MODELLING OF WELDING HAZARDS IN AN INDUSTRIAL WORKSHOP USING FFTA METHOD

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Abstract: Dealing with common and special hazards in welding and fabrication workshops requires experiences of welding professionals to employ advanced methodologies to tackle various risk scenarios associated with welding operations. This paper therefore, presents a model to evaluate welding accident in an industrial workshop under uncertainty. Given that fault tree analysis (FTA) is a known methodology used to analyse engineering systems with known failure data, welding operations are usually performed in an uncertain environment requiring flexible but robust algorithm for its analysis. Therefore, fuzzy set theory (FST) is employed to allow experts express their opinions on the failure probabilities of the basic events (BEs) leading to welding accident, enabling the treatment of uncertainty. Result from the analysis shows that minimum cut sets (MCS) (R) fire and explosion and (S) electric shock have the highest contribution to the occurrence probability of the top event (TE) while welding and flow dust, welding/hazardous fumes and ionisation radiation, hot metallic part, spatters, entanglement and flying objects/sparks were the least contributing (MCS) to welding accident. In order to reduce or prevent the occurrence probability of the TE, the occurrence likelihood of all the basic events (BEs) and (MCS) must be reduced or prevented while special attention must be paid to redesigns and replacing of worn out workstations to enhance welders' posture, maintenance and inspection of damage sockets, naked wires and local exhaust, using the right Personnel Protecting Equipment (PPE) to minimize or reduce radiation exposure and installation of safety guards to ensure robust safety of welder.

KEY WORDS — Hazards, Safety, Welding, Workshop.

1 INTRODUCTION

Welding is a fabrication process that joins materials, usually metals or thermoplastics, by causing coalescence. This is often done by melting the work-pieces and adding a filler material to form a pool of molten material (the *weld pool*) that cools to become a strong joint, with pressure sometimes used in conjunction with heat, or by itself, to produce the weld.

This is in contrast with soldering and brazing, which involve melting a lower-melting-point material between the pieces to form a bond between them, without melting the work pieces. Many different energy sources can be used for welding, including a gas flame, an electric arc, a laser, an electron beam, friction, and ultrasound. Welding can be done in many

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different industrial environments, including open air, under water, and in outer space [1].

Due to the increase in technological advancement, welding related operations and services are being performed in numerous industries, including shipbuilding, construction, fabrication shops, railroads and aerospace amongst others. Also, the type of welding to be used in these industries can be based on a number of considerations, including the type of base metal used, the quality of the weld required, and other variables.

It is also observed that many distinct factors influences the strength of welds and the material around them, including the welding method, the amount and concentration of energy input, the weldability of the base material, filler material, flux material, the design of the joint, and the interactions among all these factors.

Critical review of welding related accidents revealed that electrical and mechanical factors, human errors, ergonomics, fire and explosion, chemical and bacterial factors are the prevalent causes of welding accidents leading to disruption of operations and the impact of such accidents can cause both direct and indirect damage with long term financial consequence [2].

Experience of welding in both the oil and gas, petrochemical, refining, maritime and other critical sectors revealed that the complexity of welding application is caused by the integration of technical, operational and organisational factors into its everyday operations. In order to analyse the complex structure of welding systems and operations, methods such as fuzzy set theory and fault tree analysis can be used to model the system due to its flexibility and ease and for accounting for uncertainties during operations and in revealing the system's vulnerability. It is worthy to note that such methods have been widely used in many industrial sectors such as emergency response planning [3], fire and explosion of crude oil tanks [4], oil and gas offshore pipelines [5], construction [6], computing and telecommunication [7] for safety assessment of the systems in order to reveal their vulnerabilities.

The aim of this paper is to propose a modelling approach for evaluating welding operational hazards in an industrial workshop using the Fuzzy Sets Theory (FST) and Fault Tree Analysis (FTA) approach. This has been organised as follows: Section 2 provides literature on welding processes, presents and discusses various risk parameters of welding processes; Modelling approach using the FTA and FST are presented in section 3; Section 4 explains the methodology of the study. Section 5 focuses on the case study to show how it can be applied. Finally, discussions and conclusion are offered in sections 6 and 7 respectively.

2 Literature Review

Welding operation is a highly engineered process that has evolved as technology has evolved. It is a process that is conducted by highly skilled personnel. The objective is to fuse two pieces of metal using a minimal amount of consumable electrodes. The more smoke and fume are generated, the more consumable electrodes are wasted and one must have a basic understanding of welding processes in order to assess the many risks exposed by the welders. Based on the research conducted by John et al., [8], Spear [9], Col-

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well and Layo [10] and Fiore [11], the following welding processes are highlighted.

2.1 Shielded metal arc welding (SMAW or "stick welding") is commonly used for mild steel, low-alloy steel and stainless steel welding. In SMAW, the electrode is held manually, and the electric arc flows between the electrode and the base metal. The electrode is covered with a flux material, which provides a shielding gas for the weld to help minimize impurities. The electrode is consumed in the process, and the filler metal contributes to the weld. SMAW can produce high levels of metal fume and fluoride exposure; however, SMAW is considered to have little potential for generating ozone, nitric oxide and nitrogen dioxide gases.

2.2 Gas metal arc welding (GMAW) is also known as metal inert gas (MIG) welding. GMAW is typically used for most types of metal and is faster than SMAW. This process involves the flow of an electric arc between the base metal and a continuously spool-fed solid-core consumable electrode. Shielding gas is supplied externally, and the electrode has no flux coating or core. Although GMAW requires a higher electrical current than SMAW, it produces fewer fumes since the electrode has no fluxing agents. However, due to the intense current levels, GMAW produces significant levels of ozone, nitrogen oxide and nitrogen dioxide gases.

2.3 Flux-cored arc welding (FCAW) is commonly used for mild steel, low-alloy steel and stainless steel welding. This process has similarities to both SMAW and GMAW. The consumable electrode is continuously fed from a spool and an electric arc flows between the electrode and base metal. The electrode wire has a central core containing fluxing agents and additional shielding gas may be supplied externally. This process generates a substantial amount of fumes due to the high electrical currents and the flux cored electrode. However, FCAW generates little ozone, nitric oxide and nitrogen dioxide gases.

2.4 Gas tungsten arc welding (GTAW) is also known as tungsten inert gas (TIG) welding. GTAW is used on metals such as aluminium, magnesium, mild steel, stainless steel, brass, silver and copper-nickel alloys. This technique uses a non-consumable tungsten electrode. The filler metal is fed manually and the shielding gas is supplied externally. High electrical currents are used which causes this process to produce significant levels of ozone, nitric oxide and nitrogen dioxide gases. However, GTAW produces very few fumes.

2.5 Submerged arc welding (SAW) is a common welding process used to weld thick plates of mild steel and low-alloy steels. In this process, the electric arc flows between the base metal and a consumable wire electrode; however, the arc is not visible since it is submerged under flux material. This flux material keeps the fumes low since the arc is not visible. Little ozone, nitric oxide and nitrogen dioxide gases are generated. The major potential airborne hazard with SAW is the fluoride compounds generated from the flux material.

2.6 Plasma arc welding (PAW): is an arc welding process similar to gas tungsten arc welding (GTAW).

The electric arc is formed between an electrode (which is usually, but not always, made of sintered tungsten) and the work piece. The key difference between GTAW and PAW is that in PAW, by positioning the electrode within the body of the torch, the plasma arc can be separated from the shielding gas envelope. Plasma arc welding is advancement over the GTAW process. This process uses a non-consumable tungsten electrode and an arc constricted through a fine-bore copper nozzle. PAW can be used to join all metals that are weldable with GTAW (i.e., most commercial metals and alloys).

2.7 Oxy-fuel welding: This is commonly called oxyacetylene welding, oxy welding, or gas welding in the US and oxy-fuel cutting are processes that use fuel gases and oxygen to weld and cut metals, respectively. Pure oxygen, instead of air (20% oxygen/80% nitrogen), is used to increase the flame temperature to allow localized melting of the work piece material (e.g., steel) in a room environment. A common propane/air flame burns at about 3630 °F (2000 °C), a propane/oxygen flame burns at about 4530 °F (2500 °C), and an acetylene/oxygen flame burns at about 6330 °F (3500 °C).

Oxy-fuel is widely used for welding pipes and tubes, as well as for repair work. It is also frequently well suited, and favoured, for fabricating some types of metal-based artwork. The process is commonly used in industry, especially for large products and in the manufacture of welded pressure vessels. Other arc welding processes include atomic hydrogen welding, electro-slag welding, electro-gas welding, and stud arc welding.

2.8 Occupational Hazards Associated With Welding Operations

Safety is a critical consideration for any welding project. Arc welding is probably the most common type of welding done today and is a safe occupation when proper precautions are taken. But, if safety measures are ignored, welders face an array of hazards which can be potentially dangerous with long term consequence.

To help keep welders safe, organizations such as the Health and Safety Executive (HSE), American Welding Society (AWS), The Welding Institute (TWI) amongst others offer safety guidelines to help control, minimize or help employers and workers avoid welding hazards and workers are encouraged to comply with the following important guidelines in the workplace [9]*:*

- Read and understand manufacturer's instructions for equipment
- Carefully review material safety data sheets
- Follow the company's internal safety practices

Knowledge and attention to hazards associated with welding operations is a critical safeguard to enhancing business operations in a systematic manner. John et al, [8] established that welding operations is dependent on multitudes of factors encompassing technical, operational, organisational and external issues; thus, necessitating the development of a generic model that can be used to model disruption scenarios in welding operations.

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Further review of literature revealed that collaboration amongst the multitudes of stakeholders involved in welding/fabrications projects would help to achieve efficiency and ensure safety of welders. It is worth noting that the ability of fabrication operators to maximize performance depends on the availability of the right information, which could be quantitative or qualitative. The quantitative information needs to be complemented by the qualitative information to provide a broader view of welding hazards in order to propose strategies aimed at improving safety.

Hazards associated with the welding operations include electric shock, fumes and gases, fire and explosions, arc radiation, hot parts, flying sparks, spatter, metal or dirt, electric and magnetic field (EMF), noise, moving part, gas cylinders, falling equipment and surface coatings and containments amongst others. The selection of these risks factors is based on discussions with experts in the field and literature review [12], [13], [14], [15]. The major causes identified in literature are used to construct a generic model for analysing welding operational hazards/accidents in welding workshop of a training institute as shown in Table 1.

Table 1: List of Operational Hazards in a Welding Workshop

S/No	Risk Factors	S/No	Risk Factors
1	Electric shock	10	Tetanus bacteria
2	Fumes and dust	11	Moving parts
3	Arc radiations	12	Falling equipment
4	Fire or explosion	13	Surface coating and containment
5	Hot parts	14	Stress
6	Flying sparks	15	Poor house keeping
7	Noise	16	Uneven floor
8	Entanglement	17	Trailing cables
9	Insufficient workstation	18	Low moral

3 Modelling using Fault Tree Analysis (FTA)

In the conventional approach to solving safety risks using the fault tree (FT), the probability theory is used. The crisp values of the basic events (BEs) probabilities must be known. It is usually assumed that the basic events in FTs are independent and could be represented as probabilistic numbers [16].

In the case where the top event (TE) of the FT contains only one independent basic events that appeared in the tree construction, the TE probability can be obtained by working the BE probabilities up through the tree [17]. The intermediate gates events (AND or OR) probability can be calculated by working from the bottom of the tree upward until the TE probability is obtain. The "AND" probability is obtained using Equation 1.

$$P = \prod_{i=1}^{n} P_i \qquad (1)$$

Where P stands for the occurrence probability of TE, P_i stands for the failure probability of BE i. n stands for number of basic events associated with the "AND" gate. In the case of the "OR", Equation 2 is used to obtain the probability.

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$$P = 1 - \prod_{i=1}^{n} (1 - P_i) \qquad (2)$$

where P stands for the probability of the TE, P_i stands for the occurrence probability of BE i, n stands for the number of BEs associated with the "OR" gate.

If a FT have many BEs in the tree, the probability of the TE can be obtained by utilising the minimal cut sets (MCS). The MCS is the collection of the smallest BEs such that if the entire BEs occurred, the TE event will definitely occur. If these BEs are prevented from happening, the TE of the system will not happen. If a FT has MCSs which is presented by MC_i, $i = 1, 2 \dots n_c$, then, the TE (T) exists if at least one MCS exists. [25]

$$T = MC_1 + MC_2 + \dots + MC_{nc} = \bigcup_{i=1}^{nc} MC_i \qquad (3)$$

The exact evaluation of the TE happening can be obtained by:

$$P(T) = P(MC_1 \cup MC_2 \cup \dots \cup MC_N) = P(MC_1) + P(MC_2) + \dots P(MC_N) - (P(MC_1 \cap MC_2) + \qquad (4)$$

$$+ P(MC_1 \cap MC_3) + ..P(MC_i \cap MC_j)...)..+(-1)^{N-1} P(MC_1 \cap MC_2 \cap \dots \cap MC_N)$$

where $P(MC_i)$ is the occurrence likelihood of MC_i and N is the number of MC[17].

3.1 Fuzzy Fault Tree Analysis

The FTA has for the past five decades been used as a powerful technique in the analysis of risks. FTA is a logical and diagrammatic technique used to systematically estimate system safety and reliability by means of qualitative and quantitative method [18] and [19]. The application of FTA requires the failure probability of failure events. However, it is often difficult to obtain failure probabilities of past events or historical accidents. This is because of the ever dynamic nature of the environment and the high levels of uncertainty associated with engineering systems [20]. Furthermore, failure probabilities of components are considered as exact values in which the failure probabilities have to gain either full membership or no membership. This method has difficulty in obtaining failure probabilities of component due to the unavailability of sufficient failure data. Moreover, the imprecision or vagueness in failure data may render the overall result questionable [21]. In order to overcome this challenge in the application of FTA, it is necessary to incorporate experts' judgement in order to obtain rough estimate of failure data. However, the obtained failure possibilities from experts cannot be used directly as failure probabilities or exact failure rates to carry out risk assessment of engineering component. This is because these estimates contains some level of imprecision or vagueness, therefore the Fuzzy Fault Tree Analysis (FFTA) is adopted to deal with such imprecisions and ambiguity arising from expert's judgement and to translate the linguistic values into exact failure rates that can be used to evaluate system safety and reliability [19].

Fuzzy Set Theory (FST) has over the years served as an important tool in the analysis of system safety and reliability Yuhua and Datao, 2005). FST generally uses triangular, trapezoidal and Gaussian fuzzy numbers to convert linguistic terms to fuzzy number and the fuzzy number are further converted to fuzzy probability which can be used in risk estimation. The process involves assigning subjective judgement from experts to the vague basic events; the individual expert subjective judgement is then aggregated to reach single censuses by the use of linguistic terms (very low, low, medium, high and very high). Fuzzy numbers are converted into fuzzy possibility and fuzzy possibilities are converted into fuzzy probabilities which are used in risk assessment [7] and [19].

Many researchers have successfully used the FFTA techniques over the years in many fields of expertise to overcome the shortfall encountered when using the conventional FTA method. Some of these areas include disciplines of operations management, Marine and offshore industry, engineering management amongst others. In light of the above, it is noteworthy to mention that FFTA has been studied and used for a very long time in many engineering problems. However, its application in industrial welding operational hazard evaluation is still limited. This research aims to propose and extend the application of FFTA in evaluating welding operations hazards in an industrial workshop.

4 Methodology

A methodology to model operational hazards during welding operations using FFTA has been introduced. The proposed framework provides the flexibility needed by experts to represent their vague information resulting from the lack of quantitative data. The framework is illustrated through the following steps and presented in Figure 1:

1. Safety survey or inspection to identify risk factors
2. Selection of experts.
3. Estimating weights of experts.
4. Rating phase.
5. Aggregation phase.
6. Defuzzifying state.
7. Converting fuzzy possibilities scores to fuzzy failure probabilities.
8. Estimation of minimal cut sets.
9. Ranking of minimum cut sets and performing sensitivity study.

These steps are mainly derived from the existing literature and can be deployed for modelling operational hazards associated with welding operations.

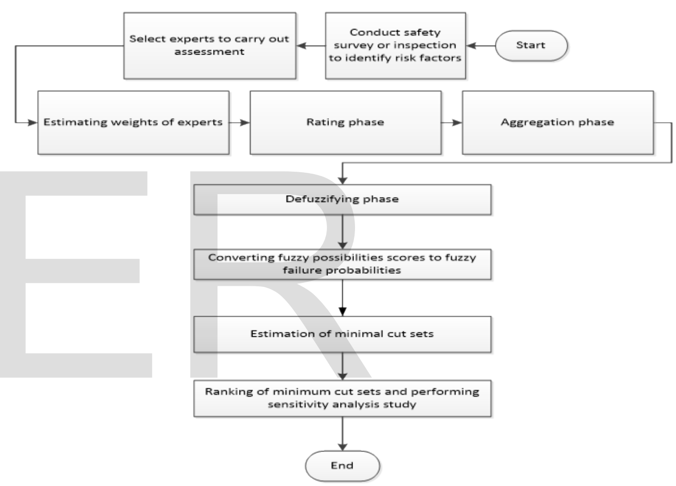

Figure 1: Flow Chart of the Proposed Methodology

4.1 Conduct Safety Survey or Inspection to Identify Risk Factors

This section analyses welding operations of a particular workshop in West Africa and obtains relevant information from the domain experts involved with the operations of the workshop. As a consequence, a generic model for welding accident is developed as presented in Figure 2. The development of the model is based on operations performed in the welding workshop and experience of safety analysts.

4.2 Selection of Experts

Complete impartiality of expert knowledge is often difficult to achieve when carrying out assessment of a complex system due to individual perspectives and goals [16]. Hence, an important consideration in the selection of experts is whether to use a heterogeneous group of experts (e.g. both scientists and workers) or a homogenous group of experts (e.g. only scientists or only workers). The effect of difference in personal experience on expert judgement is assumed to be smaller in homogenous group compared to a heterogeneous group. A heterogeneous group of experts can have an advantage over a homogenous group through considering all possible opinions [5]. In summary, criteria to identify experts are based on the person's period of learning, experience and analytical behaviour in a specific domain of knowledge, thus influencing his or her judgment, and the specific circumstances of the heterogeneous group of expert.

4.3 Estimating Weights of Experts

In line with the modelling approach presented by Yuhua and Datao [22], this phase of the analysis deals with the calculations of experts' weights, which are determined using the Delphi method. As an example, if an expert is more experienced and 'better' than others due to his or her knowledge proficiency during a group decision making session, he or she is given a greater score. Accordingly, the weight of the expert can be determined in a simplified manner. For instance, let E_1, E_2, E_3 …E_n, be scores of experts, Based on Equations 5 and 6, the weighting score and factor of experts can be determined as:

Weight score of E_i = IP score of E_i + ST score of E_i + AQ score of E_i + Age of E_i (5)

where IP stands for industrial position, ST and AQ represent service time and academic qualification of the domain experts respectively.

$$\text{Weight factor of } E_i = \frac{\text{Weight score of } E_i}{\left(\sum_{i=1}^{n} \text{Weight score of } E_k\right)} \quad (6)$$

Table 2: Weighting Scores and Constitution of Different Experts

Constitution	Classification	Score
Professional Position (PP)	Senior Lecturer Welding Engineer Welding Technologist Welding Technician Others	5 4 3 2 1
Service Time (ST)	> 30 years 20-29 10-19 6-9 <5 years	5 4 3 2 1
Educational Level (EL)	PhD Master Bachelor HND/OND School Leaver	5 4 3 2 1
Age	>50 40-49 31-39 20-30 <20	5 4 3 2 1

Source: Adopted and Modified from [22]

4.4 Rating State

This phase provide experts with the flexibility of expressing their opinion on each basic events due to insufficient data using sets of linguistic variables. The linguistic variables are convenient in dealing with circumstances that are complex or ill-defined to be described quantitatively. Fuzzy set theory (FST) is well suited to modelling such subjective linguistic variables [23]. Due to their easiness of use, trapezoidal fuzzy numbers are usually used for this analysis by the experts based on a common interval [0, 1]. In FST, conversion scales are applied to transform the linguistic terms of experts into fuzzy numbers for system modelling and analysis. In line with the conversion scale proposed by Chen and Hwang, [24], this study adopts a similar approach for the experts' rating where both the performance score (x) and the membership degree $(\mu\ (x))$ are in the range of 0 and 1 as shown in Figure 3.

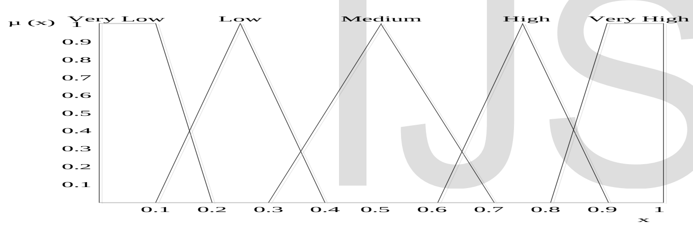

Figure 3: Membership functions of experts' opinion, source: [24]

4.5 Aggregation State

When carrying out a modelling of a large engineering system, experts may have different opinions; it is therefore necessary to aggregate these opinions in a logical, systematic and simplified manner. There are many techniques employed in aggregating expert's opinion such as in[25] which presented an algorithm to aggregate the linguistic opinions of a heterogeneous/homogeneous group of experts and [26] which used a linear opinion pool for aggregating expert's judgements. The linear opinion pool technique is employed in this study to aggregate expert's opinion.

$$M_i = \sum_{i=1}^{m} W_i A_{ii} \qquad j = 1,2,......,n \qquad (7)$$

Where A_{ii} is the linguistic expression of a basic event *i* given by expert *j*, *m* is the number of basic events, *n* is the number of the experts. w_j is a weighting factor of the expert *j* and m_j represent the combined fuzzy number of the basic event *i*.

4.6 Defuzzification Phase

Defuzzification is an inverse method used to transform the output from the fuzzy domain back into crisp domain in order to produce a quantifiable result in the fuzzy logic. In order to rank the minimal cut sets, all aggregated fuzzy numbers must be defuzzified. Due to its ease of use when compared to other techniques, the centre area defuzzification technique proposed by Sugeno [27] is used in this analysis. Each element of matrix $\tilde{x}_i = (a_1, a_2, a_3, a_4)$ can be converted to a crisp value using Equation 8.

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} x\,dx + \int_{a_2}^{a_3} x\,dx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} x\,dx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} dx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} dx} = \frac{1}{3}\frac{(a_4+a_3)^2 - a_4 a_3 - (a_1+a_2)^2 + a_1 a_2}{(a_4+a_3-a_1-a_2)} \qquad (8)$$

4.7 Converting Fuzzy Possibilities Scores to Fuzzy Failure Probabilities

When converting fuzzy possibilities to fuzzy failure probabilities, it is important to keep the same unit (e.g. occurrence probability with a period of time set). Since the data obtained for this analysis are subjective in nature, this need to be converted to fuzzy failure probabilities so as to be used in the fault tree software.

In line with the modelling approach presented in Yuhua and Datao [22], this research adopts similar approach for converting fuzzy possibility scores to fuzzy failure probability score.

$$F\,\text{Pr} = \begin{cases} \dfrac{1}{10^k} & FPs \neq 0 \\ & FPs = 0 \end{cases} \quad (9)$$

where,

$$K = \left[\frac{(1-FPs)}{FPs}\right]^{(1/3)} \times 2.301 \quad (10)$$

4.8 Estimation of Minimal Cut Sets

Cut sets are sets of system events that lead to the failure occurrence of the system. MCS are irreducible path that leads to the occurrence of an undesirable event or TE. For the TE to occur, all the failure events in the MCS must happen. One-component MCS represent the single failure event that will cause the TE, while two-component MCSs represents double failures that will happen together to cause the failure of the TE. In light of the above, TE can be obtained from the MCS by using Equation 3.

4.9 Ranking of Minimal Cut Sets and Performing Sensitivity Analysis

The calculation of MCS is of importance in FTA. This process is used to determine the contribution of each MCS to the occurrence probability of the TE. The ranking serve as significant information for obtaining the required information of basic events with high contribution to the probability of TE. Analysis of literature revealed various methods used in ranking MCSs. The most widely used in literature is the fussell-vesely measure of importance (F-VIM). It is the contribution of the MCSs to the TE probability. F-VIM is determinable for every MCSs modelled in the fault tree. This provides a numerical significance of all the fault tree elements and allows them to be prioritized. The F-VIM is calculated by summing all the causes (MCSs) of the TE involving the particular event. This measure has been applied to MCSs to determine the importance of individual MCS [16], [21]. The measure can be quantified as follows:

$$I_i^{fv}(t) = \frac{Q_i(t)}{Q_s(t)} \quad (11)$$

where $I_i^{fv}(t)$ stands for the importance of minimal cut set (MC_i)

Q_i (t) stands for the occurrence probability of MC_i

Q_s (t) stands for the occurrence probability of the TE due to all MCs.

5.0 Demonstration of the methodology

This test case is used to illustrate how the methodology can be implemented to analyse welding operational hazards in a typical welding workshop in West Africa. The phases of the proposed approach are analysed as follows:

5.1 Safety Survey or Workshop Inspection to Identify Risk Factors

As indicated earlier, the welding workshop was inspected for the identification of hazards associated with welding operations, also, discussion with domain experts was conducted and literature reviewed. A specific model for a welding accident is constructed as shown in Figure 2.

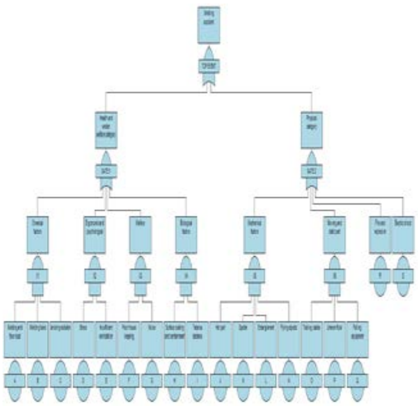

Figure 2: Specific Model for Welding Accident

5.2 Selection of Experts

Expert elicitation is the synthesis of experts' opinions on a subject where there is uncertainty due to insufficient quantitative data because of physical constraints or lack of resources. Heterogeneous group of experts were selected comprising three experts whose experience spanned welding and fabrication, material/metallurgical and mechanical engineering, operations and management with different service time, qualification, age and present job title were selected for this analysis and a set of questionnaires were sent to them and implemented based on their ratings and assessment.

5.3 Estimating Weights of Experts

Based on the available information in Section 2 and by using Equations 5 and 6, the weights of the experts were calculated. The industrial positions, service times, and academic qualifications and age of the experts are extracted from Table 2. By using Equations 5 and 6, the weights of the experts are calculated and presented in Table 3.

Table 3: Weighting of Expert Judgements

No of Experts	Professional Position	Service Time	Educational Level	Age	Weighting Factors	Experts' Weights
EXP 1	Senior Lecturer	>30 yrs	Masters	40-49	5+4+4+5=18	[illegible] = 0.36
EXP 2	Welding Technologist	20-29 yrs	Masters	>50	3+4+4+5=16	[illegible] = 0.33
EXP 3	Welding Engineer	20-29 yrs	Bachelors	40-49	4+4+3+4=15	[illegible] = 0.31
					Total = 49	Total = 1

5.4 Rating State

In line with the proposed method, a modelling approach presented by Chen and Mon, [28] is used to convert linguistic terms to their corresponding fuzzy numbers. The conversion scale of trapezoidal fuzzy membership function as illustrated in Figure 3 is used to analyse the experts' opinion presented in Table 4 on the occurrence probability of welding accident in the workshop, the figure contained both triangular and trapezoidal fuzzy numbers. All of the triangular fuzzy numbers can be converted into the corresponding trapezoidal fuzzy numbers for the ease of computational analysis [21]. As previously mentioned, three experts are employed to rate the basic events for subsequent analysis, the background of the experts are briefly stated as follows:

- An International Welding Engineer (IWE) with an MSc degree in Metallurgical and Materials
- Engineering who has been involved with lecturing welding, safety and Non Destructive Testing (NDT) for over 30 years.
- An ASNT level II NDT practitioner with MSc degree in Welding and Fabrication Technology

who has been a technologist in welding and NDT operations and management for over 25 years.

- An International Welding Specialist with a BSc degree in Mechanical Engineering and has been involved with welding services for over 25 years.

Table 4: Linguistic assessment/Ratings of experts

Basic events		Exp1	Exp2	Exp3
1	Fire and explosion	High	Medium	Medium
2	Electric shock	Medium	Medium	Low
3	Falling equipment	Medium	Medium	High
4	Uneven floor	Medium	Medium	Medium
5	Trailing cables	High	Medium	Medium
6	Flying sparks	Medium	High	Medium
7	Entangle-ment	Medium	High	Medium
8	Spatter	Medium	High	High
9	Hot metallic part	High	Medium	Medium
10	Insufficient workstations	High	Medium	Medium
11	Stress and low moral	Medium	High	Medium
12	Welding and floor dust	Medium	Low	Low
13	Welding fume	High	High	High
14	Tetanus bacteria	Low	Low	Medium
15	Surface coating and contamina-tion	Medium	High	High
16	Noise	Low	Low	Low
17	Poor house keeping	Medium	High	Medium
18	Ionising radiation	Medium	Low	Low

In light of the above, the obtained trapezoidal fuzzy number assessed based on Figure 3 is illustrated in Table 5.

Table 5: Conversion of linguistic terms to fuzzy numbers

Linguistic terms	Trapezoidal fuzzy number
Very Low	(0.000, 0.000, 0.100, 0.200)
Low	(0.100, 0.250, 0.250, 0.400)
Medium	(0.300, 0.500, 0.500, 0.700)
High	(0.600,0.750, 0.750, 0.900)
Very High	(0.800, 0.900, 1.000, 1.000)

5.5 Aggregating State

This stage of the analysis involves aggregation calculations based on the experts' opinion. It is important to aggregate the opinions of the experts in order to arrive at a consensus and reliable result. Aggregation calculation is conducted using Equations 7; as an example, the detailed calculation for falling equipment is presented in Table 6. As a consequence, similar calculations were conducted on the other parameters and their corresponding fuzzy estimates are presented in **Table 7.**

Table 6: Demonstration of aggregation calculations for falling equipment

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$E_1 =$ 0.36 (0.3, 0.5, 0.5, 0.7) (0.108, 0.18, 0.18, 0.252)

$E_2 =$ 0.33 (0.3, 0.5, 0.5, 0.7)

$E_3 =$ 0.31 (0.6, 0.75, 0.75, 0.9) (0.204, 0.255, 0.255, 0.306)

AG = (0.108, 0.18, 0.18, 0.252) + (0.099, 0.165, 0.165, 0.089) + (0.204, 0.255, 0.255, 0.306)

Aggregation = (0.393, 0.5775, 0.5775, 0.762)

Table 7: Aggregation calculations results for all BEs

Basic events	Aggregation result
Fire and explosion	(0.501, 0.668, 0.668, 0.834)
Electric shock	(0.238, 0.423, 0.423, 0.607)
Falling equipment	(0.393, 0.5775, 0.5775, 0.762)
Uneven floor	(0.300, 0.500, 0.500, 0.700)
Trailing cables	(0.408, 0.590, 0.590, 0.772)
Flying sparks	(0.399, 0.583, 0.583, 0.766)
Entanglement	(0.399, 0.583, 0.583, 0.766)
spatter	(0.428, 0.66, 0.66. 0.828)
Hot metallic part	(0.372, 0.590, 0.590, 0.772)
Insufficient workstation	(0.372, 0.590, 0.590, 0.772)
Stress and low morals	(0.399, 0.583, 0.583, 0.766)
Welding and floor dust	(0.172, 0.340, 0.340, 0.508)
Welding/Hazardous fumes	(0.500, 0.750, 0.750, 0.900)
Tetanus bacteria	(0.162, 0.328, 0.328, 0.493)
Surface coating & contamination	(0.428, 0.660, 0.660, 0.828)
Noise	0.100, 0.250, 0.250, 0.500)
Poor house keeping	(0.366, 0.583, 0.583, 0.766)
Ionization radiation	(0.172, 0.34, 0.34, 0.508)

5.6 Defuzzification State

The aggregated trapezoidal fuzzy numbers presented in Table 7 are deffuzzified using the centre of area defuzzification technique. As an example, the aggregated fuzzy numbers for Falling equipment (0.411, 0.60, 0.60, 0.647), is converted as follows; $a_1 = 0.411$, $a_2 = 0.600$, $a_3 = 0.600$ and $a_4 = 0.647$

$$X^* = \frac{1}{3}\frac{(0.762+0.5775)^2 - 0.762\times 0.5775 - (0.393+0.5775)^2 + (0.393\times 0.5775)}{(0.762+0.5775-0.393-0.5775)}$$

$X^* = 0.5775$

In a similar manner, the above procedure is repeated for all other basic events and the results are presented in Table 8.

Table 8: Defuzzified results of basic events

Basic events	Deffuzification result
Fire and explosion	0.6675
Electric shock	0.4225
Falling equipment	0.5775

Uneven floor	0.5000
Trailing cables	0.5900
Flying sparks	0.5825
Entanglement	0.5825
spatter	0.6386
Hot metallic part	0.578
Insufficient workstation	0.578
Stress and low morals	0.583
Welding and floor dust	0.3400
Welding/Hazardous fumes	0.7166
Tetanus bacteria	0.3275
Surface coating & contamination	0.6387
Noise	0.2500
Poor house keeping	0.5715
Ionization radiation	0.3400

5.7 Converting Fuzzy Possibilities Scores to Fuzzy Failure Probabilities

The crisp fuzzy failure possibilities scores presented in Table 8 are converted to fuzzy failure probabilities using Equation 13 and 14. As an example, the fuzzy possibility score for falling equipment (0.5775) is performed as follows:

$$K = \left[\frac{(1-0.5775)}{0.5775}\right]^{(1/3)} \times 2.301$$

K = 2.073

$$F\,\text{Pr} = \left\{\frac{1}{10^{2.073}} = 0.0084\right.$$

In a similar manner, the above procedure is repeated for all basic events and the results of the analysis are presented in Table 9.

Table 9: Results of basic events failure probabilities

Basic events	**Fault tree reference number**	**Result of basic failure probability scores (/yr)**
Fire and explosion	R	0.0150
Electric shock	S	0.0028
Falling equipment	Q	0.0084
Uneven floor	P	0.0050
Trailing cables	O	0.0092
Flying objects/sparks	N	0.0087
Entanglement	L	0.0087
spatter	K	0.0125
Hot metallic part	J	0.0085
Insufficient workstation	E	0.0085
Stress and low morals	D	0.0088
Welding and floor dust	A	0.0014
Welding/Hazardous fumes	B	0.0205
Tetanus bacteria	I	0.0012
Surface coating & contamination	H	0.0125
Noise	G	0.0005
Poor house keeping	F	0.0081
Ionization radiation	C	0.0014

5.8 Estimation of Failure Probability of TE

In order to establish the occurrence likelihood of the TE of the FT model, the occurrence likelihood for each basic event must be obtained and propagated upward to the TE using the Boolean relationships. The BE probabilities of the fault tree model were propagated upward using the MCSs whose failure probability are presented in Table 9. The MCSs are estimated using the Boolean algebra simplification rules and the occurrence likelihood of TE was obtained based on Equation 4 as 0.00382/year. This value represents the experts' assessment of welding accident regarding the workshop under investigation. Such a result can be used to initiate formal safety audit and key performance indicators of welding workshop to ensure a robust welding operation. It is envisaged that the approach could provide flexibility in performing risk assessment where statistical or objective data is lacking.

5.9 Ranking of Minimal Cut Sets and Sensitivity Analysis

An important objective of ranking parameters and performing sensitivity analysis test in risk and reliability engineering is to identify those parameters or MCSs that are the most important so that they can be targeted for improvements. The ranking of the MCSs based on their calculated level of importance is performed with Equation 11 and presented in Table 10.

Table 10: Ranking of Minimal Cut Sets

Cut set	Importance of minimal cut sets
ABC	4.018×10^{-8}
DE	7.48×10^{-5}
FG	4.05×10^{-6}
HI	1.5×10^{-5}
JKLN	8.042×10^{-9}
OPQ	$\left[3.86\times10^{-7}\right]$
R	1.50×10^{-2}
S	2.8×10^{-3}

There are different methods of performing sensitivity in science and engineering, whichever method employed (dimensional consistency tests (DCT), boundary adequacy Tests (BAT), structure verification tests (SVT) [29] and sensitivity-valued approach (SVA) [30] largely depend on the type of model developed to achieve a particular need. For the purpose of this paper and due to the fact that it has not been possible to find any proven benchmark results for its full validation in the literature, a possible method of validating the model can be achieved by using an incremental process, through conducting more industrial case studies. The developed model can then be refined and applied in real industrial applications. In light of the above, a partial validation may be the most realistic way to validate the proposed model using sensitivity analysis.

Therefore input parameter such as a component failure probability is changed, and the corresponding change in the TE probability is obtained. This analysis is performed for a certain amount using either different values for the same parameter or changing different parameters, e.g., changing different failure probabilities for the same parameter. The sensitivity analysis was implemented to observe the effect on the output data (TE) given an increase in the input data (basic event). Figure 4 shows the changes in the final ranking of the basic events when their failure probabilities were changed by 10%, 20% and 30% respectively. It was established that (B) welding/hazardous fumes, (R) fire and explosion and (K) spatter were more sensitive to changes in input data. This is to help identify the basic event with the highest effect on the occurrence probability of the TE.

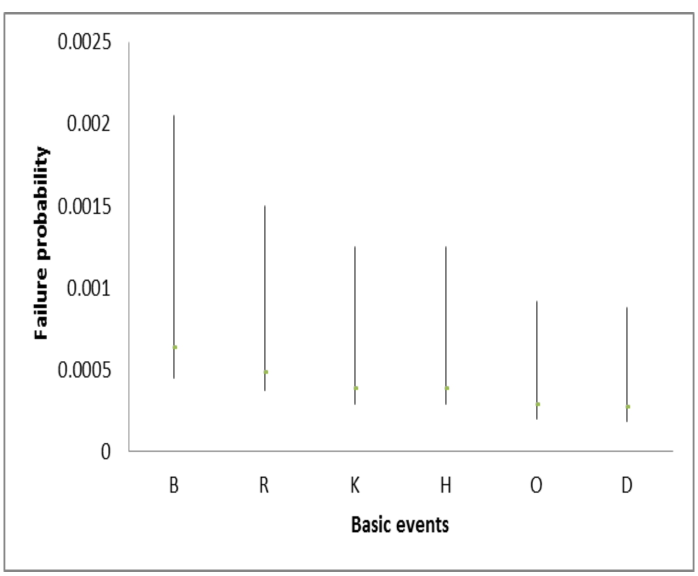

Figure 4: Ranking of Basic Events

6.0 Results and Discussion

Based on Figure 4, the sensitivity analysis performed on basic events shows that welding/hazardous fumes (B), fire and explosion (R), spatter (K), surface coating & contamination (H), trailing cables (O) and stress and low morals (D) showed significant difference in their output values when slight changes were made on their input values. Also, from Table 10, the ranking of the MCS indicated that presence of ignition sources and combustible materials in the workshop leading to fire and explosion (R) and electric shock (S) has the highest contribution of (1.5×10^{-2}) and (2.8×10^{-3}) respectively to the occurrence probability of the TE. This implies that more attention needs to be focused on preventing R and S from occurring in order to prevent or minimize the occurrence probability of TE or welding accident in the workshop. The MCS stress/low morals and insufficient workstations (DE) and surface coating/contaminations and bacterial tetanus (HI) has the third highest contribution as (7.48×10^{-5} and (1.5×10^{-5}) respectively, cut set (poor housekeeping and noise (FG) has the contributing factor of (4.05×10^{-5}), cut set (trailing cables, uneven floor and falling equipment (OPQ)) has the contributing factor of (3.86×10^{-7}), cut set welding and floor dust, welding/hazardous fumes and ionisation radiation (ABC) with the contributing factor of (4.018×10^{-8}) and cut set hot metallic part, spatter, entanglement and flying objects/spark (JKLN) (8.042×10^{-9}). However, it is worth mentioning that in order to reduce or prevent the occurrence probability of the TE, the occurrence probabilities of all the basic events most be reduce and special attention must be paid to fire and explosion and electric shock which has the highest contributing factor to the occurrence of welding accident in workshops thereby leading to disruptions of operations. Also, it is suggested that more attention needs to be paid to redesigns and replacing of worn out workstations to enhance welders' posture, maintenance and inspection of damage sockets, naked wires and local exhaust, using the right Personnel Protecting Equipment (PPE) to minimize or reduce exposure to radiations and installation of safety guards to ensure robust safety of welders.

7.0 Conclusion

This paper has presented a modelling approach to evaluate the risks of welding accident in an industrial workshop under uncertainty. The methodology combines FST and FTA to overcome the inadequacy of traditional FTA. It is designed to assist welding operators or industrial analyst to evaluate the various welding hazards in a flexible manner. FST allows experts to express their opinions on the failure probability of the BEs enabling the treatment of uncertainty. The approach can be applied to situations where information from different experts have to be integrated and synthesized in the absence of exact data. The obtained value for risk of welding accident can then be incorporated into the facility's QRA studies and safety case document or control of major accident hazards (COMAH) Report in order to demonstrate that hazards have been identified and risks control measures have been developed for that project. This information may then be used during hazard and operability study (HAZOP) for the workshop. It is envisaged that the outcome will help welding analysts in proposing practical measures that will help to avoid accident during critical welding project in industrial facilities.

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