) in relation to the measured data. Then identify and extract the necessary exposure data, i.e., process type, room size and welding time. Next the approach to assigning parameter distributions.

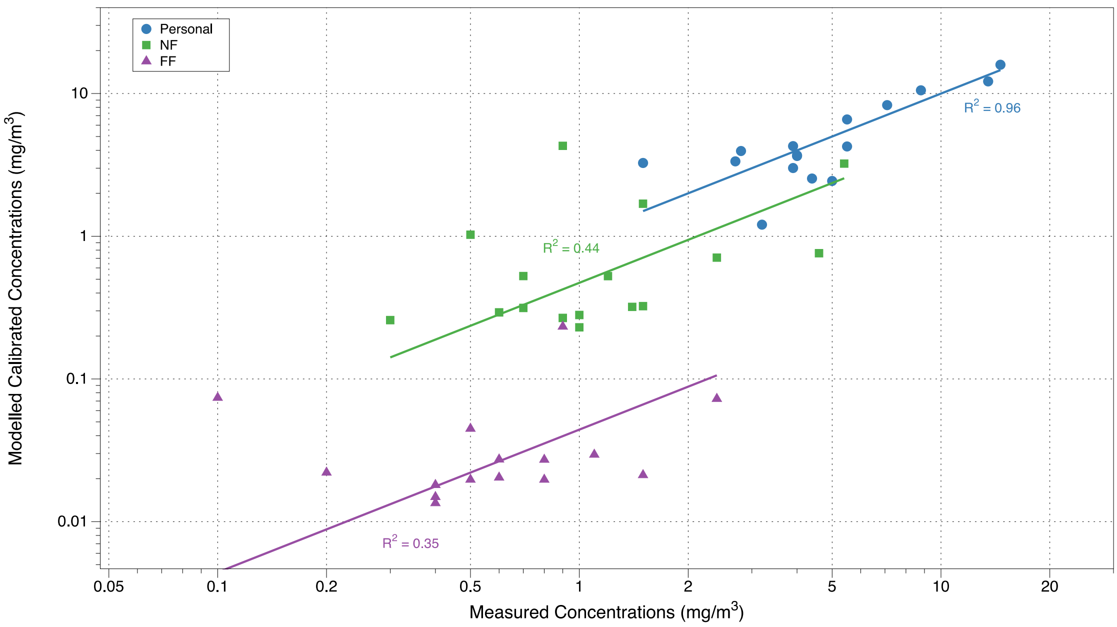

Figure 18 Scatterplot with R-square between measured and initial weldART model concentration.

The model was adjusted to account for uncertainty in the compartment flowrates (β) in relation to the measured data. This process aims to discover the nearest ratio (close to 1.0) between measurement and model concentrations by using pseudo-random numbers from a symmetric triangular distribution approach. This is actually the adjustment of the deterministic model to get a better fit. The results are shown in Table 6, the compartment flowrates that provided the good fit measured:modelled ratio of personal, NF and FF compartments are the model testing No. 6.

Table 6 The estimated values of β were used to generate pseudo-random numbers from a symmetric triangular distribution.

Model Testing	β_1 (m^3/s)	β_1' (m^3/s)	β_2 (m^3/s)	β_2' (m^3/s)	β_3 (m^3/s)	β_3' (m^3/s)	Ratio Measured to Modelled		
							Personal	NF	FF
No. 1	0.0125	0.0575	0.2175	0.1725	0.1200	0.1650	1.2	2.6	24.6
No. 2	0.0458	0.0045	0.0450	0.0863	0.5000	0.4588	1.2	3.1	92.0
No. 3	0.0700	0.0575	0.1025	0.1150	0.1000	0.0875	1.5	0.9	74.6
No. 4	0.0700	0.0575	0.1025	0.1150	0.1200	0.1075	1.4	1.0	70.7
No. 5	0.1275	0.0575	0.1025	0.1725	0.1200	0.0500	1.7	0.6	69.0
No. 6	0.0125	0.0288	0.0738	0.0575	0.0300	0.0463	1.2	1.1	87.3
Min	0.0125	0.0045	0.0450	0.0863	0.1000	0.0500			
Max	0.1275	0.0575	0.2175	0.1725	0.5000	0.4588			

Figure 19 shows the data from the final model estimates following adjustment of the compartment flowrates in relation to the measured data.

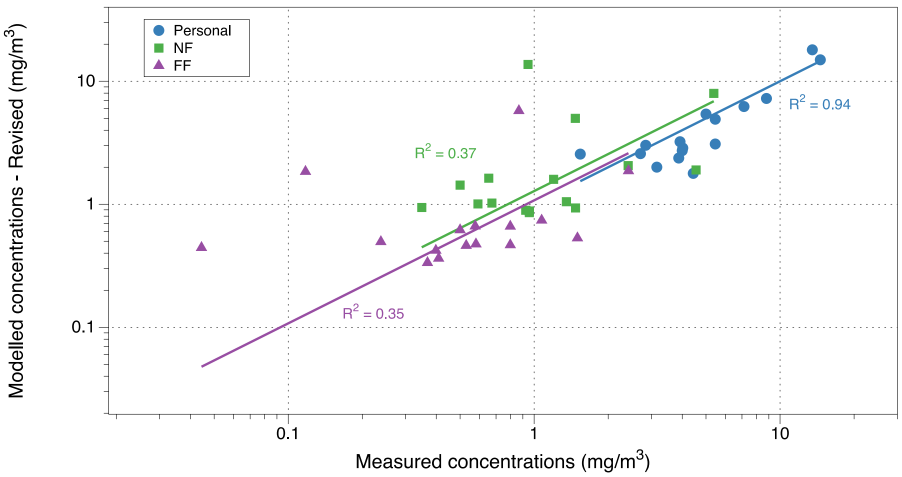

Figure 19 Scatterplot with R-square between measured and weldART (4-compartment) model concentration.

The initial model was composed of three subdivisions - NF, FF, and WP (Personal). In addition, the RM was incorporated in the final model. The FF volume (V_{FF}) was fixed at 300 m^3 and the V_{RM} was therefore 35,200 m^3 in the final model (Table 4). A high correlation between personal exposure (C_{WP}) estimates and the measured values was obtained. The average estimated values were 1.3 times that of the measured values. The correlation between NF and FF simulation outcomes and the compartment measurements were low (R^2 = 0.37 and 0.35, respectively). Nonetheless, the numbers were in conformity with the average data (the ratio of the average model estimate to the corresponding value for the measurements was 0.9 and 1.0 and NF and FF, respectively).

Figures 20 – 22 show the Bland-Altman plots of the data for personal exposure, NF exposure and FF exposure. These plots provide further insight into the agreement between measured and weldART concentrations. The two dotted lines in these plots are the 95% confidence limits of agreement. These plots confirm there is a good agreement between the weldART estimates and the measured concentrations with 95% limits of agreement.

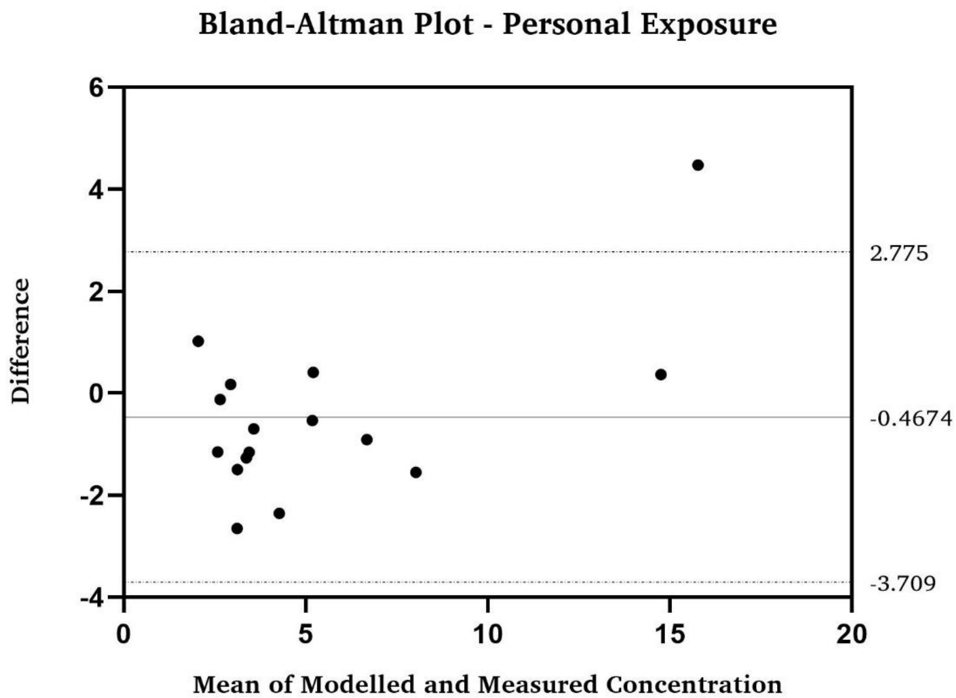

Figure 20 Bland-Altman plots of the personal exposure against the mean of the modelled and measured concentrations.

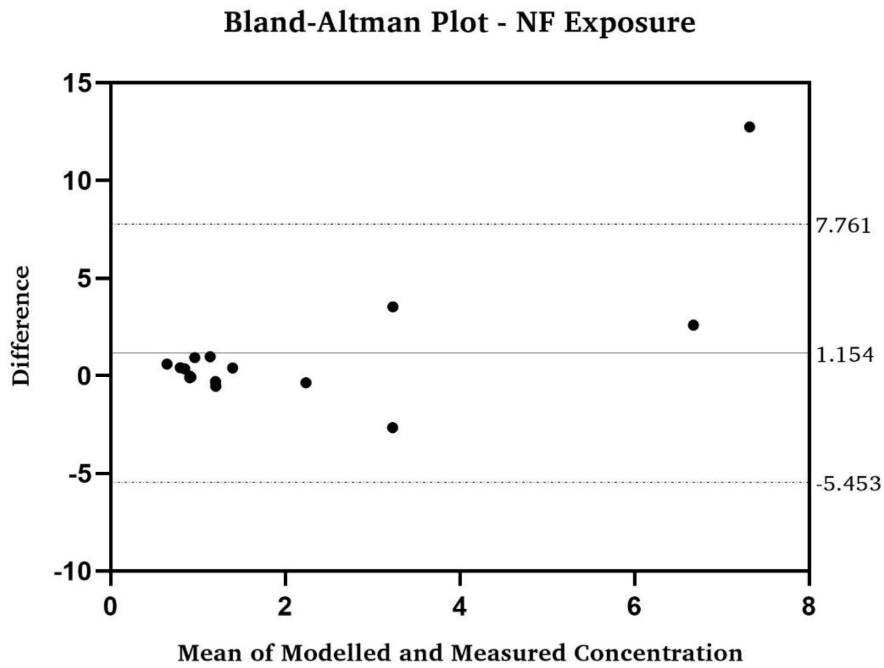

Figure 21 Bland-Altman plots of the NF exposure against the mean of the modelled and measured concentrations.

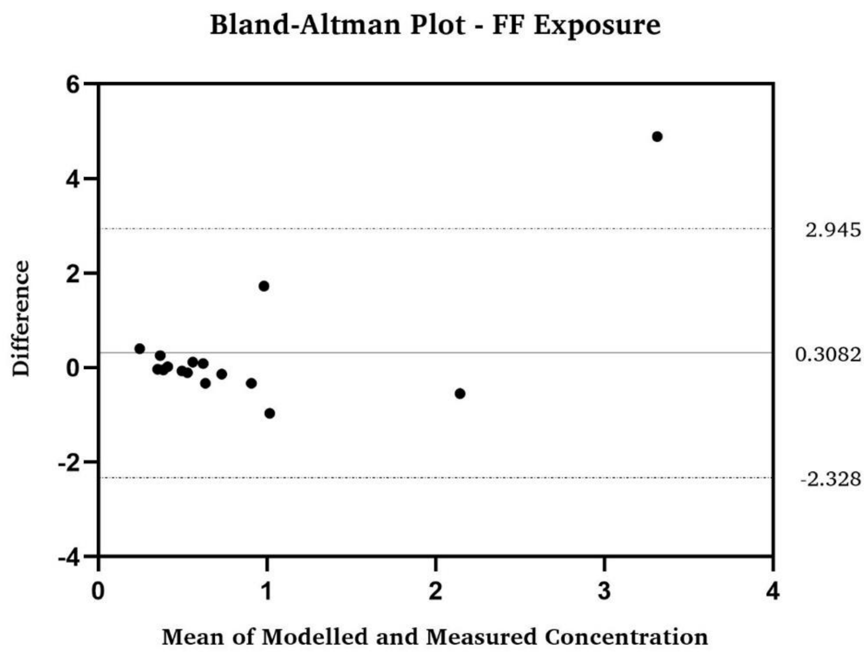

Figure 22 Bland-Altman plots of the FF exposure against the mean of the modelled and measured concentrations.

5.4 Discussion

The weldART calibration datasets was relatively small because it was difficult to identify existing welding fume datasets that had the relevant exposure determinant information to parameterise the model and so it was necessary to collect new measurements for the weldART calibration.

The initial weldART model comprised of three spatial compartments. However, an additional RM compartment was incorporated because there was some discrepancy between the initial modelled concentrations for the FF and the measured values. Specifically, we found that with a FF compartment that comprised the whole workroom the modelled FF concentration was higher than the measured concentration values (mean of model to measurements ratio was 87.3; $R^2 = 0.34$). In contrast, the simulated individual and NF concentrations in this initial three-compartment model were in close agreement with the measured data (exposure ratio 1.2; $R^2 = 0.97$, and NF 1.1; $R^2 = 0.45$). The addition of the RM compartment led to a better prediction of FF concentration in a large space where welding was being performed. The method also maintained a good prediction for personal exposure (model to measurements ratio was 1.3; $R^2 = 0.94$).

The lower correlation between the simulated and measured concentrations in the NF and FF may partially be due to the low concentrations and the short sampling periods, i.e., the random errors associated with weighing smaller masses are likely more influential in these circumstances. There may also be some effect from background airborne particle sources, e.g., other welding in the RM, which would also add to the random variation in the measured NF and FF. However, it is recommended that further study should consider these effects to take into the model, and in particular more sensitive measurement methods should be used to measure in the NF and FF.

The four-compartment weldART model was designed to estimate total welding fume and not the mass of each metal element in the fume. This is in accordance with the evaluation of the International Agency for Research on Cancer (IARC), whose assessment suggests that the cancer risk from welding fume is mainly attributable to the fume particles regardless of their elemental composition [40]. A study has shown that the overall fume concentration were poorly or moderately correlated to the metal concentrations, depending on the type of metal [102]. This makes it more difficult to use the weldART output to assess specific metal concentrations, and for this reason this is not advised.

An accurate model to estimate exposure should include terms for local ventilation controls. However, the weldART model was calibrated without this factor because there was no specific local ventilation control in the workplace where the data were collected, i.e., a Small and Medium Enterprises (SMEs) in a developing country. Local controls are one of the MFs in the ART model (ranging from 0.5 for a canopy hood or moveable captor hood to 0.01 for ventilated enclosures like fume cabinets) [103]. In the absence of specific data on the effectiveness of LEV controls in welding it seems reasonable to recommend that the ventilation control MF from ART should also be applicable in the weldART model. This could be used as a MF applied to the FFR, reducing the effective emission into the WP.

Although the weldART model could be applied in other welding scenarios, other relevant information, including fume emission rates and air flow data between compartments, is needed for the further application of the model. However, these data are not normally described in exposure measurement studies. In practice, these parameters could be estimated by using the calibration values until have a further information.

The personal exposure measurement data in the model calibration was collected inside the visor, which is common in British occupational hygiene practice. However, some researchers and occupational hygiene practitioners collect measurements outside the visor. In the validation process (Chapter 6), it was necessary to apply a correction factor for the measurement data that collected from the outside visor before comparing such data with the model estimates. It would be helpful in a further future study to make a comparison between the fume concentration inside and outside the visor, to facilitate such adjustments.

The significance of time when welding occurred and its implication in interpretation of the data were demonstrated in Figure 23. The results illustrated estimated personal exposure as the aggregate sum between WP and NF concentrations multiplied by the length of time when welder's head was inside the WP and NF. From this set of data, the average welding period of about 50% was used to estimate the exposure time. With this approach a more realistic personal exposure concentration estimates of 11.9 mg/m^3 was obtained, rather than 17.3 mg/m^3 estimated on the assumption of one continuous welding period. These data affirm the training to provide welders with understanding of the importance of avoiding the WP could help minimise their exposure. For instance, from the sample above, if a welder kept their head out of the WP zone, the exposure concentration would be estimated at 3.0 mg/m^3, i.e., the concentration in the NF alone (as demonstrated in Figure 8 in Chapter 3). This exposure concentration increases to 7.45 mg/m^3 if the workers head was in the WP zone half the time. This evidence indicates that the time the welders head is in the WP is one of the important factors in the model estimate. Furthermore, analysts measuring welding fume exposure should record the duration of time when the head is in the plume.

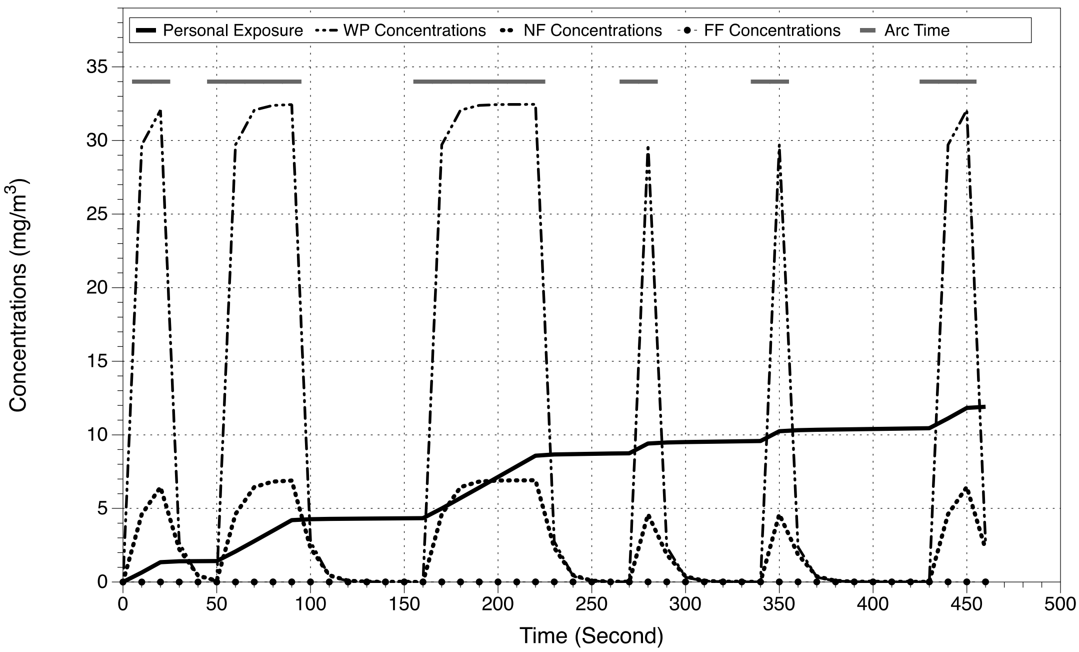

Figure 23 The example (Sample ID 2) of the pattern of welding fume concentrations in the different compartments.

The results of the model calibration show that weldART has a good potential to estimate the exposure of welders based on data on welding process (emission rate), arc time or more detailed data on times welding, time welder spends with head in plume, local ventilation, room size and ventilation rate, and interzone flow rates. However, the model still needs to be validated by comparing estimated exposures with a wider set of available measurement data from a wide range of workplaces with differing welding and environmental conditions. As much of the currently available published data lacks specific information on the weldART exposure determinants it was judged necessary to adapt the model into a probabilistic form to take account of the uncertainty from the lack of knowledge of the circumstances where the measurements were obtained. The weldART was implemented as a R script [87] and it would be possible to adapt the model code to provide distributional inputs for each determinant in a Monte Carlo simulation, e.g., to consider ambiguity in parameters such as the arc time or the intermittency of welding operation during the work shift. This adaption is described in Chapter 6. A welding data collection spreadsheet is available in Appendix A.

As a preliminary exploration of the application of the weldART model it is compared with a small study described in the peer-reviewed literratre. Boelter *et al.* [57] conducted an evaluation of welders' exposure while using SMAW on carbon steel pipes in a boiler room and breezeway using a two-zone mass-balance model. Fume emission rates for the boiler room and the breezeway were estimated to be 0.65 mg/s and 0.67 mg/s, for the boiler room and breezeway, respectively. These values are about 30% of weldART estimates. The comparison of the weldART values to Boelter and colleagues' estimations is shown in Table 7. The Boelter *et al.* model and the weldART showed the C_{exp} and the FF had values very close in the boiler room. However, both the weldART and Boelter *et al.* simulations showed higher evaluations of C_{exp} than the measured data. However, this was based on only two measurements and these discrepancies may be due to the airflow in the semi-outdoor breezeway, creating the uncertainty of airflow rates between individual model compartments. Alternatively, the measurement data may have a high degree of uncertainty attached.

Table 7 The comparison of welding fume concentrations between the Boelter *et al.*' study and the weldART model in the boiler room and the breezeway.

	Boiler Room		Breezeway	
	C_{exp}	FF	C_{exp}	FF
Boelter *et al.*'s measurement (mg/m^3)	4.73	1.37	2.89	0.57
Boelter *et al.*'s model (mg/m^3)	5.36	1.25	4.04	0.57
weldART model (mg/m^3)	5.68	1.38	8.32	2.02

5.5 Conclusion

A high correlation between personal exposure estimates and the measured values was obtained in the calibration dataset. The correlation between NF and FF model estimates and the compartment measurements were low although the model estimates were, on average, close to the measurement data; the poor correlation probably reflects the lack of sensitivity in the measurement data for these compartments. Further validation using additional parameters and variety multitude measurement datasets is necessary to ensure the validity of the tool. It is believed that the weldART model parameters should guide occupational hygienists to collect relevant exposure determinants to further advance model development.

CHAPTER 6
THE WELDART MODEL VERIFICATION

6.1 Introduction

Exposure model validation is an important step to assure accurate predictions of exposure. Validation of a model tool is the process that shows the computer codes are valid and reliably executed. In addition, the process verifies the extent to which the results of the model accurately predict actual exposures, as evaluated by reliable monitoring data [104]. The verification should be carried out using data not applied in model building, although where extensive data are not available an alternative strategy can be to split the available data into a set for model building and one for validation. Most current exposure models are not thoroughly validated, and where this has been undertaken the validation process is often not performed immediately after the model introduction. Moreover, most validation processes do not encompass a wide variety of circumstances needed to form an overview of the model performance and the validity domain.

The weldART model was formulated as a deterministic tool with MFs. Inputting the fixed parameters values in the tool will produce the same result for the scenario, i.e., the tool does not take account of uncertainty or variability in the parameterisation. To use the weldART model it is necessary to know all the parameter values. For a validation exercise it would therefore be necessary to identify exposure data that also had all the appropriate contextual data. It was impractical to collect additional data in workplaces for the validation of the weldART. Efforts to gather such data from collaboration with other researchers also proved unsuccessful. Contact was made with some researchers to request measurement data but no none were able to provide suitable data. However, there are data in the published literature, but these do not contain most of the necessary parameters (contextual data). Therefore, it was necessary to adapt the weldART model into a probabilistic tool where in place of fixed parameters it was possible to input parameter distributions to account of the uncertainty in allocating parameter values.

This study was performed to validate the applicability of the weldART model for estimation of welding fume exposure across a wide domain. The revised model was built upon that described in the previous chapter with the addition of a probabilistic component to account for uncertainties in the model input parameters. We verified the weldART model by comparing the model output to welding fume exposure data acquired from the peer-reviewed scientific literature, grey literature and unpublished measurement studies (occupational hygiene reports).

6.2 Adaption of the weldART model to a Probabilistic Form

In this section the adaption of the weldART model to a probabilistic form is described. The weldART model was adapted, searched to identify the data in the literature, extracted the available data including assessing the extent of the uncertainties (i.e., defined the distribution parameters), then ran the model.

The different measured:modelled ratio of FF (as described in Chapter 5) was very high. The final model (model testing No. 6) was adjusted by considering the welder head location. Also, this adjustment was considered in the four compartments. Therefore, both of air flowrate of FF (Q_{FF}) and Room (Q_{RM}) were changed from 0.5 to 0.25 m^3/s. The adjusted model concentrations are shown in Table 8, were calculated by using equation:

$$\frac{(C_S \cdot T_S) + (C_{NF} \cdot T_{NF})}{(T_S + T_{NF})} \tag{6.1}$$

Where;

C_S	=	Welding source concentration (mg/m^3)
T_S	=	Time of welder's head at welding source (s)
C_{NF}	=	NF concentration (mg/m^3)
T_{NF}	=	Time of welder's head at NF (s)

Table 8 The adjusted model concentrations.

Sample ID	Concentration (mg/m^3)							
	Filter Method (mg/m^3)	MicroPEM (mg/m^3)	Source (mg/m^3)	Time at Source (s)	NF (mg/m^3)	Time at NF (s)	FF (mg/m^3)	Adjusted Model (mg/m^3)
02-FCAW	14.57	0.04	12.00	140	3.10	320	0.73	5.81
03-FCAW	13.53	2.43	16.77	170	5.32	990	2.24	7.00
04-SMAW	8.80	0.02	2.82	660	0.74	0	0.21	2.82
05-SMAW	5.45	0.01	2.02	1160	0.62	100	0.26	1.91
06-SMAW	3.15	0.02	2.04	130	0.63	1130	0.26	0.78
07-SMAW	7.13	0.02	2.71	610	0.80	110	0.29	2.42
08-GTAW	5.45	0.02	1.24	1210	0.36	50	0.13	1.20
09-GTAW	5.00	0.01	6.49	40	1.94	1100	0.72	2.10
10-GTAW	4.44	0.16	1.73	1660	0.56	220	0.24	0.69

Sample ID	Concentration (mg/m³)							
	Filter Method (mg/m³)	MicroPEM (mg/m³)	Source (mg/m³)	Time at Source (s)	NF (mg/m³)	Time at NF (s)	FF (mg/m³)	Adjusted Model (mg/m³)
11-GTAW	4.00	0.03	1.16	2320	0.39	140	0.19	1.11
12-GTAW	4.00	0.02	1.09	1210	0.34	50	0.14	1.06
13-GTAW	3.92	0.02	1.25	1860	0.41	0	0.18	1.25
14-GTAW	3.87	0.02	0.92	4250	0.33	0	0.17	0.92
15-GTAW	2.84	0.05	1.23	2300	0.40	160	0.18	1.17
16-GTAW	2.70	0.02	1.05	2300	0.35	160	0.16	1.00
17-GTAW	1.54	0.04	1.03	3027	0.37	190	0.19	0.99

Figure 24 show the relationship between the filter method concentration and the adjusted model concentration with the equation 6.2:

$$y = 0.38889x \qquad (6.2)$$

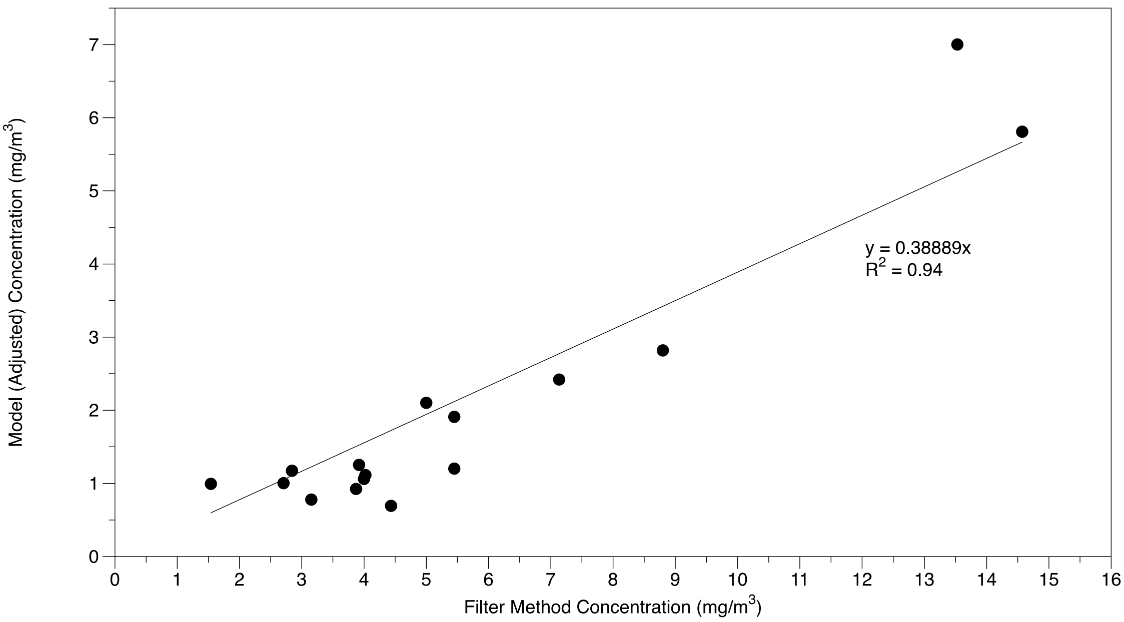

Figure 24 The relationship between the filter method concentration and the adjusted model concentration.

Table 9 and Figure 25 shows the data from the final model estimates following adjustment by using equation 6.2 in relation to the measured data. The initial model was composed of three subdivisions - NF, FF, and WP (Personal). A high correlation between personal exposure (C_{WP}) estimates and the measured values was obtained. The average estimated values were 1.3 times that of the measured values. The correlation between NF and FF simulation outcomes and the compartment measurements were low (R^2 = 0.37

and 0.35, respectively). Nonetheless, the numbers were in conformity with the average data (the ratio of the average model estimate to the corresponding value for the measurements was 0.9 and 1.0 and NF and FF, respectively).

Table 9 The data from the final model estimates following adjustment of the concentrations.

Sample ID	Model Calibrated Concentration (mg/m^3)			Measured Concentration (mg/m^3)			Ratio Measured to Modelled		
	Personal	NF	FF	Personal	NF	FF	Personal	NF	FF
02-FCAW	14.94	7.97	1.87	14.57	5.38	2.42	1.0	0.7	1.3
03-FCAW	18.00	13.69	5.76	13.53	0.94	0.87	0.8	0.1	0.2
04-SMAW	7.25	1.90	0.53	8.80	4.56	1.50	1.2	2.4	2.8
05-SMAW	4.91	1.60	0.66	5.45	1.20	0.80	1.1	0.8	1.2
06-SMAW	2.00	1.63	0.66	3.15	0.65	0.58	1.6	0.4	0.9
07-SMAW	6.22	2.06	0.74	7.13	2.41	1.07	1.1	1.2	1.4
08-GTAW	3.09	0.93	0.33	5.45	1.47	0.37	1.8	1.6	1.1
09-GTAW	5.41	4.99	1.85	5.00	1.47	0.12	0.9	0.3	0.1
10-GTAW	1.78	1.43	0.62	4.43	0.50	0.50	2.5	0.3	0.8
11-GTAW	2.87	1.01	0.47	4.02	0.59	0.58	1.4	0.6	1.2
12-GTAW	2.73	0.88	0.36	4.00	0.96	0.41	1.5	1.1	1.1
13-GTAW	3.22	1.05	0.47	3.92	1.35	0.80	1.2	1.3	1.7
14-GTAW	2.38	0.85	0.44	3.87	0.96	0.04	1.6	1.1	0.1
15-GTAW	3.02	1.02	0.46	2.84	0.67	0.53	0.9	0.7	1.1
16-GTAW	2.58	0.89	0.42	2.71	0.92	0.40	1.0	1.0	0.9
17-GTAW	2.56	0.94	0.50	1.54	0.35	0.24	0.6	0.4	0.5
Average							1.3	0.9	1.0

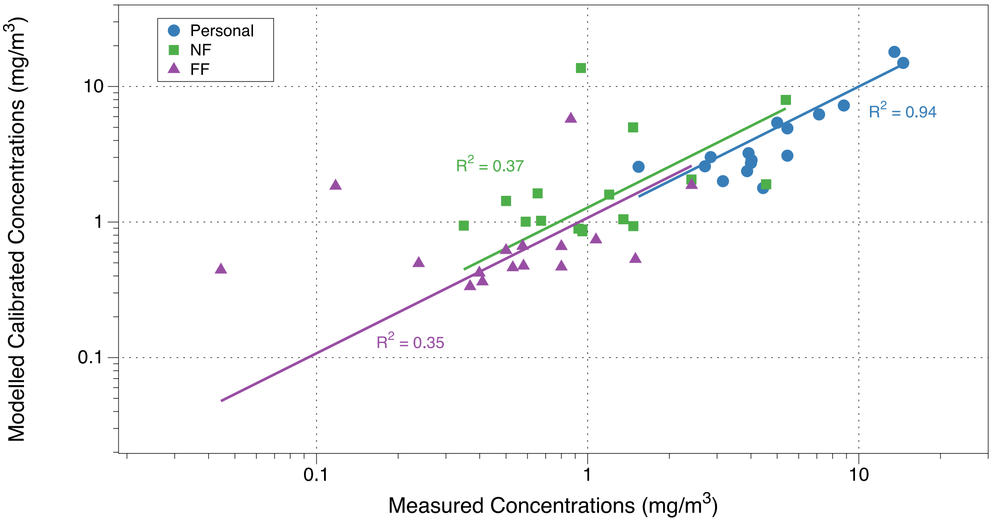

Figure 25 Scatterplot with R-square between measured and weldART model concentration.

6.3 Collation of Exposure Data for the Validation Exercise

During the exposure data collation process, inquiries were made on several occupational hygienists to provide information on welding fume measurement, i.e., welding process type, input power level, shield gas, local control measures, and welding electrodes effect fume formation rates. However, in the end, such information was not available for this research, therefore, data were obtained from the peer-reviewed literature and other sources known to the author. The measurement data that were collect in Chapter 4 included all the key parameters that were required to parameterise the model for calibration. However, these data were not used for the verification.

The welding fume concentration data used in the model verification was obtained from a systematic literature search using the Scopus English database for literature published until 19 May 2019. The search keywords were "welding fume" OR "welding fumes" AND ("exposure" OR "concentration"). Exclusion of animal, *in vitro* and *in vivo* studies reduced the search results from 1,019 to 879 (Figure 26 and Table 10). The number was further reduced to 341 after excluding those studies without measurement results by skim and scan reading technique. Finally, there were 211 studies selected for review. It was found that there were 200 studies that had measurement data on average welding fume concentrations from various samples where it was not possible to determine specific information about the welding situations to parameterise the weldART. Therefore, results of these studies are not used. As a consequence, only data from the remaining 11 studies [51], [57], [105]–[113] were used in the verification process. Additional data from occupational hygiene monitoring reports or survey reports from sampling of fume concentration in welding production available to the author were also used, although as stated above the calibration dataset (Chapter 5) was not used for the verification.

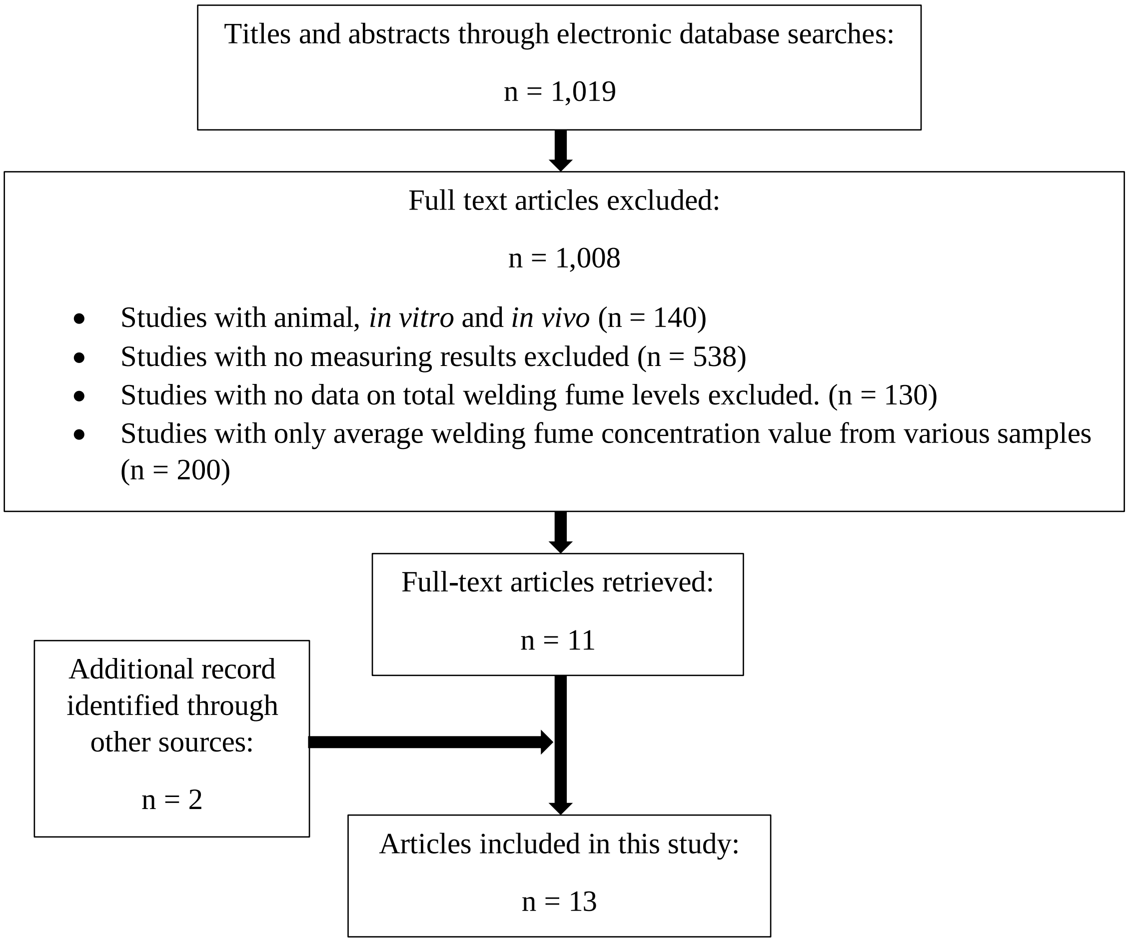

Figure 26 Flow diagram of literature search.

Table 10 Results of literature search.

Criteria	A Number of the Articles
Titles and abstracts through electronic database searches with keywords: “welding fume” OR “welding fumes” AND “exposure” OR “concentration”.	1,019
Animal, *in vitro* and *in vivo* studies excluded.	879
Studies with no measuring results excluded.	341
Studies with no data on total welding fume levels excluded.	211
Studies with only average welding fume concentration value from various samples.	11

6.4 Extraction of the Exposure and Contextual Data, and Assignment of Model Parameter Distributions

The necessary data for the verification was extracted from the papers and input to an Excel spreadsheet, where the exact data required for the model calculation was unavailable data was inferred from the scenario descriptions. For unavailable data where specific values were unknown, R was used to simulate values using the Monte Carlo technique into the model.

Key variables needed to model fume exposure, including work area characteristics, welding type, flow rate or air velocity in the welding area (including the free-standing fans), working area size, welding time, break time, emission rate (welding process type), localized controls and ventilation system, were collated into an Excel worksheet. However, most of the required exposure parameters were incomplete, making the verification process difficult.

For those variables where specific values were unknown, R was used to simulate values using the Monte Carlo technique into the model by using the function "rtri" to generate pseudo-random numbers from a symmetric triangular distribution, i.e., minimum, maximum and mode. Each parameter typically contained 100,000 simulations. The syntax for function "rtri" is:

```
rtri <- function (n, min, max, mode)
```

Arguments;

n = sample size. If length (n) is larger than 1, then length (n) random values are returned. For this study, the value is n = 100,000.

min = vector of minimum values of the distribution of the random variable. The default value is min = 0.

max = vector of maximum values of the distribution of the random variable. The default value is max = 1.

mode = vector of modes of the random variable. The default value is mode = (max-min)/2.

The R code generated lists of random numbers between a minimum and maximum value in each variable, as shown in Table 5.

Table 11 The minimum and maximum values of key variables were generated from R.

Value	β_1 (m^3/s)	β'_1 (m^3/s)	β_2 (m^3/s)	β'_2 (m^3/s)	β_3 (m^3/s)	β'_3 (m^3/s)	Q_{FF} (m^3/s)	Q'_{FF} (m^3/s)	Q_{RM} (m^3/s)
Min	0.0125	0.0045	0.0450	0.0863	0.1000	0.0500	0.0025	0.0025	0.0250
Max	0.1275	0.0575	0.2175	0.1725	0.5000	0.4588	2.5000	2.5000	293.3333
Mode	0.0575	0.0265	0.0863	0.0431	0.2000	0.2044	1.2513	1.2513	146.6792

The minimum and maximum values in Table 11 were the estimated values from the calibration model process that estimates following adjustment of the compartment flowrates in relation to the measured data (Table 8).

The room volumes of fume plume zone (V_{WP}) and near-field (V_{NF}) were set to 0.2875 m^3 (0.5 m × 0.5 m x 1.15 m) as a default. The volume of far-field (V_{FF}) and room zone (V_{RM}) were selected on the basis of the values used in the ART model. The emission time (E_{WP}Time) provided as the usual working time within 8 hours. These variables are shown in Table 12.

Table 12 The minimum and maximum values of the room volumes and time of emission.

Value	V_{WP} (m^3)	V_{NF} (m^3)	V_{FF} (m^3)	V_{RM} (m^3)	E_{WP}Time (s)
Min	0.2875	0.2875	30	300	1
Max	0.2875	0.2875	300	35200	28800

The emission rate (EwpVal) of each welding process obtained from the literature review (Table 13). Technical Rules for Hazardous Substances (TRGS) Report of the Federal Institute for Occupational Safety and Health (BAuA) [91] states that FCAW (without shielding gas) has emission rate of more than 25 mg/s. However, from relevant studies, no FCAW with emission rate of more than 30 mg/s is found [91]. Therefore, the maximum value was set to be at 30 mg/s. In addition, GTAW, SAW and gas welding reports indicate that the emission rate is less than 1 mg/s [91].

Table 13 Emission rate of each welding process.

Welding Process	Emission Rate (mg/s)	References
FCAW		
- Without Shielding Gas	26 - 30	[91]
- With Shielding Gas	6 - 25	[91]
GMAW		
- MAG (Flux-cored Wire)	26 - 30	[91]
- MAG (Solid Wire)	6 - 25	[91]
- MIG (General)	2 - 8	[91]
- MIG/MAG (Low Energy Gas-Shielded Welding)	1 - 4	[91]
SMAW	0.8 - 3.4	[91], [106]
GTAW	0.01 - 1	[91]
SAW	0.01 - 1	[91]
Gas Welding	0.01 - 1	[91]

Volume airflow in the far-field (Q_{FF}) was divided according to ventilation characteristics, such as no limitation on general air circulation, effective natural ventilation, mechanical circulation and specialised room ventilation. At the same time, Volume airflow flowing in the room (Q_{RM}) is divided according to room volume, including small, medium and large. The classifications of ventilation and room volume were based on the ART model. The minimum-maximum range of Q_{FF} and Q_{RM} to be used in the verification process are obtained from R programme simulation using Monte Carlo method (as shown in Table 14 and Table 15).

Table 14 Q_{FF} according to the ventilation rate of each room size.

Room Volume	V_{FF} (m^3)	Q_{FF} (m^3/s)			
		no Limitation on General Air Circulation	Effective Natural Ventilation	Mechanical Circulation	Specialised Room Ventilation
Small	1 - 30	0.0732 - 0.1625	0.0146 - 0.065	0.02 - 0.0680	0.2249 - 0.4
Medium	31 - 100	0.0871 - 0.2166	0.0174 - 0.0866	0.0458 - 0.0810	0.4167 - 0.9166
Large	101 - 300	0.1075 - 0.375	0.0215 - 0.15	0.1099 - 0.125	0.9166 - 2.5

Table 15 Q_{RM} according to the ventilation rate of each room size.

Room Volume	V_{RM} (m^3)	Q_{RM} (m^3/s)			
		Limitation on General Air Circulation	Effective Natural Ventilation	Mechanical Circulation	Specialised Room Ventilation
Small	300 - 999	0.085 - 0.15	0.017 - 0.06	0.0125 - 0.0687	0.1666 - 0.25
Medium	1,000 - 2,999	0.0833 - 0.1667	0.0166 - 0.0667	0.0083 - 0.0764	0.1666 - 0.2778
Large	3,000 - 35,200	0.075 - 0.25	0.015 - 0.1	0.0125 - 0.0917	0.1666 - 0.25

In addition to the variables mentioned above, in order to develop effective and probabilistic weldART model, variables, namely welder's head (WH) and localized control (LC) [92] were also taken into consideration. Multiplier of WH will be considered according to distance from welding fume plume as shown in Table 16. Meanwhile, multiplier of LC would adopt similar criteria of ART model as shown in Table 17.

Table 16 Descriptions and multipliers of welder's head variable for weldART model.

Description	Multiplier
Welder's head is within the fume plume	1.0
Welder's head is outside the fume plume but within the WP zone	0.6
Welder's head is outside the WP zone	0.2

Table 17 Descriptions and multipliers of localized control variable for weldART model.

Description	Multiplier
No localized controls	1.0
Receiving hoods	
- Canopy hoods	0.5
- Other receiving hoods	0.2
Capturing hoods	
- Movable capturing hoods	0.5
- Fixed capturing hoods	0.1
- On-tool extraction	0.1
Enclosing hoods	
- Fume cupboard	0.01
- Horizontal/downward laminar flow booth	0.1
- Other enclosing hoods	0.1

6.5 Validation of the weldART Model

6.5.1 Methodology

For adapting the model into a probabilistic form, the weldART model with 125 data sets were run by R script. The example R codes are shown in Appendix B. The exposure data were statistically analysed by DataGraph Software and run in weldART to find the fume concentration to WH and LC variables. The results were then compared to the log-normal distribution of measured exposure concentrations. Descriptive statistics was used to display values of exposure concentration and geometric mean levels with geometric standard deviation.

6.5.2 Results

After applying weldART model with 125 data sets to determine fume concentration using variables obtained from systematic review articles and R programme simulation using Monte Carlo method without incorporating terms for the WH and LC variables, it was found that the average fume concentration obtained from weldART model was 28.55 mg/m^3 (95% confidence interval, 26.85 - 30.25). The obtained result overestimated the measured data by about 5.3 times (5.37 mg/m^3).

Table 18 shows the range, arithmetic mean and SD of the measured concentrations and weldART concentrations classified according to welding process type, localized control and ventilation condition. For each situation, it was found that the initial weldART model concentrations were higher than the measured concentrations. However, when the distance of welder's head (WH) to the plume and the effect of localized control (LC) were applied in weldART model, the concentration values were closer to the measured concentrations.

When considering welding process type, when the model with WH added is considered, it was found that concentration of SMAW was closest to the measured concentrations when comparing with other welding process types. In case of adding LC, it was found that concentrations of FCAW, GMAW and GTAW were closer to the measured concentrations than SMAW. When considering the data grouped by the type of localized control, it was found that when the model only included the WH, the concentrations of the group without localized control has the values closest to measured concentrations. However, adding the LC to the model along with WH terms provided estimated that were in better agreement with the measurements for all three ventilation categories.

Table 18 Comparison of fume concentration between measured concentrations and weldART concentrations according to variables.

Variable	Samples, n	Range (mg/m^3)					Arithmetic Mean (SD) (mg/m^3)				
		Measured	weldART Concentration				Measured	weldART Concentration			
		Concentration	Initial Model	Adding WH	Adding LC	Adding WH & LC	Concentration	Initial Model	Adding WH	Adding LC	Adding WH & LC
Welding Process											
FCAW	9	1.37 - 32.91	34.82 - 52.19	34.82 - 50.06	3.56 - 34.82	3.56 - 34.82	8.43 (9.56)	43.54 (6.26)	42.69 (5.38)	8.98 (9.91)	8.98 (9.91)
GMAW	6	1.08 - 17.8	18.17 - 31.11	10.78 - 21.28	1.91 - 30.38	1.91 - 18.84	6.16 (6.72)	22.66 (4.45)	17.15 (4.85)	9.4 (10.99)	6.34 (6.52)
GTAW	16	0.09 - 3.9	6.38 - 18.99	5.32 - 16.34	0.56 - 8.94	0.56 - 5.63	0.9 (1.05)	10.5 (3.78)	8.06 (3.75)	2.93 (2.55)	1.94 (1.37)
SMAW	94	0.13 - 24	13.9 - 50.79	3.91 - 19.96	2.17 - 57.04	1.28 - 19.96	5.78 (5.24)	30.57 (5.89)	8.75 (3.84)	27.9 (9.99)	7.77 (4.19)
Localized Control											
None	81	0.14 - 32.91	8.64 - 50.79	5.28 - 34.82	4.83 - 57.04	2.96 - 34.82	7.17 (5.96)	31.12 (6.29)	9.25 (4.98)	31 (7.33)	9.09 (5.03)
Movable capturing hoods	14	0.16 - 10.64	9.15 - 33.33	3.91 - 10.78	4.38 - 16.61	1.65 - 6.97	1.32 (2.76)	24.5 (8.81)	6.32 (1.54)	12.39 (4.71)	3.28 (1.16)
Fixed capturing hoods	30	0.09 - 10.04	6.38 - 52.19	5.85 - 50.06	0.56 - 10.24	0.56 - 8.22	2.38 (2.96)	23.51 (14.36)	20.02 (15.32)	4.07 (2.9)	3.26 (2.31)
Ventilation Condition											
General ventilation	78	0.12 - 32.91	8.64 - 38.03	5.28 - 38.26	1.29 - 34.82	1.28 - 34.82	5.51 (6.01)	26.64 (7.11)	10.28 (6.95)	22.26 (12.34)	6.98 (5.19)
Mechanical ventilation	26	0.09 - 24	18.41 - 52.19	3.91 - 50.06	3.75 - 42.72	1.65 - 19.89	4.6 (5.16)	37.44 (7.93)	16.92 (16.57)	22.39 (14.34)	6.69 (4.53)
Specialised room	21	0.13 - 19	6.38 - 50.79	5.85 - 19.96	0.56 -57.04	0.56 - 19.96	5.78 (4.94)	24.67 (13.34)	9.37 (3.3)	23.26 (16.47)	7.68 (5.3)
All Scenario	125	0.09 - 32.91	6.38 - 52.19	3.91 - 50.06	0.56 - 57.04	0.56 - 34.82	5.37 (5.65)	28.55 (9.71)	11.51 (9.75)	22.45 (13.41)	7.04 (5.05)

Figure 27 provides a box plot showing a comparison of the measured concentrations used in the verification process and the weldART concentrations with the model including the terms for LC and WH. The median of both measured concentrations and weldART concentrations have similar trend such that FCAW has the highest concentration, followed by SMAW, GMAW and GTAW respectively.

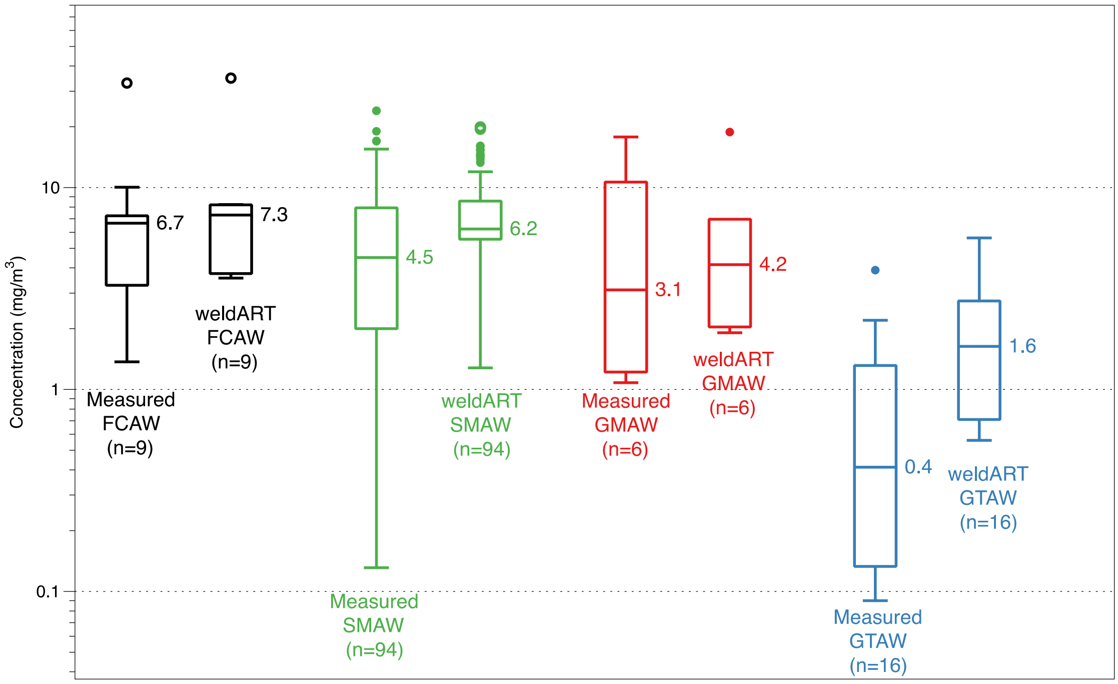

Figure 27 Box plot of measured and weldART concentrations according to welding process type.

When considering the effect of adding the distance of the welder's head (WH) and localized control (LC) to the weldART model according to welding process type (Table 19), it was found that after applying both WH and LC factors in the model, the correlation between the model and measured values increased over that with the initial model and for the final model the correlation was higher than 0.8. It was concluded that to achieve a satisfactory model it was necessary to incorporate terms for both WH and LC. Therefore, weldART has to include these two modifying factors.

Table 19 Statistical values of the relation variables divided by welding process type.

Welding Process	Correlation	R^2	Sig.	β	SE	95% CI
SMAW						
Initial Model	0.36	0.13	0.000	0.315	0.087	0.143 - 0.488
Adding WH	0.67	0.45	0.000	0.912	0.106	0.702 - 1.123
Adding LC	0.47	0.23	0.000	0.249	0.048	0.153 - 0.345
Adding WH & LC	0.82	0.67	0.000	1.022	0.075	0.872 - 1.172
GTAW						
Initial Model	0.59	0.34	0.000	0.312	0.05	0.212 - 0.412
Adding WH	0.54	0.29	0.000	0.752	0.138	0.477 - 1.026
Adding LC	0.61	0.38	0.000	0.238	0.036	0.167 - 0.309
Adding WH & LC	0.83	0.69	0.000	0.978	0.076	0.827 - 1.129
GMAW						
Initial Model	0.42	0.17	0.000	0.322	0.088	0.146 - 0.498
Adding WH	0.4	0.16	0.000	0.491	0.14	0.211 - 0.772
Adding LC	0.47	0.22	0.000	0.214	0.051	0.112 - 0.315
Adding WH & LC	0.8	0.64	0.000	0.991	0.093	0.805 - 1.176
FCAW						
Initial Model	0.27	0.07	0.000	0.199	0.088	0.025 - 0.374
Adding WH	0.19	0.03	0.000	0.095	0.062	-0.028 - 0.218
Adding LC	0.41	0.17	0.000	0.199	0.054	0.091 - 0.307
Adding WH & LC	0.84	0.71	0.000	0.983	0.077	0.83 - 1.136

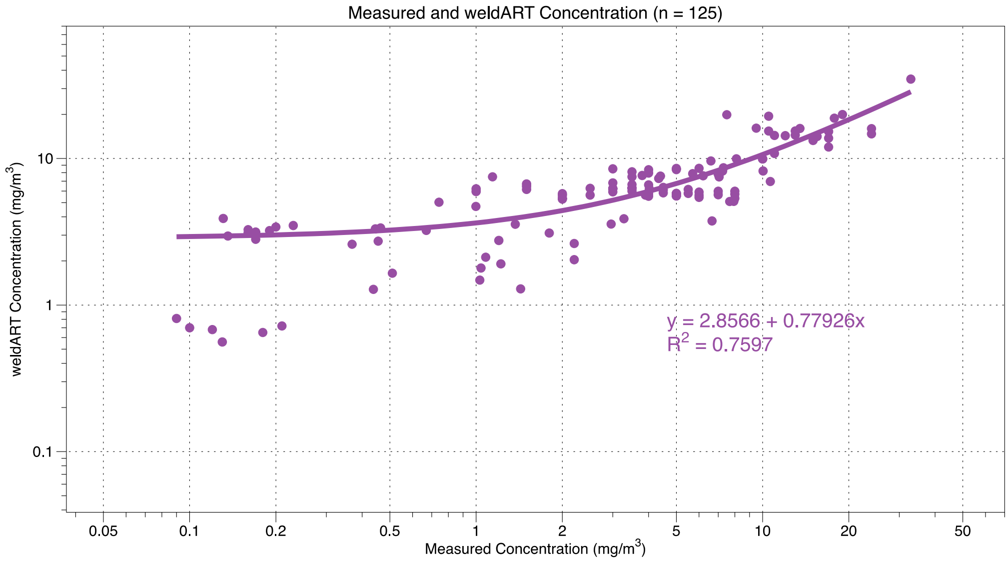

Figure 28 Relationship between measured concentration and weldART concentration

Figure 28 shows the relationship between the measured concentrations and weldART concentrations with the linear regression equation of y = 2.86 + 0.78x (R^2 = 0.76). From the plot, it can be seen that the weldART model tends to overestimate the measured values, especially in concentrations below around 0.5 mg/m^3.

Figure 29 - 33 shows the fitted linear regression models for measured concentrations and weldART concentrations according to welding process type for the base model and with the addition of the distance of welder's head (WH) and localized controls (LC).

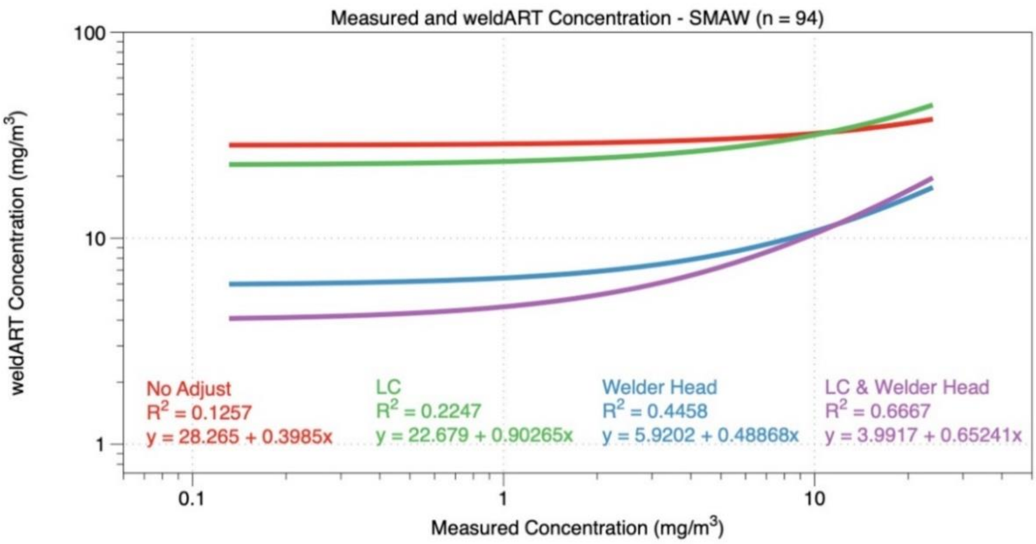

Figure 29 Relationship between measured concentrations and weldART concentrations for SMAW.

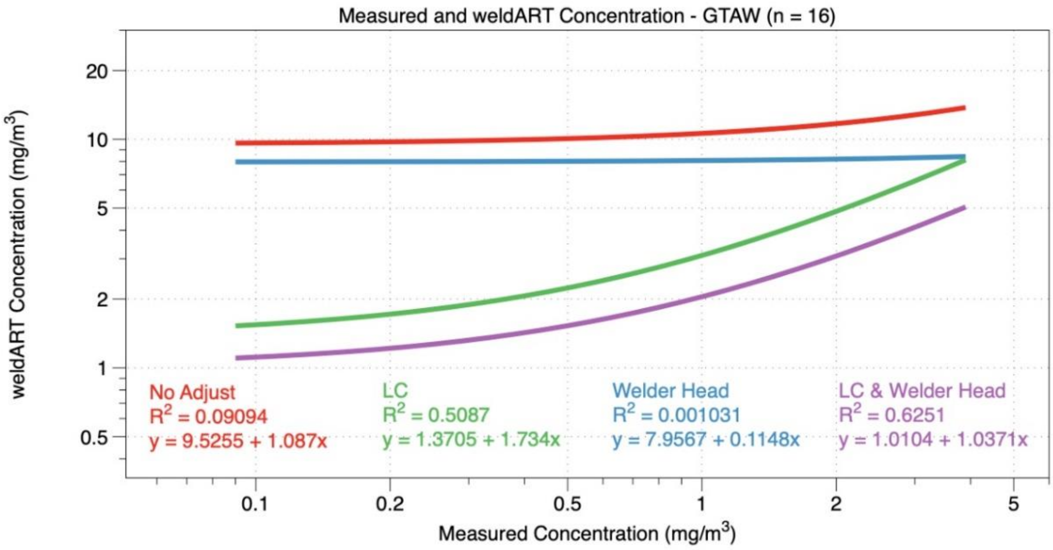

Figure 30 Relationship between measured concentrations and weldART concentrations for GTAW.

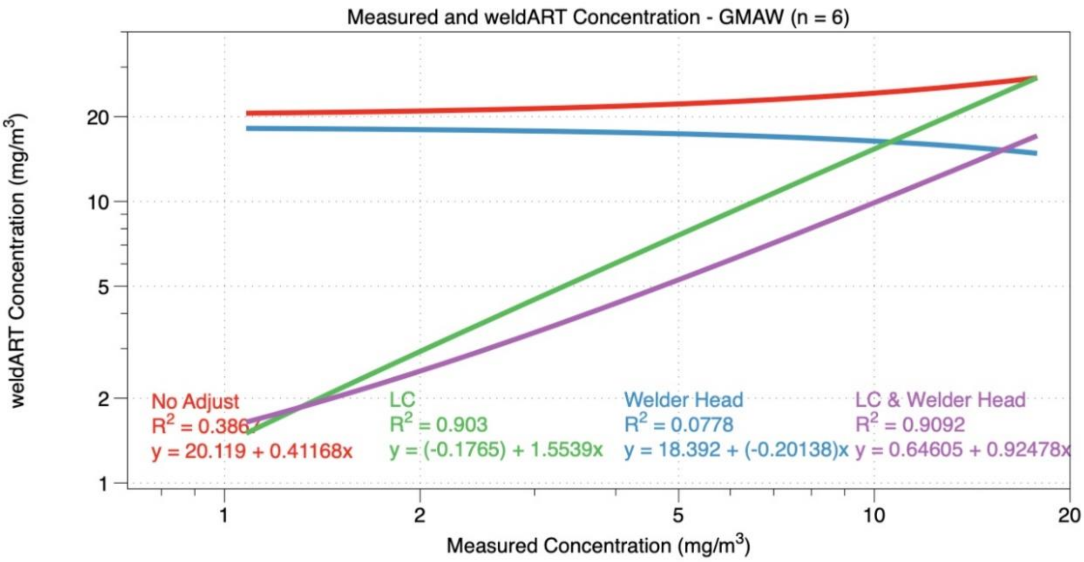

Figure 31 Relationship between measured concentrations and weldART concentrations for GMAW.

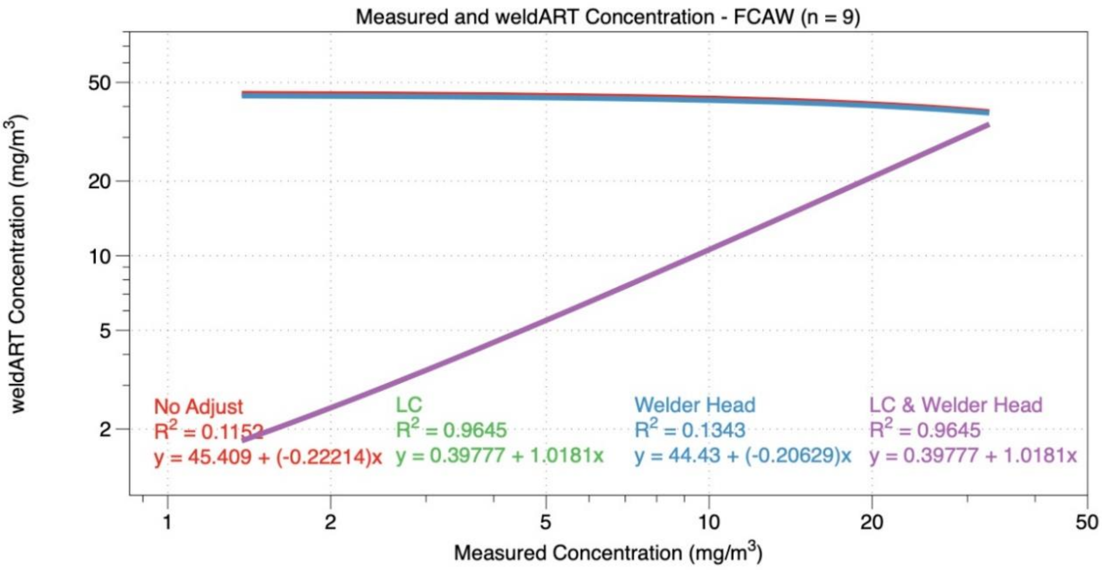

Figure 32 Relation between measured concentration and weldART concentration divided by FCAW variables.

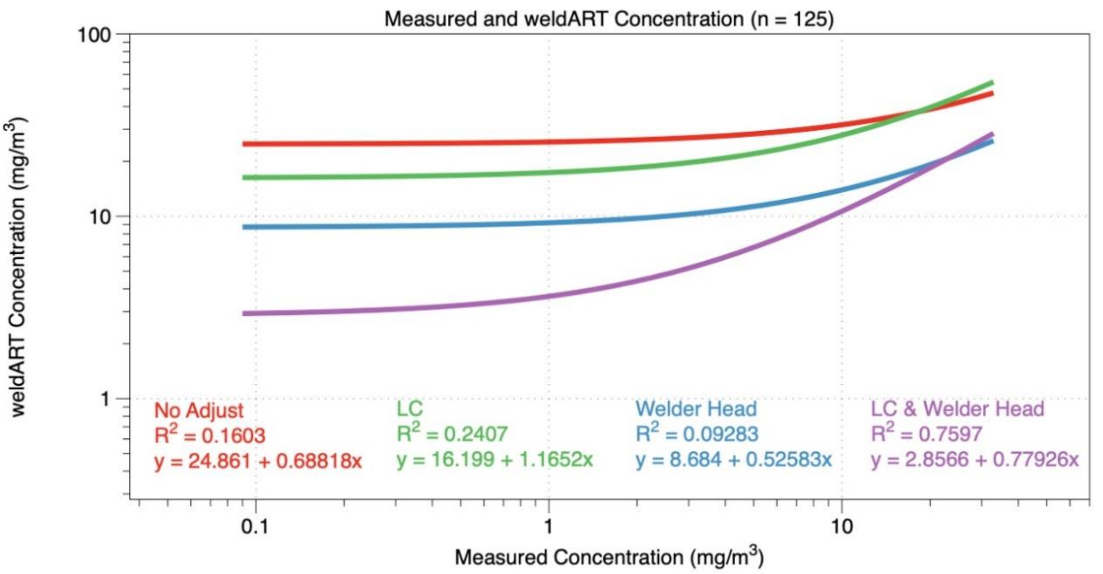

Figure 33 Relationship between measured concentrations and weldART concentrations for all data.

6.5.3 Discussion

It was found that the initial weldART model overestimated the fume concentrations, but the modelled values were closer to the evaluated concentrations when factors such as the distance of welder's head and localized control ($R^2 = 0.63 - 0.96$) were taken into account (Figure 29 - 33). WH and LC were not taken into account in the first place because all most measurement data did not include these factors, so it difficult to in put these factors in the weldART model. Various studies [114]–[116] show that the welders head position affects the ability of the local exhaust ventilation (LEV) to control the fumes, therefore it was assumed that the distance of welder's head and localized control could be affect the welder's exposure. When both of these factors were added to the weldART model the model predictions were closer to the measured values. However, the weldART still overestimates at low measured concentrations, particularly for the SMAW and GTAW welding processes. The range in weldART concentration estimates is smaller than the range in measured concentration values (Figure 33) because the probabilistic weldART are simulated the variation in the geometric mean due to parameter uncertainty, but the variation in the data is due to variability in the scenario, e.g., differences in work procedures or the environmental airflows.

The overestimation of weldART model at low concentration is consistent with other model studies, for example a study from the US EPA [117] where they developed the Human Air Pollution Exposure (SHAPE) model to predict air pollution exposure using the concept of human exposure modeling. SHAPE also applied human activity as a factor to assess the concentration of carbon monoxide (CO) in the micro-environment. The results of using SHAPE model to assess CO exposure indicated that at low concentrations, the SHAPE model overestimated. However, the author did not discuss the possible reasons for the overestimation. The finding was also consistent with study results of Behar *et al*. [118] who adapted the SHAPE principle to further develop the Benzene Exposure Assessment Model (BEAM). BEAM applies data from actual human activity in the micro-environment between 1985 and 1987 in the study model. The results of using BEAM to assess benzene exposure have the same effect as SHAPE model, i.e., at low concentrations, the BEAM overestimated.

The cause of overestimation of the weldART model at low concentrations is possibly due to a positive systematic bias across the whole applicability domain, which becomes dominant at low measured values [119]. In addition, this may also be because the weldART model does not include other factors that may affect the welders exposure, for example the localized increased air exchange rate where the working area is equipped with free-standing fans which are intended to help reduce the heat exposure for welders. These standing fans are generally adjusted to blow directly at the welders' bodies and would increase the air exchange in the near field and welding plume compartments. However, weldART model does not consider this factor. Because the model tends to overpredict concentrations it is necessary to further investigate the cause of the bias and refine the model so that it can predict more realistic results [120].

The evidence in this study suggests that the accuracy of the weldART model could be enhanced by identifying factors that are important for the estimation, specifically in the far-field. This will require a more comprehensive and detailed exposure data collection, and therefore, occupational hygienists will need to be aware when collecting measurements that it is important to obtain contextual data relating to all factors that may influence exposure, especially the welder’s head position relative to the fume plume, localized control, fume emission rates and localized airflow velocities in the working area.

The Monte Carlo technique was used to estimate the flowrate (Q) for the situations in the weldART model. Better data on the localized airflow around welding and the welder would help improve the reliability of the model predictions. In addition, all welding fume measurement data of this study were collected from indoor areas. Including welding fume measurement data obtained from the outdoor welding would be necessary to properly validate the model and the weldART should also be used cautiously when predicting exposure in outdoor situations. The ART model incorporated higher dispersion rates in outdoor areas compared to indoor areas [103], and this would also most probably be the case for welding. If this is the case the current weldART would be expected to overestimate the exposure for welders outdoors and so may be precautionary.

Conclusions obtained from the model calibration process indicated that the key welding-specific MFs to be used in the weldART model are the type of welding process, input power level, shield gas, and welding electrodes. However, when performing the model verification process, in addition to MFs obtained from model calibration, it was found that localized control and the distance of welder's head were two other critical MF that needed to be incorporated to provide accurate exposure estimates. Thus, these two factors were included as MFs in the weldART model. However, to further increase the capability of the weldART model, the effect or wearing personal respiratory protective equipment should also be studied and incorporated. There are many types of personal protective equipment for welding activities that can affect the welding fume concentration. For example, a welder using a welding face shield is more likely to be exposed to welding fume than a welder who uses a respirator helmet.

As most of welding fume measurement data applied in model calibration and model verification were collected from a very large indoor spaces (over 3,000 m^3), it was necessary to incorporate a 4-compartment in the model, the RM compartment, so that the model could represent and apply to more comprehensive welding situations. Application of weldART model in small areas would not require this degree of refinement and the FF compartment could be combined with the residual room zone (RM).

6.6 Conclusions from the Verification Exercise

Results of model verification revealed that weldART model overestimated measured concentration, especially at low concentrations. The main reason may be because there were additional sources in the FF during the calibration that were unaccounted for in the model. Most of the welding fume measurement data applied in this study were collected from very large working areas without effective general ventilation systems. It was reported that dispersion depends on the area of the working space and air circulation of that area. The larger the area, the lower the personal exposure levels when compared with smaller area [103]. Therefore, to verify this hypothesis, it is important to study the number of fume concentrations in all types of situations in the future. In European work situations, welding in such a large area seems to be an exception and usually welding is performed in smaller workplaces. In such situations the weldART may be used with three compartments.

When the weldART model verification was performed, it was found that the model can be a useful tool to predict welding fume exposure to some extent, especially at concentrations higher than around 1 mg/m^3. In further study, however, the weldART model should be further validated with a wider variety of situations and much more measurement data to verify this statement.

CHAPTER 7
DISCUSSION AND FUTURE PROSPECTS

7.1 Introduction

Both evaluation and impact simulations are used to assess the scope of human exposure, although retrospective exposure estimation may adopt additional or hybrid methods. Common form of exposure models is as follows [121]:

$$\text{Exposure Intensity} = f(\text{Predictors of Exposures})$$

The construction and use of mathematical models is an important aspect of forecasting the possible effects of chemical emissions on worker health, some of which may be new in surroundings [101]. This is a complementary approach to measuring exposure and should not be seen as an alternative to measurement; measurement and modelling are closely intertwined, and each relies heavily on the other. There are a number of possible applications for exposure models, including retrospective risk assessments for epidemiological studies, risk prediction before processes are constructed, or support for a systematic programme of exposure measurement. Measurements and models can be combined through the application of Bayesian statistics, as has been done in the ART model tool. The amount of occupational hygiene samples necessary to sufficiently identify exposure to enable improved cost-effective target-based impact assessment strategies [122] can be reduced by combination of exposure estimations and evaluations in a risk assessment.

The objectives of this study were to develop a model tool to predict concentrations of welding fumes as total particulate concentration without separation of metal component of the fume. This study was developed to extend the ART model tool, which does not contain the capability to model welding fume exposures within its applicability domain. At present, there is no general model that can be used predict welding fume exposure.

This study consisted of five main phases. The first stage was a literature review including a study of the ART model, principle of exposure modelling, and various research works related to welding fume, particularly the main characteristics that could determine worker exposure during the process. At this stage, it was identified that a key modifying factor (MF) to be used in model development was the fume formation rate. The variables that have been identified to affect fume formation rate were type of welding process, input electrical power level, shielding gas, and welding consumables. In addition to fume formation rate, convective airflows and the interaction of the welder with the fume plume were other MFs that were recognised must be applied in the model development.

The second stage of the research was collection of welding fume exposure data and associated contextual information during welding operations. In this stage, air samples were obtained from an area where welders worked in a fabrication plant with metal structures. There were three types of welding undertaken by welders including FCAW, SMAW and GTAW. Samples were collected from three areas: the WP area, NF area and FF area. For the WP area, two types of air sampling device were used: a Swinnex sampler and MicroPEM, were placed together in the behind the welding visor to evaluate welder exposure. In this regard, the Swinnex sampler collected samples for gravimetric assessment of exposure. Meanwhile, the MicroPEM obtained real-time monitoring data using a light scattering methodology. The study results indicated that the welding types with highest to lowest welding fume particulate concentrations were FCAW, SMAW and GTAW, respectively. The comparison of fume concentrations between the Swinnex sampler and MicroPEM showed that the MicroPEM monitors underestimated and had poor correlation with the corresponding data from the Swinnex samplers. The cause for underestimation was partly as a result of MicroPEM measuring $PM_{2.5}$ while the sizes of welding fume particles are between a few nanometres to 20 µm [14]. The Swinnex samplers gather particles with larger size than the MicroPEMs [33], [99]. However, it is probable that particles deposited in the sampling tube before they entered the aerosol sensor because of the electrostatic deposition [100]. Furthermore, the MicroPEM monitors may have underestimated because air inlet of sampling tube of MicroPEM was place in a position higher than air inlet of Swinnex sampler and being inserted deeper inside the welding visor. Therefore, the data obtained from the MicroPEM was not used directly in the model calibration, although these data were adopted to prescribe duration of welding activities.

The third stage of the research was model development for welding fume exposure (the weldART model). This step began with a conceptual diagram of the weldART model with three compartments linked to welding-specific MFs. It was found that welding process type, input power level, shielding gas, and welding electrodes are main MFs for development of weldART model. In addition, other important factors to be considered in the model calibration process were the dissipation of the fume away from the arc and the welder’s exposure to the fume plume. Nonetheless, it was found that when the model verification process was performed, in addition to MFs determined from model calibration, localized control and distance of welder's head were two other crucial MFs that had to be taken into consideration in order to obtain more accurate exposure estimated. Therefore, these two factors were included as MFs in final weldART model.

The fourth stage was model calibration, which used the data obtained from the sampling in stage 2. In this stage the conceptual diagram of the weldART model was adjusted from three compartments to four compartments to account for the very large work site where the samples were collected. This stage originally aimed to develop a multiplicative deterministic model with the same structure as the ART tool with multipliers associated with definite model factors. However, the researcher identified that it was possible to create a sophisticated multi-compartment mass balance model because welding involves a limited set of similar procedures and processes. However, this model is specific to welding because it requires inputs and MFs, namely compartment airflow rates, emission strengths and other determinants in order to create more realistic modelling [93]. As a result, the calibrated four-compartment mass-balance weldART model was able to predict welding fume exposure with a reasonable degree of confidence.

The last stage was model verification, which used welding fume measurement data from reports and published papers to assess the reliability of the weldART model. This verification study suffered from limitations in the available published information on welding fume measurement data, which were obtained from the reports and published papers, and were missing key contextual data such as information on airflow rate in the work room, workspace volume, welding input power level, shielding gas etc. Therefore, a Monte Carlo technique was adopted to generate the missing data and account for uncertainties in the model process. It was found that the basic weldART model overestimated the fume concentrations, but when the factors related to the distance of welder’s head from the welding fume and the effectiveness of localized controls were taken into account, as noted above, the weldART model could produce more reliable and accurate results, although still overestimating exposure at lower concentrations. The overestimation may be due to contribution of background process which are excluded in the model. For example, the verification process may have been affected by other welding or dust-generating processes in the FF, particularly when there were low concentrations arising from the welding activity.

7.2 Discussion

Welding is a source of ultra-fine particles [30]. The threshold limits for ultra-fine particles are under discussion in many jurisdictions. However, determining the right exposure metric remains quite a challenge. While gravimetric assessment is used to evaluate the mass concentrations of inhalable particles, particle counts are now applied to estimate exposure to ultra-fine particles whether the conversion between these metrics be explored for the OEL settings or not. Most of the welding fumes are produced as nanoparticles [123], although the welders' ultra-fine particle exposure has not been adequately described and the chemistry-physics of nanoparticle welding fume is still being studied [52]. The weldART model could be extended and developed by testing with fume in nanoparticles size to predict particle number concentrations, but this would require further fundamental research on emission characteristics. It was also found that welding fume nanoparticles caused more harm to the body at cellular level than large welding fume particles [124]. Therefore, particle number concentration could be a better exposure measurement than the mass concentration. Moreover, particle number concentration is more important than mass for biological interactions (i.e., absorption, translocation, and localized chemical exposure). This is because under identical mass, substantial amount of smaller particles will interact and/or pass through biological surfaces [125]. One of the main restrictions of adopting particle mass standards is that the concentration values are heavily biased towards larger particles; the mass of a lesser amount of large particles can be significantly larger than density of substantial amount of small particles [126]. Lehnert *et al*. [52] concluded that integration of various exposure metrics such as particle number and mass welding fume concentration remains challenging.

The risk of making a mistake in decisions about health risks depends greatly on the applicability of exposure estimations. Analysts should use data obtained from reliable trustworthy sources, which can be direct measurements or from validated models. The complication in meeting the validation requirements of a model is that it increases as the domain of application extends. Also, it is not surprising that in health risk assessment, the greater the number of estimates that need to be made, the greater the need for dependence on a model to perform the evaluations. It becomes more burdensome to quantify the model's accuracy and precision with the increase in complexity and size of the model, particularly when a diverse range of input parameters are needed. Moreover, the probability of material errors attached to many of the model's components may be increased in such circumstances. Such uncertainty could lead to ambiguity in the model's predictions. Combining multiple values for the parameters may assist in providing an identical characteristics of the model's behaviour with past examination, but there is no precise indication of suitable combinations to be applied for the forecasts [101]. Elements of a sophisticated and comprehensive model can be examined by the peer group of analysts to review the system, which may minimize the risk of errors.

Most emission rates measurements for exposure estimation studies have been conducted in controlled laboratory settings such as fume chambers or controlled welding booth enclosures and focused mainly on the welding activity. However, in actual work settings, a welder is also exposed from other activities including grinding, gouging, drilling and metal cutting. Therefore, emission data developed under laboratory-controlled conditions do not reflect the range of real activities that affect overall particle emission for welders. In contrast, field-based emission factors are more likely to take into account factors that welders encounter during normal work operations. Although these factors could also be derived through less complicated assumptions (e.g., defaults) or from non-representative data of the populations or conditions of interest (e.g., by referring to results obtained for other purposes), obtaining real emission data would result in more accurate exposure models [65]. Furthermore, this would allow hygienists to collect sufficient and relevant parameters such as sources and media of concern, key exposure microenvironments, and exposure direction [65].

Development of weldART model required both calibration and validation to verify the model's accuracy and determine whether it is appropriate to be used as a tool to evaluate welding fume exposure. These two stages required welding fume measurement data. However, in addition to fume concentration data, it was necessary to have complete description of the work environment and nature of welding works including welding process type, size of the working area, localized control and arc time. Also, information about air flowrate at the four working areas (WP, NF, FF and RM) and fume emission rate were also required. In particular, air flowrate and fume emission rates were observed in some specific studies or in laboratory chamber. This was because determination of air flowrate and fume emission rate required tools and methods in addition to those used in the evaluation of welding fume exposure. However, there were only a few studies on this issue and not covering all types of welding. Therefore, there should be more studies on air flowrate and fume emission rate data in a variety of situations to further develop weldART model to be more reliable.

In addition to the factors mentioned above, localized control and distance of welder's head to the welding plume were identified by the researcher at the verification stage as important. The localized control factor of this study used multiplier values according to ART model [103]. Factors relating to distance of welder's head in this study were determined by whether the welder's head was near and aligned with welding fume plume or not. Nonetheless, the factors did not consider whether the welder stood or sat while welding. Studies have shown that a welder who conducted welding in a standing position could be exposed to higher fume exposure than when seated [127]. It was reported that when comparing standing, sitting and crouching positions, standing position could produce the highest fume exposure, follow by crouching and sitting position respectively. In addition, there are three natures of common welding positions namely flat (downhand), horizontal, vertical and overhead. In this regard, most welders would use the downhand position for welding which is the position with highest fume exposure around welder's breathing zone [128]. If these factors were taken into the model as a modifying factor (MF) then it could further improve the accuracy of weldART model. Therefore, it is important that these data should be recorded when performed welding fume measurement as the data can be applied in the weldART model and evaluation of welding fume exposure by occupational hygienists. Furthermore, the obtained data could be used in development of preventive measures and/or practices to reduce fume exposure by the welder's avoiding their head and shoulders from coming near the welding fume plume.

Factors regarding the size of the working area also have major influences on the amount of fume exposure. In large areas (as in this study in Chapter 4) or open spaces, some of the welding fume would be dispersed and diluted by air movement as well as spread in the surrounding atmosphere without accumulation in the working area of the welders. On the other hand, if the working area is small or an enclosed space, welding fume will not be able to disperse easily. Similarly, in the confined spaces such as in ship construction, the welding fume would accumulate, and the welding fume concentration would be higher than for the same operation in a large well-ventilated room.

There were two objectives for selection of MicroPEM, a real-time monitoring instrument, in this study, including to compare the measurement results with gravimetric method and to observe fume concentration level in each sampling period. The results of the study showed that fume concentrations obtained from the MicroPEM were underestimated when comparing with the fume concentration obtained from gravimetric method. The reasons for this are described in detail in Chapter 4. The sampling period data obtained from the MicroPEM can, nonetheless, be used to study fume concentrations during welding period and non-welding period, i.e., to identify the arc time. In addition, the MicroPEM has capabilities to measure both $PM_{2.5}$ and PM_{10}. In this study, only $PM_{2.5}$ was measured. It was reported that the sizes of the fume were varied widely, ranging from 0.005 µm to 20 µm [14]. Therefore, in the future, if there are studies of fume concentrations using MicroPEM, samples of both $PM_{2.5}$ and PM_{10} should be collected, although care needs to be taken to avoid underestimation using this method. This may provide more accurate study results.

The sampling periods in the calibration study ranged from 8 to 71 minutes, which were the actual working time of one welder per job task. Some welders took periodic breaks to change the filler wire or change welding posture. The arc times were between 4 - 69 minutes, representing 36.8 - 100% of the sampling period. Because the sampling periods were relatively short. The data could not be used to compare with the occupational exposure limit over the operating period (time-weighted average; TWA).

7.3 Strengths and Weaknesses of the Research

Strengths of the research:

- This study created the weldART model, a tool used for evaluation of welding fume exposure which, currently, cannot be effectively measured by any other available model.

- Calibration of weldART model indicated a good estimation of personal welding fume exposure with ratio of the simulated exposure to the evaluated values equal to 1.3 (R^2 = 0.94).

- The weldART model was formed by calibration using measurement data obtained from large workspaces, which represent most of the welding works as welders usually perform the works in large workspaces. Nonetheless, the model can also be used for evaluation of smaller areas.

The validation of the weldART model using published data identified further improvements necessary to provide a general model for welding processes; in particular, the incorporation of factors relating to the time the welders head was in the welding plume and the effectiveness of localized control measures.

Weaknesses of the research:

- In the calibration dataset, the poor correlation between simulated and evaluated concentrations in the NF and FF may be due to low concentrations and the short sampling period resulting in poor sensitivity for the gravimetric samples.

- When the welding fume exposure evaluation area has low concentrations, discrepancies in near-field and far-field areas may be found, probably due to the contribution of background process is excluded in the model, e.g., other welding or dust-generating processes in the FF.

- There is no study of parameter related to the effectiveness of respiratory protective equipment (RPE). In addition, this study does not make determination using quantitative comparison of the level of welding fume 'outside' and 'inside' the protective equipment, as well as does not make any comparative study on classification of RPE in terms of mask type and filter type.

7.4 Main Conclusions

This study involved model development for welding fume exposure as total particulate concentration without separation of metal component of the fume, also known as the weldART model. The weldART model was an elaborate four-compartment mass balance model. Key variables needed to model fume exposure, include work area characteristics, welding type, flow rate or air velocity in the welding area, working area size, welding time, break time, emission rate, localized controls and ventilation system, were collated into an Excel worksheet, where the exact data required for the model calculation were held. For unknown variables, R was used to simulate likely values using a Monte Carlo technique to generate data for the model.

After applying weldART model with data sets to determine fume concentration using variables obtained from systematic review articles and R programme simulation using Monte Carlo method without WH and LC variables, it was found that the average fume concentration obtained from weldART model was overestimated. Regarding weldART concentrations, when considering key factors, it was found that when WH and LC were applied in weldART model, the concentration value would be closer to the measured concentrations. It is considered that the weldART model is an effective mechanism to estimate welding fume exposure.

7.5 Future Prospects

The Welding Advanced REACH Tool (weldART) model could offer an alternative approach to evaluate fume concentration for occupational hygienists. At present the model is available as standalone R-code that are freely available, but it lacks a suitable user-friendly user interface. The weldART is calibrated and has had a limited verification exercise completed, but further evaluation is necessary.

(1) As particle size varies with operating parameters in the weldART model, the particle size distribution of welding fumes is a critical factor that required further studies. As fumes are particles with a relatively varied size distribution, especially at nanometre size [19], they are more hazardous to health than large particles. Therefore, there should be study on weldART model's effectiveness on evaluation of welding fume exposure at nanometre size levels.

(2) Further investigation on elemental composition within various particle sizes in fumes should be taken and the weldART model should be adapted to predict specific metal exposure.

(3) The study should apply more levels of various operating parameters to determine variation in the fume formation process, such as, a comparative study on classification of RPE in terms of mask type and filter type. In addition, the study of Goller and Paik [129] regarding FCAW indicated that the range of fume mass concentrations inside helmet was between 36 - 71% of mass concentrations outside helmet. Similarly, studies on GMAW and BTAW performed by Cole *et al*. [130] showed that fume mass concentration in inside the welding helmet were reduced by more than 99% when comparing with mass concentration outside helmet. A study should be conducted to compare the level of welding fume outside and inside welding helmets.

(4) Exposure predictions in real workplace environments are limited by insufficient quantitative data of exposure determinants and arithmetical exposure models that are suitable for the situations. Most companies do not have any information on simple determinants such as general ventilation rates on workrooms or worker activity patterns and data such as time spent in close proximity to welding fume plumes. Fundamental

data, such as fume generation rates, are difficult to establish in most circumstances and these data are not systematically provided by equipment suppliers [131].

Practical tool for conducting welding fume measurement of occupational hygienist should be developed. In addition, measurement information should be recorded accurately and completely as shown in Appendix A.

(5) Welding fume measurement data of this study, which were applied in both model calibration and model verification stages were relatively small. Therefore, to reduce the uncertainty of the development of weldART model in the future, a greater number of welding fume measurement data is needed. Welding fume exposure should be studied by simulating a situation in connection to laboratory and/or experimental chamber and assessed by weldART model. This modelling will allow the researcher to control and define variables adopted in the model, and can enhance validation and, at the same time, reduce uncertainties in the model.

(6) Most of the welding fume measurement data applied in model verification contain uncertain emission rate. When these data were used in the model, they must be simulated using the range values obtained from Table 4. Therefore, results may contain some discrepancies. As a result, emission rate is another variable that should be recorded when conducting welding fume measurement. In addition, information on the current fume emission rate did not cover all types of welding works. Therefore, there should be studies on fume emission rate as well. Emission rate is a parameter that depends on various factors and is difficult to control. Thus, there should be a study on comparison of emission rate of each welding process type and welding characteristics, both in laboratory and the actual welding situation to gather the information as database for used in models.

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APPENDIX A

Table 20 Sample of welding data collection spreadsheet.

ID	**Process type**	**Concentration (mg/m^3)** (over the sampling time, i.e. NOT a time-weighted average)	**Sampling time (min)**	**Room volume (m^3)** or Room dimension (W x L x H) or Outdoor close to buildings or far form buildings - include approximate size, e.g. within about 10% of true value	**Room ventilation**	**Local ventilation**	**Other welders present in the workroom?** (Number of other workers welding)	**Air changes per hour** (approximate, e.g. 0.1, 0.3, 1, 3, 10)	**Arc time (min)**	**Particulate type measured**	**Sampling head position**	**Sample type**	**Welding electrode**	**Current (A)**	**Voltage (V)**	**Shielding gas** (e.g. Ag, Ar-2%O2, Ar-18%CO2)	**Note**
1																	
2																	
3																	
4																	
5																	
6																	
7																	
8																	
9																	
10																	

APPENDIX B

The Example R Code for the Deterministic and Probabilistic Models

```
# required libraries
library(deSolve)
library(ggplot2)
library(purrr)
library(tibble)
library(tidyr)

# this fuction is for checking if the input parameter is a single value or a vector (the sampling interval)
# if vector --> return  a random number which sampling from the input interval
# if single --> return that input value
###
FixedOrSampling <- function(parameter) {
  val <- NULL
  if(length(parameter)==1 & is.numeric(parameter)){
    val <- parameter
  }
  if(length(parameter)==2 & is.numeric(parameter)){
    min <- parameter[1]
    max <- parameter[2]
    val <- runif(1,min,max)
  }
  return(val)
}

# this function is for calculating the 95% confidence interval of a parameter in the output data frame (outdf)
#
CI95 <- function(parameter, outdf) {
  par.data <- outdf[[parameter]]
  ci <- confint(lm(par.data ~ 1),level = 0.95)
  return(ci)
}

#
# the main function for doing the simulation
# fixed parameters: Vwp, Vnf
# random parameters: B1, B1R, B2, B2R, B3, B3R, Qff, QffR, Qrm, Vff, Vrm, EwpVal, EwpTime
#
```

```
# each parameter can be input as a single value or a two dimension vector, which represent the interval
# for sampling, i.e., B1 = 0.5 for fixing B1 at 0.5 or B1 = c(0,1) for sampling the value of B1 between 0-1.
###
Simulation <- function(B1, B1R, B2, B2R, B3, B3R, Qff, QffR, Qrm,
                       Vff, Vrm, EwpVal, EwpTime, Vwp = 0.2875, Vnf = 0.2875,
                       Tint = 10, Ttot = 28800, nsim = 1, filename , CI = FALSE){

  if(nsim <= 0){
    stop("nsim must be positive and greater than 0 !")
  }

  message("Please wait ...")

  # set progress bar
  pb <- txtProgressBar(min = 0, max = nsim, style = 3)

  pars <- list(B1 = B1, B1R = B1R, B2 = B2, B2R = B2R, B3 = B3, B3R = B3R, Qff = Qff, QffR = QffR,
            Qrm = Qrm, Vff = Vff, Vrm = Vrm, EwpVal = EwpVal, EwpTime = EwpTime, Vwp = Vwp,
Vnf = Vnf)

  # initial values
  yini <- c(Cwp = 0, Cnf = 0, Cff = 0, Crm = 0)
  Ttot <- Ttot
  Tint <- Tint
  times <- seq(0, Ttot, by = Tint)

  #model
  LVmod0D.X <- function(Time, State, Pars) {
    with(as.list(c(State, Pars)), {
      Twpnf <- Cwp * B1
      Tnfwp <- Cnf * B1R
      Twpff <- Cwp * B2
      Tffwp <- Cff * B2R
      Tnfff <- Cnf * B3
      Tffnf <- Cff * B3R
      Tffrm <- Cff * Qff
      Trmff <- Crm * QffR
      Trmout <- Crm * Qrm
      Ewp <- ifelse(Time < EwpTime,EwpVal,0)
      dCwp <- (Ewp + Tnfwp - Twpnf + Tffwp - Twpff)/Vwp
      dCnf <- (Twpnf + Tffnf - Tnfwp - Tnfff)/Vnf
      dCff <- (Twpff + Tnfff - Tffwp - Tffnf - Tffrm)/Vff
```

```
    dCrm <- (Tffrm - Trmff - Trmout)/Vrm
    return(list(c(dCwp, dCnf, dCff, dCrm)))  })
}

# the output dataframe
outdf <- data.frame()

for(i in 1:nsim){

  pars.random <- unlist(map(pars, FixedOrSampling))

  out <- ode(func = LVmod0D.X, y = yini, parms = pars.random, times = times)

  # uncomment if you would like to calculate the ratios
  # ratio1 <- sum(out[,2])/sum(out[,3])
  # ratio2 <- sum(out[,3])/sum(out[,4])
  # ratio3 <- sum(out[,4])/sum(out[,5])
  # ratios <- c(ratio1 = ratio1, ratio2 = ratio2, ratio3 = ratio3)

  # show all parameters + ratios
  #outdf <- rbind(outdf,t(c(pars.random, colSums(out[,2:5]*Tint/Ttot),ratios)))
  outdf <- rbind(outdf,t(c(pars.random, colSums(out[,2:5]*Tint/Ttot))))

  setTxtProgressBar(pb, i)
}
close(pb)

## calculte the confidence interval
if(isTRUE(CI)){
  pars.names <- list("B1","B1R","B2","B2R","B3","B3R","Qff","QffR","Qrm",
                "Vff","Vrm","EwpVal","EwpTime","Vwp","Vnf","Cwp","Cnf","Cff","Crm")
  outdf.list <- rep(list(outdf),length(pars.names))
  ci.list <- map2(pars.names,outdf.list,CI95)
  ci.df <- data.frame()
  for(i in 1:length(pars.names)){
    vec <- ci.list[[i]]
    row.names(vec) <- pars.names[[i]]
    ci.df <- rbind(ci.df,vec)
  }

  #show CI on the console
```

```
    print(ci.df)

    #show histogram
    hst <- PlotHistogram(outdf = outdf)
    print(hst)
  }
  # write the output file (in CSV format)
  write.csv(outdf, file = filename)
  message(paste(filename, "has been writen.\n"))

  #return the output (not print on the console)
  invisible(outdf)
}

# ploting the histogram of each parameter
# outdf - the output from Simulation function
###
PlotHistogram <- function(outdf) {

  outdf.temp <- outdf %>% pivot_longer(names(outdf), names_to = "parameters", values_to = "values")

  pars.names <- list("B1","B1R","B2","B2R","B3","B3R","Qff","QffR","Qrm",
                     "Vff","Vrm","EwpVal","EwpTime","Vwp","Vnf","Cwp","Cnf","Cff","Crm")
  outdf.list <- rep(list(outdf),length(pars.names))
  ci.list <- map2(pars.names,outdf.list,CI95)
  ci.df <- data.frame()
  for(i in 1:length(pars.names)){
    vec <- ci.list[[i]]
    row.names(vec) <- pars.names[[i]]
    ci.df <- rbind(ci.df,vec)
  }

  ci.df2 <- rownames_to_column(ci.df, var = "parameters")

  names(ci.df2) <- c("parameters", "CILower","CIUpper")

  ggplot(data=outdf.temp ,aes(values)) +
    geom_histogram(binwidth = function(x) 2 * IQR(x) / (length(x)^(1/3))) +
    geom_vline(data = ci.df2, mapping = aes(xintercept = CILower), color = 'red', linetype='dashed') +
    geom_vline(data = ci.df2, mapping = aes(xintercept = CIUpper), color = 'red', linetype='dashed') +
    ylim(c(0,100)) + facet_wrap(~parameters, scales = 'free_x')
```

```
}

# running the simulation for 10,000 iterations and save the output to file
test <- Simulation(B1 = c(0.0063, 0.025),
                   B1R = c(0.0145, 0.0575),
                   B2 = c(0.0371, 0.1472),
                   B2R = c(0.029, 0.1148),
                   B3 = c(0.0151, 0.0599),
                   B3R = c(0.0234, 0.0924),
                   Qff = c(0.1075, 0.375),
                   QffR = c(0.1075, 0.375),
                   Qrm = c(0.075, 0.25),
                   Vff = c(101, 300),
                   Vrm = 14400,
                   EwpVal = c(0.48, 2.04),
                   EwpTime = 22932,
                   Vwp = 0.2875,
                   Vnf = 0.2875,
                   Tint = 10,
                   Ttot = 28800,
                   nsim = 10000, filename = "test.csv")

# plotting the histogram using the output from Simulation function
PlotHistogram(test)
```

APPENDIX C

PUBLICATIONS BY THE CANDIDATE

International Journal of
Environmental Research and Public Health

MDPI

Review

Extension of the Advanced REACH Tool (ART) to Include Welding Fume Exposure

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Abstract: The Advanced REACH Tool (ART) is a mechanistic higher tier model to estimate inhalation exposure to chemicals using a Bayesian approach. Currently the ART model does not include exposure to welding fumes within its applicability domain; it has only been calibrated for vapours, mists, and dusts. To extend the scope to metal fumes it is necessary to review the model structure to ensure that it is appropriate, and to calibrate the updated model using available welding fume exposure measurements. This paper provides a discussion of the key modifying factors (MFs) that should be considered to extend the ART model to include welding fume exposure. Based on our literature review, welding process type, input power level, shield gas, and welding electrodes have important impact on fume formation rates (FFRs). In addition, the convective dispersion of the fume away from the weld and the interaction of the welder with the fume plume should be incorporated into the ART model. Other aspects of the ART, such as the local ventilation, do not require modification to accommodate welding fume exposure. The ART does not include the impact of wearing personal protective equipment and so this is not included in our evaluation. Proposals are made for extending the scope of the ART to include welding processes.

Keywords: ART; exposure modelling; welding; fume

1. Introduction

Welding is one of the commonest activities carried out in the workplace, and the most popular method for joining metal materials together [1]. Due to rapid industrial development, welding is used in many processes and fields of production, and the number of welders is growing [2], with approximately two-million people around the world who are involved in welding [3]. In the UK there are about 190,000 welders, with around 73,000 professional and skilled welders, and the remainder are semi-skilled welders who carry out welding as part of their job [4–6].

There are many risks to health related to welding, for example, electrical shock hazards, heat or fire risks along with risks from metal fume and gases, and ultraviolet (UV) radiation from the arc [7]. These hazards mean that, if preventive measures are not adequate, in welders a range of health problems are possible, from acute health effects such as irritation of the respiratory tract, to an increased risk of asthma, neurological damage, through to lung cancer [8]. Amani et al. [9] reported that 92% of welders suffer eye injuries from UV radiation from the arc [10,11]. It is estimated that each year there are 175 welders in Britain who die prematurely from lung cancer because of welding fume exposure [12].

The electric arc or flame vaporizes the welding electrode and/or base metal, which then condenses into submicron particles called fumes. Fumes may be suspended in the air for long periods of time and may be inhaled into the lungs [13]. At high concentrations, welding fumes may cause a health hazard [14] and steps need to be taken to control exposure. Without adequate controls, the fume concentrations may be higher than the appropriate occupational exposure limit. To ensure that control measures are adequate it is prudent to undertake a risk assessment, which involves estimation of the exposure of workers to the fumes and, where appropriate, identification of the steps required to control that exposure. Exposure can be estimated by measuring the concentration of fumes inhaled by workers in a number of specific instances and/or by using a mathematical model of exposure concentration.

Exposure models are used in risk assessments and risk management to describe the association between emissions and concentrations, and to predict the impact of risk management measures. The important point in using models is that they allow us to think about the relationship between the process and environmental factors and exposure [15]. Exposure models are developed to reconstruct historical exposures or to assess possible future exposure in investigational scenarios [16].

The recent scientific interest in occupational exposure modelling has been tied to the need to quantify exposure for risk assessment required by chemical regulations in the European Union, i.e., the Registration, Evaluation, Authorisation & Restriction of Chemicals (REACH) Regulations [16], although welding fumes are not included within the scope of REACH. The European Chemicals Agency (ECHA) has outlined a tiered method for occupational exposure modelling. Tier 1 assessments use fundamental, reasonable screening models, which have some limitations in their input parameters. Several screening model tools are available at Tier 1 of REACH, such as Stoffenmanager, the European Centre for Ecotoxicology and Toxicology of Chemicals' Targeted Risk Assessment (ECETOC TRA) tool, and the Einfaches Maßnahmenkonzept für Gefahrstoffe Exposure Tool (EMKG-Expo-Tool) [17]. Tier 1 models are generally designed to overestimate exposure, i.e., they are "conservative". If a Tier 1 assessment cannot demonstrate there is sufficient protection for workers, then use of a Tier 2 assessment should be considered. ECHA advises that using a Tier 2 assessments can increase accuracy and validity of assessments [17]. However, these assessments are used to evaluate explicit exposure situations, and require extensive input data in order to control uncertainty [18]. The only higher tier model for inhalation exposure assessments recognised by ECHA is the Advanced REACH Tool (ART) [17]. The ART uses a Bayesian methodology; a mechanistic model evaluates inhalation exposure and any appropriate exposure measurements can then be used to update the model estimates [19]. However, neither the current ART model nor any of the Tier 1 model tools include welding processes within their scope, and they are therefore not useful for assessing health risks for welders.

This paper reviews the structure of the ART model in relation to exposure arising from welding fume to identify changes to the model's structure to extend the applicability domain of the ART to include these processes.

2. Methods

2.1. Search Strategy

There are a number of research studies that provide insight into the factors that influence the particulate and gaseous emissions generated by welding. We searched the scientific literature using the Scopus database for articles that provided relevant information. Search terms included 'welding fume' and 'factor' in the title, abstract or keyword. Articles with publication dates between 1 January 1969 and 1 August 2018 were selected. In total 351 articles were identified, and these were then screened (by the first author) using the title and abstract to identify those that were informative.

2.2. Inclusion and Exclusion Criteria

Studies were included in this review only if they related to metal welding fume and had relevant data concerning potential modifying factors related to the ART model, i.e., in relation to the generation of welding fume, fume dispersal in the workplace, localized controls or the interaction of workers with the air contaminants. Studies were excluded if they were published in a language other than English or were published in a non-peer reviewed journal or report. In total 52 articles are included in this review.

3. Welding and Welding Fumes

Welding is a metal joining process that uses heat and/or pressure. There are allied processes of cutting, brazing, and soldering, which are often grouped along with welding. The welding process is usually classified into two main groups, i.e., gas welding and arc welding (Figure 1). In turn arc welding is categorised into two sub-groups, i.e., metal arc welding such as shielded metal arc welding (SMAW), also known as manual metal arc welding (MMAW), and gas shielded arc welding such as gas metal arc welding (GMAW), flux cored arc welding (FCAW), gas tungsten arc welding (GTAW), also known as tungsten inert gas welding (TIG), and metal inert gas (MIG) welding. Typically, the inert gases used for MIG welding are argon or helium. Metal active gas (MAG) welding is a similar process that uses a reactive gas condition, also known as 'shielded with an active gas' [20,21]; CO_2 is mainly used as the shielding gas in this process. More than 90% of steel used in welding are mild steels, carbon steels or low alloy steels, with the remainder being stainless steel. Welding can also be carried out on aluminum, titanium, nickel or other metals [5].

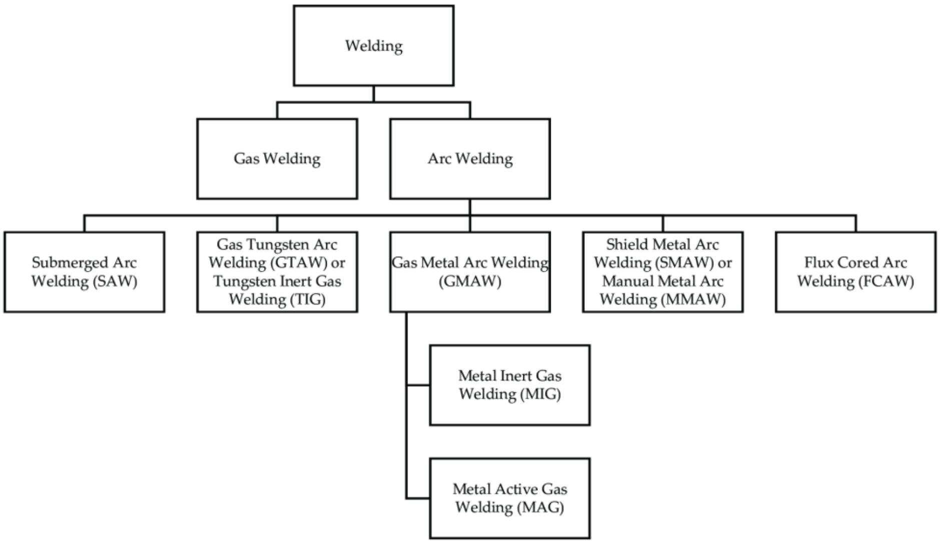

Figure 1. Schematic of welding methods.

Fumes are created when metal is heated above boiling point temperature, including heating from the arc via UV radiation, and the vapours produced rapidly oxidise and condense into a fine aerosol of solid particles [1]. The arc welding process can generate particles between 5 nm and 20 µm [22–27]. The main metal vapour elements come from the electrode [28]. Welding fume may consist of a mixture of many different metals, including aluminium (Al), chromium (Cr), hexavalent chromium (Cr(VI)), copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), nickel (Ni), phosphorus (P), tin (Sn), titanium (Ti), and zinc (Zn) [6,29,30].

In the 1970s, Heile and Hill [31] reported that the welding fume formation rate from GMAW was linked to welding conditions such as shielding gas, current, voltage, and metal transfer mode, including welding process parameters such as the electrode wire. The fume formation rate (FFR) is the rate at which welding fumes are generated; measured in mass per unit time [32]. From a review of the literature there are many factors identified that can influence the FFR, for example, electrode, shielding gas, welding parameters (voltage and current), and base metal [33]. In exposure modelling, these factors are known as modifying factors (MFs).

4. The ART Model

The best approach to assess exposure to hazardous substances would be to carry out personal monitoring on all workers in specific situations, but this is clearly impractical because of cost and resource limitations. Also, personal monitoring may not reflect exposure in the past because of changes in circumstances [34] and may not be representative of future conditions for similar reasons. As discussed above, many models of exposure have been developed for chemical exposure estimation to try to overcome some of these limitations. Exposure models can estimate the air concentration of hazardous substances for worker groups and periods of time for which personal monitoring is impracticable.

These models are often conceived within the source-receptor paradigm. These model inputs comprise factors related to the source of contaminant, generation, exposure control strategies and contaminant dispersal. The aims of the exposure assessment model should be to obtain accurate and precise estimates of the distribution of exposure [35]. Sometimes a model calculation can yield information more quickly than through monitoring in the workplace. Finally, models can be used to create testable hypotheses to improve the potential to evaluate actual exposures [16]. However, the validation of these model tools has not usually been performed before their release, and only sometimes afterwards [4].

Several generic exposure models exist to estimate inhalation exposure to hazardous substances [36,37]. The ART mechanistic model probably provides the most reliable generic tool for estimation of inhalation occupational exposure level. It has been selected a priori as the most suitable basis to develop a model for welding fume exposure. The ART can provide a prediction of inhalation exposure in situations where exposure data are unavailable, although it can also be used with a Bayesian updating process to incorporate available monitoring data for improved accuracy and precision [38]. The precision improvement depends on the relationship between the data and the scenario being modelled, the quantity of accessible measurements, and the variability of the measurements [39].

The ART mechanistic model uses a source-receptor structure with MFs related to the source, emission, transfer to the worker [17]. The mechanistic model, or the "prior" model in the Bayesian process, combines MFs in a multiplicative model form. Within the model, the work environment is conceptualised as two spatial volumes: the near-field (NF) surrounding the worker's head (i.e., a cube with 1-m sides) and the far-field (FF), which comprises the reminder of the work area [40]. The ART does not include the impact of wearing personal respiratory protection on inhaled intake of contaminants.

The ART tool has some limitations because it was calibrated separately to evaluate exposure to inhalable dusts, vapours, and mists. Estimates from fumes, gases, and fibre exposures have not been available from the tool because of the lack of suitable calibration data and the lack of the appropriate model formulation for these situations [19]. To date there have been no studies reported on the development of the model for estimating these exposures, including for welding fume inhalation exposure.

5. Characterization of Principal Exposure Modifying Factors for Welding

Cherrie et al. [41] noted that small localized sources that involve elevated temperature, e.g., welding, present a difficult problem in terms of characterising the dispersion of the hazardous agents. For example, in these cases, the workers may place their head into, or close to, the dispersing plume, giving higher than otherwise exposures. The authors suggested further work should be considered on this issue in the ART model.

Boelter et al. [30] investigated welding fume concentrations using a two-zone mechanistic model like the ART. They used the model to estimate the FFRs in two work situations. This model is based on the breathing zone of a worker (the NF) and the surrounding area (the FF). In tests they found that the average concentration in the NF was higher than in the FF (2–10×) and was relatively independent of the general ventilation in the work areas (FF) investigated. They also identified that the general ventilation in the working area affected background concentrations and, for example, in a semi-outdoor area they found the FF concentration of welding fume was about half that in an indoor area, which was consistent with the lower measured airflow exchange rate in the latter situation. The estimated welding FFRs were similar in both situations where the field tests were carried out, but these values were approximately an order of magnitude lower than the FFRs obtained from laboratory tests. The authors recommended that the two-zone model can be used for estimation of both NF and FF air concentrations for welding fume, although it is important to have realistic data for the input parameters.

Hobson and colleagues [28] developed and validated a multivariate regression model to assess welding fume exposures using data retrieved from the published literature. They had particulate mass and manganese (Mn) concentrations from the activities of welders, which were reported as arithmetic means. Hobson et al. summarized the exposure measurements and related contextual factors, for example, sampling year, type of industry, type of welding process, ventilation type, degree of enclosure of the work environment, base metal, and sampler positioning of the worker. This study was performed to select related factors as the independent variables to build the model. The results showed that the best model included the type of welding process and degree of enclosure as the significant factors to predict the welding particulates and Mn concentrations (r^2 = 0.76). The welding process in this study was identified as one of four types, i.e., SMAW, GMAW, GTAW, and FCAW and the enclosure was grouped into four categories, i.e., open space, enclosed space, confined space, and not specified space. Hobson et al. suggested that if more detailed descriptions of exposure determinants had been available this could have improved their model, for example, including electrode type as a factor in welding fume generation.

Weiss et al. [42] measured respirable and inhalable welding fumes to determine the exposure of welders to Cr and Ni. They measured both external inhalation exposure and internal exposure using biological monitoring via urine and blood. The results of this study show a strong relationship between respirable and inhalable concentrations for both Cr and Ni, with correlation coefficients (r) of 0.87 and 0.85, respectively. The average concentration in the inhalable welding fume was around twice the respirable welding fume concentration. In addition, the respirable Cr and Ni concentrations were significantly associated (r = 0.79). Likewise, Pesch et al. [43] studied the exposure to Cr(VI) and Ni in welders. They also found a strong relationship between respirable Cr and Ni concentration with r = 0.83, but Cr(VI) and Ni concentrations were weakly correlated (r = 0.42) to total welding fume concentration. In addition, the median level of exposure to welding fumes decreased from GMAW (1.06 mg/m^3), to GTAW (0.35 mg/m^3), and SMAW (0.25 mg/m^3). In Weiss et al.'s paper [42], the welding process was categorised into four groups, i.e., GMAW, FCAW, GTAW, and SMAW. The average welding fume concentrations decreased, for respirable and inhalable concentrations, respectively, from FCAW (6.87 mg/m^3 and 6.24 mg/m^3), GMAW (1.64 mg/m^3 and 2.71 mg/m^3), SMAW (<0.50 mg/m^3 and 0.82 mg/m^3), and TIG (<0.42 mg/m^3 and <0.58 mg/m^3). Electrode and base metal were the most important variables that affected the concentration of Cr and Ni. Weiss et al. [42] concluded that the main factors influencing welding fume concentration and emission rate were electrode/base metal and welding process type. Pesch et al. [44] also studied the exposure to manganese (Mn) and iron (Fe) in welders. They concluded that the main factor that affected the concentration was welding process type. Moreover, Weiss et al. [42] and Pesch et al. [44] claimed that working in a confined space increased the exposure by two-fold compared to non-confined areas, and using "efficient" ventilation decreased the exposure level by approximately two-fold compared to an "inefficient" ventilation systems.

Flynn and Susi [45] developed a regression model for welding fume exposure. They obtained the welding fume exposure data for pipefitters and boiler workers from the Center for Construction Research and Training (CPWR). They fitted a regression equation to estimate Mn exposure and variance, given the total welding fume exposure. They showed that the average concentrations of Mn and total welding fume for the boiler workers were higher than for the pipefitters by three and four times, respectively. The high exposure for boiler workers was attributed to poor ventilation in the work space. There was a good relationship between manganese and total fume concentration of the pipefitters and boiler workers with r^2 0.51 and 0.64, respectively.

Generally, gas welding and arc welding need to use filler materials for welding. The filler material suitable for gas welding is provided by a non-electrode material (i.e., filler rod or filler wire) while for arc welding the electrode or base material may provide the filler. Electrodes can be divided into two types, depending on the welding process type. The first electrode type is consumed during welding providing both electrode and filling material. This electrode type is usually used for SMAW and GMAW. The second type of electrode is non-consumable and is usually used for GTAW. Therefore, the electrode types and welding process types should be considered together as factors related to welding fume generation. Due to the electrodes involvement in fume generation, the chemical composition of the electrode should also be considered in relation to the fume composition. The commonest chemical substances found in electrodes are Cr, Ni, Mn, and Fe [27], and it is important to be aware of the impact of consumables on welding fume composition.

It is clear that the location of welding activity, particularly the degree of enclosure, influences welding fume exposure. Different approaches have been taken by the various studies reviewed have to categorising ventilation and enclosure and all these seem compatible with the approach used in the ART model. Information from studies that investigated specific aspects of welding, for example, electrical current and voltage, electrode type, and shielding gas are described below.

5.1. Current and Voltage

The electrical current and voltage used in welding processes are probably the single greatest influencing factors on the generation of welding fumes for FCAW [46] and GMAW [47]. These factors affect the FFR due to differences in temperature of the electrode tip, type of metal transferring to the electrode, and type of current, i.e., alternating current (AC) and direct current (DC). High electrode tip temperature produces increased FFRs from an elevated evaporation rate and a rise in melting rate of the electrode, facilitating easy electrode material transfer through the arc [32].

In GMAW, the molten droplets of metal transferring from the electrode to the base material, referred to as metal transfer mode, can be categorised into five types, i.e., short-circuit transfer, globular transfer, spray transfer, pulse-spray transfer, and rotating transfer [48]. A very typical transfer mode is short-circuit transfer [49]. Each metal transfer mode has a different metal transfer stability, resulting in different FFRs. Transfer mode type depends on electrical current and voltage, for example, globular transfer operates at low current and high voltage and produces high FFRs [32]. Pires et al. [50] and Quimby and Ulrich [51] concluded that the FFR was highest for the globular transfer mode, at around 23.5 V with pulsed current and 26.5 V with steady current [51].

Hovde and Raynor [52] studied the effects of voltage on particle mass concentration in welding fume. The results showed that increasing the voltage from 16 to 21.5 V increased particle concentration, but between 21.5 and 23.5 V the fume concentrations remained almost constant.

De Meneses et al. [49] investigated short-circuit transfer mode in GMAW and concluded that increasing voltage resulted in increasing FFR; at 25 V the FFR was around five times that at 17 V. However, in their experiments it was not clear what other uncontrolled factors were important, e.g., short-circuiting current, droplets diameter, arc length, and arcing time.

For welding, the current is generally catagorised into three types, i.e., alternating current (AC), direct current electrode positive (DCEP), and direct current electrode negative (DCEN). According to Slater [32], the difference between a DCEP and DCEN may produce differences in FFRs of up to 30% in SMAW. In this process, the higher fume generation using the DCEP comes from the higher temperature of the electrode tip. Conversely, in GMAW, DCEN produced a FFR higher than DCEP [32]. This result may be related to shielding gas effects. In addition, Slater noted that use of AC in GMAW can result in fume emission similar to DCEN.

In FCAW, increasing current and input power (i.e., current × voltage) caused an increased rate of fume generation by an exponent of 1.75 and 1.19 respectively (Equations (1) and (2) below) [46].

$$\text{FFR} = 6.2\ \text{E} - 2(\text{Current}^{1.75}),\ r^2 = 0.86 \tag{1}$$

$$\text{FFR} = 7.1\ \text{E} - 1(\text{Input Power}^{1.19}),\ r^2 = 0.86 \tag{2}$$

Generally, an increase in the current will also require an increase in voltage [32]. A change in voltage of 1–5% can produce up to 20% increase in the FFR [31].

In SMAW, Chan et al. [53] found that increasing the current from 90 A to 120 A resulted in increased FFR as described by the equations below:

$$\text{FFR}_{\text{DC}} = (0.0218 \cdot \text{Current})^{1.94} \tag{3}$$

$$\text{FFR}_{\text{AC}} = (0.0128 \cdot \text{Current})^{1.94} \tag{4}$$

In Equations (3) and (4), the FFR for direct current (FFR_{DC}) and the FFR of the alternating current (FFR_{AC}) have units of mg/min, and the current has units of A.

In GMAW, Pires et al. [54] concluded that for the same current, there is an increase of FFR with a decrease in the wire diameter, as described by the equations below:

$$\text{FFR}_{0.8\ \text{mm}} = 0.019e^{0.0102(\text{Current})} \tag{5}$$

$$\text{FFR}_{1.0\ \text{mm}} = 0.0268e^{0.0057(\text{Current})} \tag{6}$$

$$\text{FFR}_{1.6\ \text{mm}} = 0.0164e^{0.0051(\text{Current})} \tag{7}$$

Variation in electrode diameter has a relatively small effect on the FFR [31], which is probably due to differences in welding current and voltage rather than the diameter of the electrode.

In summary, considering the current and voltage factors, it can be concluded that: the current influences FFR; increasing the current results in increasing FFR. Also, changing current also requires a change in voltage, and so these are not completely independent. It is therefore probably sufficient to just consider current as the main MF for modelling exposure to welding fume. Increasing current generally resulted in increased FFR. The type of current is important (i.e., AC or DC) and may affect FFR by around ±30%.

5.2. Electrode Type

For arc welding, the electrode or welding rod, is often described as the "consumable"; it is the major source of the welding fume [5,55]. Electrodes are usually of similar composition to the base material being welded. Yoon et al. [56] stated that the main fume compositions from FCAW arose from the inner flux and tubular wire more than the base metal. The most common metal used in electrodes is mild steel, although there are types of steel used that contain additional metals. For example, stainless steel electrodes may contain up to 26% Cr and 21% Ni, high-manganese hardfacing electrodes contain Mn at around 14%, and high-chromium hardfacing electrodes contain Cr up to 30% [27].

5.3. Shielding Gas

Shielding gas is an important factor for the quality of the GMAW, but also directly influences the FFR [47]. Several authors [31,50] stated that increasing O_2 and CO_2 inside the shielding gas mixture with Ar results in increasing FFR; CO_2, especially, had a strong influence in increasing the FFR [57]. For example, the maximum FFRs of the Ar + 25% CO_2 is approximately two-fold higher than the FFR for Ar + 2% CO_2 [31,50], and the FFR increased from 162 to 270 mg/min for Ar + 5% CO_2 + 2% O_2 and Ar + 20% CO_2 + 2% O_2, respectively [57]. There was an insignificant effect on the FFR when 2% O_2 was added to Ar-CO_2 mixtures [47,50]. For the He-based mixtures, there was an insignificant change in the FFR with CO_2 and O_2 additions [47].

For spray transfer mode at low arc voltages in GMAW, a small increase in CO_2 inside the shielding gas mixture with Ar and He resulted in increased FFR [27]. Moreover, Heile and Hill [31] investigated the effect of shielding gas composition (Ar + 5% O_2 versus CO_2) on the relationship between the FFR and current and voltage in GMAW. The relationship differed for the two gas mixtures. For the CO_2 mixture, the FFR increased monotonically with both current and voltage. However, for the Ar-O_2 mixture, the FFR decreased to a minimum and then rose again, separately for both increasing voltage and current. The lowest FFR was found for welding at 28 V and 250 A.

It may be concluded that increasing the current and CO_2 concentration in the shielding gas causes a greater amount of fume. Moreover, the main fume compositions arise from the inner flux and tubular wire of the electrode more than the base metal.

6. Discussion

Exposure to welding fumes is an important occupational hygiene problem that results in exposure to a complex mixture of metal fumes and gases. Using appropriate exposure models could play a vital role in the assessment of welding fume exposure. Currently, there are no validated generic models for welding fume exposure assessment.

A suitable model could be based on a multiplicative structure involving a series of welding and generic specific MFs, in a similar way to the ART model used for chemicals. The key modifying factors specific to welding are related to FFRs and the convective airflows resulting in the dispersion of fumes from the source and the interaction of the welder with the fume plume. These aspects could be incorporated in the ART tool to extend the applicability domain; the remainder of the ART model is considered appropriate for welding fume exposure. The ART does not include an assessment of the impact of personal respiratory protective equipment on the amount of contaminant inhaled by workers and we do not plan to extend the model to include this for welders. However, this is a limitation that applies to all types of contaminant and, we consider the further effort should be undertaken to extend the ART model to accommodate this.

It is clear that the welding process type is a key determinant of FFR. Zimmer and colleagues [58] identified that FFR may vary by almost two orders of magnitude depending on process, with higher emissions from FCAW (750–2502 mg/min) compared to GMAW (36–372 mg/min). Part of the explanation for this variation in FFR is the process, but, within a process, factors such as input electrical current, type of electrode, and shielding gas composition may affect emissions. In general, higher current produces a higher FFR, although some studies [31,59] showed a minimum FFR in GMAW at 240–270 A, which may be due to the use of an Ar-based shielding gas. Hobson et al. [28] concluded that the average concentrations of Mn and total welding fume correlated with welding process type, with the concentration from GMAW being 0.45× that of SMAW, GTAW 1.20× and FCAW 1.24× the concentration from SMAW.

Shielding gas can affect the FFR in GMAW, where shielding with O_2 affects FFRs less than shielding with CO_2, especially, with O_2 concentrations less than or equal 2% [47,50]. In practice, however, using O_2 of more than 2% will have a negative effect on the welded joint and so this is unlikely to be used in industrial welding processes [60]. Increasing CO_2 inside the shielding gas mixture will increase the FFR [27,57], that is, a shielding gas that contains 25% CO_2 can produce a FFR that is more than twice that with a 2% CO_2 in Ar-based mixture.

In practice, when occupational hygiene measurements are made, there is often little detail recorded about the welding process. Information about the process category may generally be found but details of the welding current or voltage, or even the shielding gas composition may be unavailable. This presents practical problems in adapting the ART model for welding because there is expected to be a lack of suitable data to calibrate a modified tool. However, because the functional relationship between these specific welding parameters and the FFR is known from controlled laboratory experiments it may still be possible to include them in the modified ART. In future studies of welding fume exposure, we recommend that investigators record more details about the process to facilitate the use of their data in exposure model development.

In welding, the base metal composition can vary widely, e.g., from mild steel to stainless steel containing Cr, Ni, and other toxic metals or metals such as Al. Base metal may determine to some extent the welding process used and the composition of the electrode. However, Mn can be used in flux coated electrodes for SMAW and FCAW, which can result in Mn fumes making up 0.2 to 10% of the total fume [5]. In this case, the concentrations of Mn in fume were significantly related to the welding consumables, but not the base metal [61].

In the mixture of metals in welding fume, there are observed associations between concentrations. A strong correlation between the concentrations of respirable Ni and Cr are described by the equations below [42]:

$$\log_{10} \text{Cr} = 0.23 + 0.80 \cdot \log_{10} \text{Ni},\ r = 0.79 \tag{8}$$

There were also associations between metal concentrations and the concentration of total fume. Flynn and Susi [45] described a moderate correlation between the average concentrations of Mn and total welding fume of the pipefitters and boiler workers by the Equations (9) and (10), respectively:

$$C_{\text{Mn}} = 0.03(C_{\text{Total}}) - 0.02,\ r^2 = 0.53 \tag{9}$$

$$C_{\text{Mn}} = 0.03(C_{\text{Total}}) - 0.12,\ r^2 = 0.69 \tag{10}$$

On the other hand, Hobson et al. [28] estimated the average concentrations of Mn and total welding fume using the following non-linear equations:

$$\text{Mean}_{\text{Mn}} = \exp^{(-2.72+3.23)} \tag{11}$$

$$\text{Mean}_{\text{Total}} = \exp^{(-2.72)} \tag{12}$$

It may be possible to use these relationships to estimate individual metal fume concentrations in a welding ART model. However, there are limited data available to do this and this may add further uncertainties to the model estimates.

Enclosed or poorly ventilated areas have been shown to produce higher exposure to welding fume and the metal components when compared to open areas [28,42,45,62,63]. Confined spaces, i.e., small volume and/or low general ventilation rate, are already modelled within the ART, as is the efficacy of local controls. There is no indication that the current ART model for these factors is inappropriate for welding and it is suggested that they could be retained unmodified. However, this aspect should be investigated further during the calibration of the welding ART.

Slater [32] noted that the correlation between FFR and the breathing zone exposure depends on the convective dispersion of fume. The emissions from a welding source are buoyant relative to the surrounding air and the fume plume accelerates vertically upwards, dispersing laterally because of turbulent mixing with the surrounding air. In addition, any local ventilation control system will affect the flow characteristics of the fume plume, removing some of the emissions before disposal. When the welders head is positioned directly above the arc source, exposure levels are higher than when welding vertically with the head to the side [32]. Interaction between the welder and the source is likely to be one of the key MFs influencing welder exposure and this is a special characteristic of buoyant sources.

It is proposed that the ART model for welding fume should consider three scenarios, accounting for the interaction between the welder and the welding fume plume (WP). The first scenario is where the welder is more than 1m from another welding colleague and exposure to fume arise from her far-field (FF); there are no welding sources in her near-field (NF) (Figure 2a). The second scenario shows a welder close to the fume plume, but the NF is not within the plume (Figure 2b). The last scenario has a welder working with their NF within the fume plume, i.e., essentially the WP and NF spaces coincide (Figure 2c).

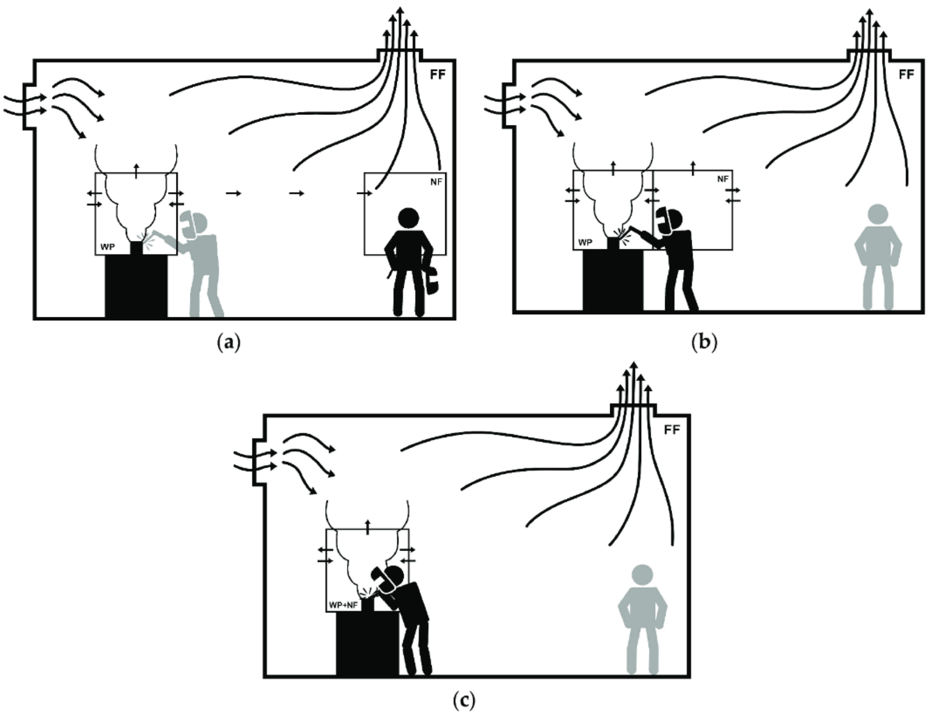

Figure 2. The ART model for welding fume should consider three scenarios, accounting for the interaction between the welder and the welding fume plume (WP): (**a**) Another welder colleague in a FF scheme; (**b**) A NF close to the WP scheme; (**c**) A NF and the WP are the same area scheme.

We propose to modify the ART algorithm to incorporate the three scenarios described above. This modification will require the estimation of the amount of time a welder in specific scenarios spends in each of these three scenarios. For exposure arising from the welders FF (Figure 2a) the form of the deterministic equation remains the same as in ART, although the MFs will differ to include welding-specific items (Equation (13)). Here the inhalable mass concentration (C_{FF}) is:

$$C_{FF} = (E_{FF} \cdot H_{FF} \cdot LC_{FF} \cdot Seg_{FF}) \cdot D_{FF} \cdot Sep \quad (13)$$

where substance emission potential (E) is a multiplicative function of welding process (PRO), electrode type (ELT), and shielding gas (GAS). Activity emission potential (H) is a multiplicative function of current (CUR), and voltage (VOT). Seg represents isolation around sources and work area. D is a ventilation type, which is related to the degree of enclosure and general ventilation airflows. Sep is a personal enclosure around the worker, e.g., an air-conditioned cab.

In the welding ART model, the NF contributions are divided into those arising from time adjacent to the welding plume (C_{NF-WP}) and those from time when the welder is in the welding plume (C_{NF+WP}). In both these situations the MFs for substance emission potential and activity emission potential are the same, i.e., E_{NF} and H_{NF}. However, for the time where her head is adjacent to the plume the local control (LC) and dispersion factors (LC_{NF-WP} and D_{NF-WP}) will differ from those when her head is in the welding plume (LC_{NF+WP} and D_{NF+WP}). These equations are shown below:

$$C_{NF-WP} = E_{NF} \cdot H_{NF} \cdot LC_{NF-WP} \cdot D_{NF-WP} \quad (14)$$

$$C_{NF+WP} = E_{NF} \cdot H_{NF} \cdot LC_{NF+WP} \cdot D_{NF+WP} \quad (15)$$

The total exposure (C_{Total}) is calculated by combining these concentrations in a time-weighted format:

$$C_{Total} = \frac{1}{t_{Total}} \left(C_{FF} \cdot t_{FF} + C_{NF-WP} \cdot t_{NF-WP} + C_{NF+WP} \cdot t_{NF+WP} + 0 \cdot t_{Non-exp} \right) \quad (16)$$

where, t_{Total} = time of a work shift, t_{FF} = exposure time for a welding source within the FF, t_{NF-WP} = exposure time when her head is adjacent to the plume, t_{NF+WP} = exposure time when her head is in the welding plume, and $t_{Non-exp}$ = time with non-exposure:

$$t_{Total} = \left(t_{FF} + t_{NF-WP} + t_{NF+WP} + t_{Non-exp} \right) \quad (17)$$

We use the data that has been obtained from literature review to assign model multipliers as described in Table 1. The multipliers are based on the fume concentration using the exposure data collated from the literature (see Appendix A). There is insufficient data to reliably assign numeric values for all the model modifying factors categories, and so we have had to use an element of judgement in these assignments. While this is not optimal it is pragmatic and in keeping with the approach used in developing the original ART. Additionally, the reliability of the final model will be evaluated in subsequent validity studies.

Table 1. Modifying factor scoring for ART welding fume exposure model.

MFs of ART for Welding Fume Classification		Multiplier	References
Substance Emission Potential [E]			
Welding Process Type (PRO)	Arc Welding		[27,28,64]
	-Flux Core Arc Welding (FCAW)	1.0	
	-Shielded Metal Arc Welding (SMAW)	0.8	
	-Gas Metal Arc Welding (GMAW)	0.4	
	-Plasma Arc Welding (PAW)	0.1	
	-Gas Tungsten Arc Welding (GTAW)	0.03	
	-Submerged Arc Welding (SAW)	0.01	
	Gas Welding	0.4	
	Laser Beam Welding	0.02	
Welding Electrode (ELT)	Non-stainless Steel	1.0	[56]
	Stainless Steel	0.8	
Shielding Gas (GAS)	CO_2	1.0	[47,57]
	Ar/He-based Mixture		
	-with 18% CO_2	0.7	
	-with 12% CO_2	0.6	
	-with 10% CO_2	0.5	
	-with 6% CO_2	0.5	
	-with 5% CO_2	0.5	
Activity Emission Potential [H]			
Current (CUR)	>230 A	1.0	[46,50]
	120–230 A	0.7	
	<120 A	0.3	
Voltage (VOT)	>30 V	1.0	[46]
	22–30 V	0.7	
	<22 V	0.3	

Although there are data in the literature to determine the parameter values for the MFs affecting FFR, there are no data to determine the MFs for the dispersion scenarios. Further research in needed to investigate the importance of these factors and to determine the numeric multiplier to be applied.

Once the ART model has been modified to include welding specific MFs it will be necessary to calibrate the model to provide estimates of welding fume exposure for different metal components in units of mass per unit volume of air. To do this it is necessary to have access to a wide range of exposure measurements from different welding processes, in different scenarios with different patterns of work. It will therefore be necessary to compile a database of existing and/or new measurements containing the associated MFs. Once finalised the welding ART model could be incorporated into a suitable software system and could then provide a useful tool for occupational hygienists and others to help manage metal fume exposure of welders.

7. Conclusions

At the moment there are no generic models to assess exposure to welding fumes. The ART model provides a basis for this type of model, but it will require adaption to make it suitable. We identified that welding process type, input power level, shield gas, and welding electrodes effect fume formation rates and should be incorporated in a welding-ART model. Additionally, the modified model needs to take account of the convective dispersion mechanism for welding fume and the potential interaction of the welder with the fume plume. Other aspects of the ART model, such as local control measures, do not need to be modified. The scientific literature provides some guidance to derive the magnitude of model modifying factors, but it is also necessary to rely on expert judgement for some specific parameter values. Further research is needed to derive the numeric values for the general ventilation modifying factors in the welding-ART.

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Appendix A. Description of the Scoring of Multipliers in Table 1

Hobson et al. [28] provided the regression coefficient for welding process types with 1.24 (FCAW), 1.00 (SMAW), 0.45 (GMAW), and −1.20 (GTAW). We convert these coefficients into the multipliers by using FCAW as the reference category (1.0). Therefore, the multipliers for each of the four welding process types are 1.00 (FCAW), 0.8 (SMAW), 0.4 (GMAW), and 0.03 (GTAW). Some papers describe SAW has having the lowest FFR. Then, in ascending order, come laser beam welding, GTAW, and PAW. The FFR of gas welding was expressed equal GMAW [64]. From this information, we assigned the multipliers as the Table 1, based on the judgement of the researchers.

Yoon et al. [56] showed that metal fumes identified higher concentrations with non-stainless steel welding (51.6%) compared with stainless steel (40.2%); based on this, the ratio between the fume content of non-stainless steel electrode and the fume contents of stainless steel electrode can be expressed as 1:0.8.

The influence of shielding gas mixtures on the FFR is a result of increasing CO_2 [57]. The FFR results of Carpenter et al.'s study [47] were used to obtain multipliers for the shielding gas factor. The FFRs were converted to the multipliers by using a FFR of 100% for CO_2 shielding gas (568 mg/min) as the reference. For example, the FFR of Ar-18% CO_2 is 396 mg/min. Therefore, 396 divided by 568 equals 0.7.

Equation (1) gives the FFR in relation to electrical current. From this equation, we assigned the FFR of the current higher than 230 A (855.81 mg/min) as the reference and then calculated the FFR for other currents compare with the reference. For example, the FFR of current 120 A is 273.77 mg/min, the ratio of 273.77 to 855.81 is 0.3 that is the multiplier of the current lower than 120 A.

The current and voltage were categorised into three groups, i.e., high input power (>230 A, >30 V), optimal input power (120–230 A, 22–30 V), and low input power (<120 A, <22 V) [46]. Slater [32] reported that an increase in the current will also require an increase in voltage. This information was used to assign the multipliers for voltage in relation to current.

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Calibration of the Welding Advanced REACH Tool (weldART)

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ABSTRACT

Objectives: This paper reports a study to develop and calibrate a deterministic model of welding fume exposure based on a four-compartment mass-balance model - The Welding Advanced REACH Tool (weldART). To achieve this aim, measurements of welding fume exposure were collected along with data on exposure determinants needed in the modelling.

Methods: The welding fume exposure data was obtained from workers in a structural steel fabrication plant. Welders were engaged in three processes: flux-cored arc welding (FCAW), shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). Aerosol concentration was measured using 13 mm diameter Swinnex sampling heads and MicroPEM direct-reading aerosol monitors. The model was initially developed with three spatial compartments (near-field (NF), far-field (FF), and welding plume (WP)). However, in the welding scenario investigated the FF had a very large volume and it was necessary to subdivide the room volume into an intermediate zone representing the FF along with the remaining room zone (RM). We fitted linear equations forced through the origin to the gravimetric concentrations measured inside the welders' visor and the weldART model estimates. The flowrates between the model compartments were adjusted by trial and error to obtain proportionate concentrations in each compartment.

Results: The FCAW process generated higher welding fume particulate concentrations than SMAW and GTAW. The MicroPEM monitors considerably underestimated and were poorly correlated with the corresponding data from the Swinnex samplers. It was concluded that the MicroPEM data were unreliable. The model calibration showed a strong association between the personal exposure measurement and the weldART model values (R^2 = 0.94), with the average estimated value 1.3 times the measurements. The NF and the FF model estimates were poorly correlated with the corresponding compartment measurements (R^2 = 0.37 and 0.35, respectively), although on average the model estimates were close to the measurement data (ratio of modelled to measured 0.9, and 1.0, respectively).

Conclusions: The calibration shows that the weldART model is able to predict the exposure of welding fume particulate.

1. Introduction

Welding is a basic manufacturing process carried out in many industries, including in maintenance of existing equipment and fabrication of new equipment or structures. The hazardous substances emitted from welding comprise metal oxide particles formed by evaporation, condensation and oxidation during the welding (fume) and gas phase contaminants such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ozone (O_3) (Pires et al., 2006; Popović et al., 2014). Welding generates a considerable amount of heat, which results in the contaminants dispersing in a turbulent buoyant plume (Olander, 1985). The plume released from the welding fume emission source and has the general form of an inverted cone where the upward air velocity and the contaminant concentrations decrease with the height in the plume (Slater, 2004). Welders may inhale these contaminants.

The standard method for assessing human exposure to welding fume relies on the collection of air samples that are analysed gravimetrically or chemically to determine the concentration. This approach is relatively expensive and time-consuming, and the data is not generally available for some time after the sample collection. A mathematical model could provide a reliable prediction of the fume exposure levels,

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although to date there are no widely accepted models that can be used to assess welding fume exposure. There are a few models for airborne contaminant exposure assessment, such as the European Centre for Ecotoxicology and Toxicology of Chemicals' Targeted Risk Assessment (ECETOC TRA), Stoffenmanager®, and Advanced REACH Tool (ART) (Riedmann et al., 2015) but they are not tailored to estimate welding fume exposure.

The Near-Field/Far-Field model, also known as the two-zone model, has been used to evaluate exposure to airborne contaminants, including welding fumes (Boelter et al., 2009; Ganser and Hewett, 2017; Nicas, 1996). The room is modelled as two compartments, the near-field (NF) that surrounds the worker and the source and the far-field (FF) the remainder of the room space. This simplified model has been shown to encompass the essence of contaminant transport and dispersion in indoor spaces. The Advanced REACH Tool (ART) is based around the NF/FF model (Fransman et al., 2011; LeBlanc et al., 2018; Tielemans et al., 2011). ART is a probabilistic model, based on a multiplicative combination of identified modifying factors (MFs), that can be used to estimate exposure to a wide range of hazardous chemicals. It is not suitable to estimate fume concentration, although Sailabaht et al. (2018) reviewed the model structure to identify how it could be adapted to include welding. The review indicated that the key MFs contributing to the model should include welding process type, electrical input power, shield gas composition, and welding electrode type. The review also recommends the extension of the model framework to include three spatial compartments: NF, FF and the welding plume (WP), which was also recommended by Nicas et al. (2009).

The objectives of the present study were to develop and calibrate a deterministic model of welding fume exposure based on a four-compartment mass-balance model (The Welding Advanced REACH Tool or weldART) by using welding fume exposure data.

2. Materials and methods

Measurements of welding fume exposure was obtained from 17 workers in a structural steel fabrication plant making pipes, pressure vessels, heat exchangers and silos. Welders were engaged in three processes: flux-cored arc welding (FCAW), shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). The majority of the welding tasks involved GTAW, with SMAW and FCAW only being used occasionally. They worked in a building with volume around 35,200 m^3 (20 m wide, 160 m long and 11 m high) that was open at both ends. There was no fresh air distribution system nor local air exhaust ventilation system at the welding workstations. Welders wore gloves and a welding visor. The environmental air temperature during the data collection ranged from 32 to 42 °C, over 17 monitoring points.

2.1. Air sample collection and analysis

The air samples were collected during a number of single welding tasks not over the whole shift by two methods: 13 mm diameter Swinnex sampling heads (T18D58550 by Merck Millipore) were connected to personal sampling pumps using the BS EN ISO 10882-1:2011 method for airborne particulates in welding and allied processes (British Standards Institution (BSI), 2011) and a MicroPEM direct-reading aerosol monitor. For each task, three Swinnex samples were collected: one located inside the welding visor to evaluate fume exposure, one approximately 50 cm from the welding at a height of 1.5 m above ground to evaluate fume concentration in the NF and one about 200 cm distant at 1.5 m height to evaluate fume concentration in the FF. Each Swinnex holder contained a pre-weighed 13 mm glass fibre filters with a nominal pore size of 2 μm. The air was drawn through the sampling system at a flowrate 1 l/min. The airflow was checked before and after each sampling session using a primary standard meter (Model: Bios Defender 510, Serial no: 112114). The mean flowrate of each personal sampling pump was calculated by averaging the flowrates at the start and the end of the sampling period. After sampling the filters were reweighed using a Sartorius filter microbalance (Model: MSA6.6S000DF, Serial no: 33505850) to within 0.001 mg and the gravimetric concentration calculated. Samples were not analysed for component metals.

The version 3.2 MicroPEM developed by RTI International (https://www.rti.org/impact/micropem-sensor-measuring-exposure-air-pollution) is a light scattering instrument that measures $PM_{2.5}$ concentration; it was used after the manufacturer's calibration. The MicroPEM has a reported response time of 10 s (Williams et al., 2014). These devices were located on a belt worn by the welder and a sampling tube was used to draw air from inside the welding visor. According to the manufacturer, the flowrate through the instrument was set at 0.5 l/min and this was remeasured at the end of the sampling period.

As a control on the quality of the weighting, ten blank filters were prepared and exposed to the same conditions as the samples, but with no air drawn. The average change in mass found in the field blanks was subtracted from the corresponding mass found in the samples. The welders head position and welding time period were recorded using a video recorder during the monitoring (this was explicitly covered by the ethical approval). The sampling records indicated when and where the monitoring was carried out and the operations in progress at the time of the survey. The MicroPEM data was also used to identify the welding periods in conjunction with the video evidence. During the sampling, the exposure determinants were also collected, i.e. process type, sampling time, arc time, working room volume, and shielding gas.

2.2. Development of the weldART model

We initially suggested a multi-compartment mass-balance model of the welding process, as described in Sailabaht et al. (2018). The model comprised of three spatial compartments: NF, FF and WP. Fig. 1 shows a conceptual diagram of the weldART model. The WP contains the welding fume emission source (E_{WP}). The breathing zone of the individual whose exposure is to be estimated is either the WP or NF compartment, depending on their head location (determine by the MicroPEM monitoring data and/or video record). During single welding tasks, however, most welders worked both in the WP and the NF, and the personal exposure concentrations (C_{exp}) were calculated as a time-weighted average concentration between those two compartments. The FF represents the remainder of the room. Airflow between compartments is represented by the β coefficients (m^3/s). The weldART model consists of three simultaneous differential equations as follows:

$$\frac{dC_{NF}}{dt}\cdot V_{NF} = (C_{WP}\cdot\beta_1) + (C_{FF}\cdot\beta_3') - (C_{NF}\cdot\beta_1') - (C_{NF}\cdot\beta_3) \tag{1}$$

$$\frac{dC_{FF}}{dt}\cdot V_{FF} = (C_{WP}\cdot\beta_2) + (C_{NF}\cdot\beta_3) - (C_{FF}\cdot\beta_2') - (C_{FF}\cdot\beta_3') - (C_{FF}\cdot Q_{FF}) \tag{2}$$

$$\frac{dC_{WP}}{dt}\cdot V_{WP} = E_{WP} + (C_{NF}\cdot\beta_1') - (C_{WP}\cdot\beta_1) + (C_{FF}\cdot\beta_2') - (C_{WP}\cdot\beta_2) \tag{3}$$

where;

C_{WP}, C_{NF} and C_{FF} are the fume concentration in the WP, NF and FF, respectively (mg/m^3)
E_{WP} is a fume emission rate in the WP (mg/s)
V_{WP}, V_{NF} and V_{FF} are compartment volume in the WP, NF and FF, respectively (m^3)
β_x and β_x' are the airflow between compartments (m^3/s)
Q_{FF}' and Q_{FF} are volume airflow flowing in and out of the FF, respectively (m^3/s)

As the development of the model progressed, it became clear that it was unrealistic to assume the emitted fume instantaneously mixed into the FF because it was a very large volume. The model was, therefore

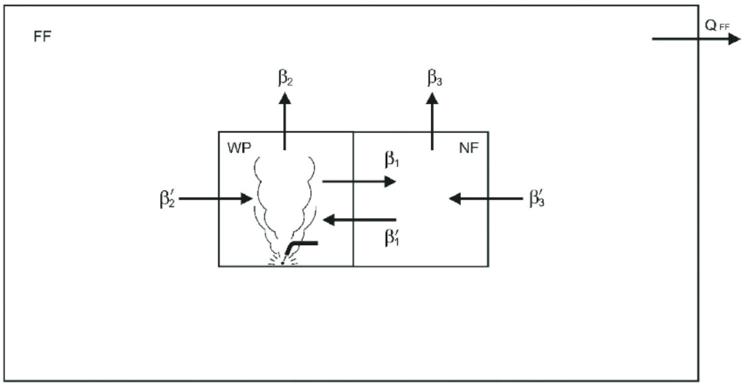

Fig. 1. A conceptual diagram of the weldART model with three compartments.

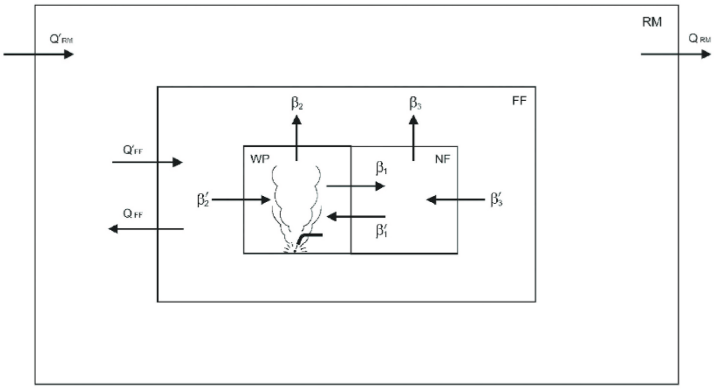

Fig. 2. A conceptual diagram of the weldART model with four compartments.

elaborated to comprise four compartments, with an intermediate zone as the FF along with the residual room zone (RM) (Fig. 2). This change resulted in an additional fourth differential equation as follows:

$$\frac{dC_{RM}}{dt}.V_{RM} = (C_{FF}.Q_{FF}) - (C_{RM}.Q'_{FF}) - (C_{RM}.Q_{RM}) \tag{4}$$

where;

C_{RM} is the air concentration in the RM (mg/m^3)
V_{RM} is compartment volume in the RM (m^3)
Q'_{RM} and Q_{RM} are volume airflow flowing in and out of the RM, respectively (m^3/s)

The equations were solved using R scripts (RStudio Team, 2016). The weldART model applies for only one source in WP although it could be extended to include other sources in the other compartments. The model assumes that air within each compartment is instantaneously well mixed and concentration starts at zero. Table 1 shows the weldART model parameters.

The fume emission rate information is necessary for the evaluation of contaminant dispersion and transport (Serageldin and Reeves, 2009). At present, there is no reliable information on fume emission rate, and the emission rate depends on many factors such as welding electrode type, electrode angle, electrode diameter, base metal, electrical input power, workpiece composition, shielding gas mixture and flow rate, arc length, polarity, and welding position, welding speed (Jilla, 2019; U.S. Environmental Protection Agency (EPA), 1994). Therefore, it is difficult to specify the emission rate in the model. However, Sailabaht et al. (2018) reported that the welding process is the key factor affecting the fume emission or formation rate (FFR). They suggested numeric values (multipliers) for the welding process factors decreased from FCAW (1.0) to SMAW (0.8), and GTAW (0.03). We tried to use these multipliers in the weldART model but the result showed the unrealistic concentrations. The emission rate values were then adjusted by trial and error, maintaining a decreasing emission rate from FCAW to SMAW and GTAW. Finally, the best emission rate values for the weldART model are 2.6 (FCAW), 2.0 (SMAW), and 1.6 (GTAW). The main change from Sailabaht et al. (2018) was the proportionate increase in emission from GTAW processes.

Slater (2004) showed that at 1.15 m above the weld, the volumetric flowrate from the welding fume plume was 0.045 m^3/s. At this height the fume plume has lost most of its buoyancy and so stops rising and starts to spread laterally; this will occur at the top of the WP compartment assuming that the welding takes place at the bottom of the compartment. However, in addition to the convective airflow out of the WP compartment, there will be air movement latterly through the

Table 1
The comparison of weldART model parameters between three compartments and four compartment models.

Parameters	Initial values (Three compartments)	Revised values (Four compartments)
Compartment volume (m^3)		
V_{NF} and V_{WP} (W x L x H)	0.2875 (0.5 m × 0.5 m x 1.15 m)	0.2875 (0.5 m × 0.5 m x 1.15 m)
V_{FF} (W x L x H)	35,200 (20 m × 160 m x 11 m)	300 (10 m × 10 m x 3 m)
V_{RM} (W x L x H)	-	35,200 (20 m × 160 m x 11 m)
Fume emission rate in the WP (E_{WP}) (mg/s)		
FCAW	2.6	2.6
SMAW	2.0	2.0
GTAW	1.6	1.6
Airflow between zones (m^3/s)		
β_1	0.0125	0.0125
β_1'	0.0288	0.0288
β_2	0.0738	0.0738
β_2'	0.0575	0.0575
β_3	0.0300	0.0300
β_3'	0.0463	0.0463
Volume airflow flowing in and out of the FF (m^3/s)		
Q_{FF}	22	0.25
Q'_{FF}	0	0.25
Volume airflow flowing in and out of the room (m^3/s)		
Q_{RM}	-	22
Q'_{RM}	-	22
Measured: Modelled ratio		
Personal	1.2	1.3
NF	1.1	0.9
FF	87.3	1.0

compartment from room draughts. Based on the study of Baldwin and Maynard (1998), we assumed this airspeed was 0.05 m/s. Therefore, the total for β_2 (assuming the lateral airflow was 0.5 m × 1.15 m x 0.05 m/s) was set at 0.0738 m^3/s. We assumed β_2', the convective airflow from the welding plume compartment, was 0.0575 m^3/s (i.e. 0.5 m × 1.15 m x 2 sides x 0.05 m/s). Further we assumed there was one face of the WP and NF with 0.05 m/s airflow though and β_1' was 0.0288 m^3/s (0.5 m × 1.15 m x 0.05 m/s). β_1 is was then calculated to balance the airflow into and out of the WP ($\beta_1 = (\beta_1' + \beta_2') - \beta_2$). Therefore, β_1 was 0.0125 m^3/s. The airflows in the NF compartment were estimated in a similar way. The study of Mahyuddin et al. (2015) estimated that the upward airflow speed above the human head is 0.12 m/s. Therefore, we assumed β_3 was 0.03 m^3/s (i.e. 0.5 m × 0.5 m x 0.12 m/s). β_3' was calculated to balance ($\beta_3' = (\beta_1' + \beta_3) - \beta_1$), i.e. β_3' was set at 0.0463 m^3/s. Airflows into and out of the FF at rate Q (m^3/s) depend on the room size and general ventilation or air changes per hour (ACH). In this paper, Q_{FF} was set at 22 m^3/s based on an estimated air exchange of *2.25* ACH.

2.3. Calibration of the weldART model

We fitted linear equations forced through the origin to the filter concentrations corresponding to the weldART model estimates of personal exposure estimates (based on a time-weighted average of the WP and NF concentration), the NF and the FF concentrations. We did not adjust the emission rate values in the process of weldART model calibration. However, the flowrates between the model compartments were adjusted by trial and error to get the average modelled concentrations in the NF and FF close to the average measured value (Table 1).

3. Results

A total of 68 air samples were collected in the workshop building as shown in Table 2. There were three sample sets for FCAW, four for SMAW and ten for GTAW.

3.1. MicroPEM monitoring

The MicroPEMs were used to measure the real-time continuous $PM_{2.5}$ concentration. The data were downloaded and compared with the welding activities from the video record. We noted the times welding when the welder started and stopped welding and plotted these on a graph to compare with the MicroPEM concentrations. Subsequently, we summarised the welding times in each welding task. These times were used to estimate personal exposure. An example of the concentration and welding periods identified from the video record is illustrated in Fig. 3.

3.2. Air sampling results

Table 2 shows the results for total particulate (TP) gravimetric concentrations and average $PM_{2.5}$ concentrations during the sampling period from the MicroPEM. The FCAW process generated a higher concentration than SMAW and GTAW. In the subsequent analyses, we excluded data from Sample ID 1 because the personal concentration was an extreme outlier.

Sampling time was positively correlated with arc time ($r^2 = 0.96$) and made up about 90% of the sampling time on each occasion. Arc time was negatively correlated with measured personal exposure ($r^2 = 0.45$) but was less clearly associated with the NF and FF concentrations. There was a weak correlation between the personal gravimetric concentrations from Swinnex sampler and MicroPEM data ($r^2 = 0.29$), both of which were sampling inside the welders' visor, with the latter being around a factor of 20 lower. The relationship between Swinnex sampler and MicroPEM data is presented in Supplemental Fig. S1. In the calibration of weldART, the MicroPEM data were only used to identify the welding periods.

3.3. weldART model development and calibration

Sixteen sets of fume exposure measurements were used to calibrate the weldART model. Each dataset comprised of four concentrations: personal exposure level measured inside the welding visor, the weldART model estimates, along with the NF and FF concentration measurements. Fig. 4 shows the data from the final model estimates following adjustment of the compartment flowrates in relation to the measured data.

The initial model comprised of three compartments, i.e. NF, FF, and WP, and the RM was included in the final model. In this model, the FF volume (V_{FF}) was set at 300 m^3, and the V_{RM} was therefore 35,200 m^3, are shown in Table 1.

The personal exposure estimates show a high correlation with the measured values ($r^2 = 0.94$), with the average estimated value 1.3 times the measurements. The NF and FF model estimates were low correlated with the corresponding compartment measurements ($R^2 = 0.37$ and 0.35, respectively), although on average they were close to the data (ratio of modelled to measured 0.9, and 1.0, respectively).

Bland-Altman plots of the data for each zone are shown in Supplementary Figs. S2–S4; the 95% limits of agreement are shown as two dotted lines in these plots. These results confirm there is a good agreement between the model and measured concentrations.

4. Discussion

We originally set out to produce a model structured in the same style as the ART tool, i.e. a multiplicative deterministic model with weighting factors (multipliers) related to specific model determinants. However, because welding comprises a narrowly defined set of similar processes, it was possible to develop a more elaborate multi-

Table 2
The results of total particulate concentrations from the Swinnex samplers and average $PM_{2.5}$ concentrations from the MicroPEMs during the sampling period.

Sample ID	Process type	Sample time (min)	Arc time (min)	% Arc time	Concentrations (mg/m^3)			
					Swinnex sampler			MicroPEM
					Personal	NF	FF	
1	FCAW	21	11	52.4	75.0	5.2	1.8	5.25
2	FCAW	8	4	50.0	14.6	3.0	0.6	0.04
3	FCAW	19	7	36.8	13.5	4.6	1.5	2.43
4	SMAW	11	11	100.0	8.8	0.7	0.2	0.02
5	SMAW	21	19	90.5	5.5	0.5	0.2	0.01
6	SMAW	21	21	100.0	3.2	0.5	0.2	0.02
7	SMAW	12	10	83.3	7.1	0.7	0.2	0.02
8	GTAW	21	20	95.2	5.5	0.3	0.1	0.02
9	GTAW	19	9	47.4	5.0	1.7	0.5	0.01
10	GTAW	31	31	100.0	4.4	0.5	0.1	0.16
11	GTAW	41	39	95.1	4.0	0.3	0.1	0.03
12	GTAW	21	20	95.2	4.0	0.3	0.1	0.02
13	GTAW	31	31	100.0	3.9	0.3	0.1	0.02
14	GTAW	71	69	97.2	3.9	0.2	0.1	0.02
15	GTAW	41	38	92.7	2.8	0.3	0.1	0.05
16	GTAW	41	38	92.7	2.7	0.3	0.1	0.02
17	GTAW	54	50	92.6	1.5	0.3	0.1	0.04

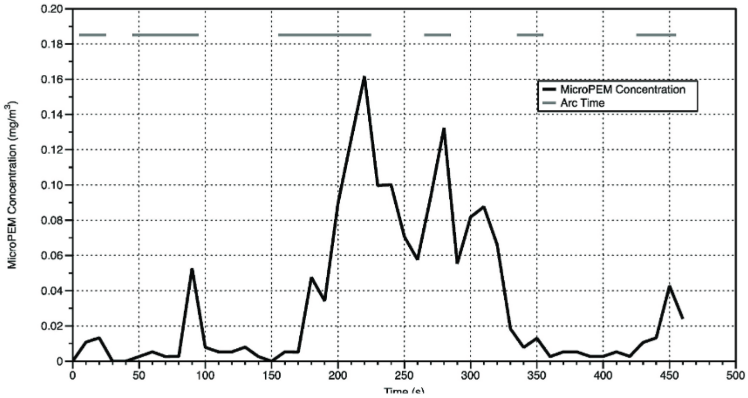

Fig. 3. The example (Sample ID 2) of the MicroPEM concentration and the arc welding period.

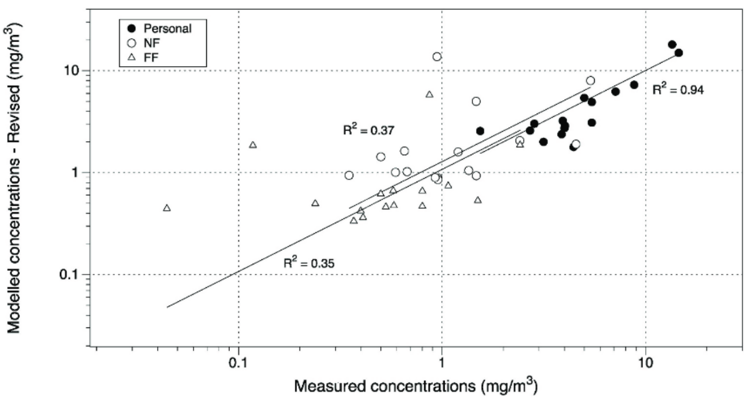

Fig. 4. Scatterplot with R-square between measured and weldART (4-compartment) model concentration.

compartment mass balance model. Elsewhere we argue that this approach is not appropriate for the broad range of scenarios that the ART tool has to encompass because of lack of knowledge about emission strengths, compartment airflow rates and other factors (Cherrie et al., 2020), but it is more realistic in the restricted context of welding.

The MicroPEM monitors used in our field investigation were poorly correlated with and underestimated the gravimetric measurements. The cause of this underestimate might be because the MicroPEM measures $PM_{2.5}$, but welding fume has particle sizes ranging from a few nanometres to 20 μm and the Swinex samplers will collect larger particles than the MicroPEMs (Jenkins and Eagar, 2005; Yang et al., 2018). However, it is also possible that particles were lost in the sampling tube before the aerosol sensor because of the electrostatic deposition (Jankovic et al., 2010). Overall, it was judged that it was not possible to use these data in the calibration, other than to help identify welding periods.

The initial weldART model comprised three spatial compartments. However, it was found that the modelled concentrations in the FF were much higher than the measured values (mean ratio of model to measurements was 87.3; $r^2 = 0.34$), while the personal and NF concentrations were much closer to the measured data (exposure ratio 1.2; $r^2 = 0.97$, and NF 1.1; $r^2 = 0.45$). Adding a fourth compartment and adjusting the airflows allowed the model to better predict FF concentrations in the large space where the welding was carried out while maintaining a good prediction of personal exposure (ratio of the modelled exposure to the measured values was 1.3; $r^2 = 0.94$). The poorer correlation between modelled and measured concentrations in the NF and FF may partly be due to the low concentrations and the short sampling times resulting in poor sensitivity for the gravimetric samples.

WeldART provides estimates of total welding fume, although in some countries it is considered more appropriate to regulate exposure using the concentration of individual metal components in the fume. However, the International Agency for Research on Cancer (IARC) evaluation of the carcinogenicity of welding fume implies that it is the fume and not the toxic metal components that are important in determining cancer risk (Cherrie and Levy, 2019). Pesch et al. (2018) studied welding exposure in chromate production and found Spearman's correlation coefficients (r_s) indicated that the concentration of Cr (r_s = 0.33, 95% CI 0.25–0.42) and Cr(VI) (r_s = 0.38, 95% CI 0.29–0.46) were weakly correlated with the overall fume concentrations; Ni (r_s = 0.44, 95% CI 0.35–0.52) concentrations were moderately correlated with welding fume concentrations. While the weldART model could be adapted to use the percentage of individual metals in the fume to estimate the exposure level it would add to the overall uncertainty of the assessment and we do not recommend that this is an appropriate strategy to estimate the metal components in the fume.

In the situation where the weldART model was calibrated there were no local ventilation controls, but to be credible the model should allow exposure estimation in this situation. Local controls are included in the ART model as one of the MFs (from 0.5 for a canopy hood or moveable captor hood to 0.01 for ventilated enclosures like fume cabinets) (Fransman et al., 2013). While we do not have specific data for welding ventilation controls it is recommended that the MFs from ART would be appropriate for the weldART model.

To apply the weldART model to other welding scenarios it is necessary to have relevant fume emission rates and airflow data, which is not usually reported in exposure measurement studies. However, Boelter et al. (2009) reported a welding fume exposure assessment amongst welders who used SMAW on carbon steel pipes in a boiler room and breezeway. These authors estimated a fume emission rate (0.65 mg/s for boiler room and 0.67 mg/s for breezeway, which were about a third of the values used in the weldART) during the welding activities and applied these data to a two-zone mass-balance model. We compared our model with their measurements and model estimates, as shown in Table 3.

The Boelter et al. (2009) model and the weldART showed the C_{exp} and the FF were much the same in the boiler room. However, both the weldART and Boelter et al. models had higher estimates of C_{exp} than the measurement data (although this was based on just two measurements). These differences may occur because of the nature of the airflow in a breezeway, which is a semi-outdoor space, giving rise to uncertainty about the airflow rate between model compartments.

Table 3
The comparison of welding fume concentrations between the Boelter et al.' study and the weldART model in the boiler room and the breezeway.

	Boiler Room		Breezeway	
	C_{exp}	FF	C_{exp}	FF
Boelter et al.'s measurement (mg/m^3)	4.73	1.37	2.89	0.57
Boelter et al.'s model (mg/m^3)	5.36	1.25	4.04	0.57
weldART model (mg/m^3)	5.68	1.38	8.32	2.02

The model also demonstrates the importance of knowing about the times when welding is taking place during sampling in interpreting the final result. For example, Fig. 5 reproduces the pattern of welding fume concentrations and exposure through work activity. Personal exposure is the average over the sampling period. It is the cumulative sum between WP and NF concentrations that they are multiplied by the time when welder's head is inside WP and NF.

The average arc time in Fig. 5 was about 50% of the measurement time. Using the arc time to estimate the exposure data, i.e. assuming one continuous welding period instead of the actual welding times, the average personal exposure concentration in this example was 17.3 mg/m^3 rather than 11.9 mg/m^3. We suggest that it is important to realistically model the pattern of welding and not just assume a simple measure of arc time. In our dataset (Table 2) welding took place during most of the sampling time, which we consider atypical.

The time that the welders head is in the WP will also affect the exposure concentration. In this study almost all welders had their head in the welding plume through the welding. Training the welders to avoid the WP could reduce their exposure. For example, in the above example if the welder completely avoided the welding plume his exposure would have been estimated to be 3.0 mg/m^3, i.e. the concentration in the NF. If the welder had only had his head in the WP for half the time his exposure would have been 7.45 mg/m^3 (rather than 11.9 mg/m^3). It is clear that knowledge of the time the welder spends with their head in the welding plume is an important exposure determinant and something that should be recorded when exposure measurements are made.

The results of the model calibration show that weldART could have good potential to estimate the exposure of welders based on data on welding process (emission rate), welding parameters - which modify emission rate (e.g. current and voltage), arc time or more detailed data on times welding, time welder spends with head in plume, local ventilation, room size and ventilation rate, interzone flow rates. However, the model must be validated by comparing estimated exposure with a wider set of available measurement data from a wide range of other workplaces with differing welding conditions. As much of the currently available data lacks specific data on the weldART exposure determinants it will be necessary to adapt the model into a probabilistic form to take account of the uncertainty from the lack of knowledge of the circumstances where the measurements were obtained. WeldART is currently implement as a R script (RStudio Team, 2016), and can easily be adapted vary the input values for each parameter in a Monte Carlo simulation, e.g. to account for uncertainty in parameters such as the arc time or the intermittency of welding during the work shift.

In the future when occupational hygienists make exposure measurements from welding activities, they should collect all relevant exposure determinant information needed for weldART to better describe the circumstances of the measurements and make the data more useful for model development. A suitable welding data collection spreadsheet

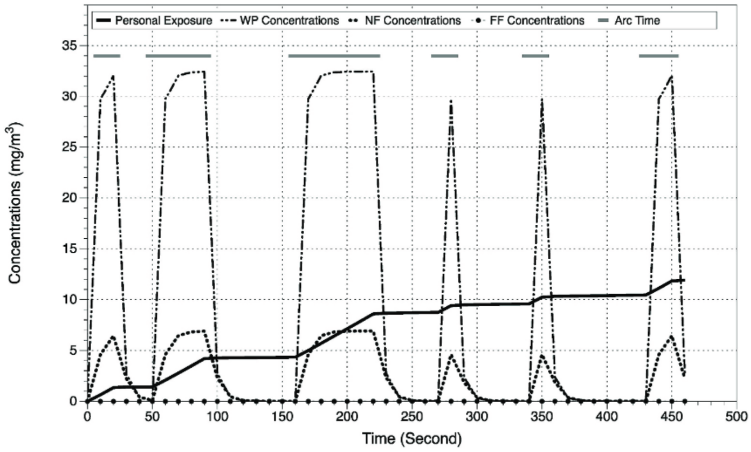

Fig. 5. The example (Sample ID 2) of the pattern of welding fume concentrations in the different compartments.

is available as an online supplement to this paper.

5. Conclusions

We developed and calibrated a model to estimate welding fume exposure. The results of the weldART model calibration demonstrate that a four-compartment mass-balance model can predict welding fume exposure. However, the next step is to extend the weldART model into a probabilistic form and undertake further validation testing using a wide variety of measurement datasets. This will ensure it is a reliable tool to predict welding fume exposure.

Ethical approval

Ethical approval for this study was received from the Ethics Committee of the School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK. The approval reference number is 19/EA/JC/2.

Informed consent

Informed consent was obtained from all study participants.

Author contributions

Aduldatch Sailabaht and John Cherrie conceived and designed the study and interpreted the results. All authors prepared and revised the manuscript. Aduldatch Sailabaht coordinated the fieldwork and analysed the data. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2020.113519.

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