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BENEFIT, COST, AND RISK ANALYSIS IN SELECTING GAS DETECTOR TECHNOLOGY FOR OIL AND GAS PROCESSING AREA, FUZZY AHP APPROACH

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ABSTRACT

In the oil and gas processing area, adequate risk control must be prearranged to prevent incidents, such as major gas leakage, fire, and explosion. Installing gas detectors at appropriate technology is one of indispensable conditions for implementation of risk reduction measures. The suitability of gas detector technology is necessary to ensure the reliability of selected gas detector. This research evaluates four alternatives of gas detector based on their characteristic in terms of benefit, risks, and cost. Integration of Delphi technique and Fuzzy Analytic Hierarchy Process (fuzzy AHP) is implemented to evaluate the suitability of gas detector technology. Ten expert panelists from production, safety, and maintenance departments are involved in Delphi Technique to assess the sub-criteria of fuzzy AHP. The fuzzy AHP evaluation reveals that point-type infrared gas detector has the highest value among all gas detector technologies. This means that point-type infrared technology has the most efficient value in delivering service to process safety operation. Point-type infrared gas detector also reveals the best value in risk criteria evaluation.

Keywords: *Gas detector technology, Delphi technique, Fuzzy Analytic Hierarchy Process*

PENDEKATAN FUZZY AHP UNTUK ANALISIS *BENEFIT*, *COST*, DAN RISIKO PADA PEMILIHAN TEKNOLOGI GAS DETEKTOR DI AREA PEMROSESAN MINYAK DAN GAS BUMI

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ABSTRAK

Pada area pemrosesan minyak dan gas bumi, pengendalian risiko yang sesuai harus dilakukan untuk mencegah terjadinya suatu insiden, misalnya kebocoran gas, kebakaran, dan peledakan. Dengan menginstal detektor gas pada teknologi yang sesuai merupakan kondisi yang tidak terelakan untuk mengurangi dampak risiko. Jenis detektor gas sesuai merupakan sebuah keharusan untuk meyakinkan reliabilitas dari sistem gas detektor tersebut. Riset ini mengevaluasi empat alternatif gas detektor berdasarkan karakteristiknya dalam kriteria benefit, risiko, dan biaya. Integrasi teknik Delphi dan Fuzzy Analytic Hierarchy Process (fuzzy AHP) digunakan untuk menilai tingkat kepentingan teknologi gas detektor. Sub-kriteria dibangun dan dinilai berdasarkan teknik Delphi. Sepuluh panelis ahli dari bidang ilmu proses, produksi, dan *maintenance* turut serta dalam menentukan sub-kriteria tersebut. Evaluasi fuzzy AHP mengungkapkan bahwa detector gas point-type infrared memiliki nilai tertinggi diantara seluruh gas detector yang lain. Hal ini berarti bahwa gas detector point-type infrared memeiliki nilai efisiensi yang baik pada operasi keselamatan pemrosesan. Detektor gas jenis point-type infrared juga memiliki nilai tebaik pada kriteria risiko..

Kata kunci: Detektor Gas, Area Pmerosesan Minyak dan Gas Bumi, Fuzzy AHP

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Surabaya, June 2018

Fermi Dwi Wicaksono

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LIST OF ABBREVIATION

AHP	: Analytic hierarchy process
ALARP	: As low as reasonable and practicable
API STD	: American Petroleum Institute standard
BLEVE	: Boiling liquid expanding vapor explosion
BOPD	: Barrel oil equivalent per day
CCPS	: Center for chemical process safety
ESD	: Emergency shutdown system
ESDV	: Emergency shut down valve
F&G	: Fire and gas system
Fuzzy AHP	: Fuzzy analytic hierarchy process
HIPPS	: High-integrity pressure protection system
IEC	: International Electro-technical Commission
IQR	: Inter quartile range
LEL	: Lower explosive limit
MCDM	: Multi criteria decision making
MMSCFD	: Million standard cubic feet per day
NFPA	: National fire protection agencies
OGPA	: Oil and gas processing area
OWT Platform	: Oily water treatment platform
PSV	: Pressure safety valve
RU V	: Refinery unit V
SIF	: Safety instrumented function
SIS	: Safety instrumented system
UEL	: Upper explosive limit
USS	: Ultimate safety system

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CHAPTER I

INTRODUCTION

1.1. Background

Oil and gas industry is a form of high risk industry following their production of hazardous material. This type of industry mainly deals with flammable liquid, explosive gas and toxic substances. This material could be very dangerous especially when there is a possibility of ignition source. Fire is major hazard in the oil and gas industry. This hazard could lead to a catastrophic event which causes total loss of the industry. As the fire mostly comes from ignited flammable liquid or explosive gas, therefore there must be a system to limit uncontrolled the hydrocarbon release and source of ignition.

Mitigation measures and further studies should be carried out to overcome the risk occurring in daily process operation. This mitigation includes all action in order to minimize the consequences of fires and explosions and ease access for firefighting when emergency situation happened. Selection right gas detector technology to identify preliminary gas detection is key to prevent incident escalation.

The capability of system to detect flammable release events is a key component of modern process safety (Legg, 2013). This safety system is then called gas detector system. Flammable gas detection relies upon the detection of a gas before it reaches its lower explosive limit (LEL). “These limits refer to the gas concentrations at which a dispersed gas cloud in air will allow a flame front to spread when exposed to an ignition source” (Legg, 2013).

In addition, proper selection of the sensor specifications is highly importance to ensure effective detection of likely gas release. Gas detector technology has been developed into four type of sensor: catalytic, point-type infrared, open-path infrared, and ultrasonic technology. Each of technology has different characteristic and features. Improper technology selection of gas detectors may reduce the probability of detecting a particular release, or even yield a sensor completely useless. Therefore, the methodology to select the best sensor technology that consider various aspects is needed.

1.1.1. Oil and Gas Processing Area and Associated Risks

The oil and gas processing area (OGPA) is petroleum field which process oil and gas from hydrocarbon (HC) wells and export crude oil to the oil and gas storage and terminal. OGPA product consists of hydrocarbon gas, crude oil and hydrocarbon condensate. Presently, facilities in OGPA cover:

1) More than 115 live hydrocarbon producer wells, produce 2500-barrel oil per day (BOPD) and 35 million standard cubic feet per day (MMSCFD)
2) four water producer wells (dedicated to produce water),
3) compression platform equipped with 4 interchangeable turbo-compressors,
4) liquid export platform equipped with 4 interchangeable electric pumps,
5) gas-lift network for enhance oil recovery, and
6) automatic fire pumps and fix firefighting means (fire monitor, deluge system, and sprinkler).

The major operating problems encountered in current operation of OGPA as follow:

1) High sand production which cause frequent valves and flow lines leak,
2) large number of sensitive well; some of them rely on gas lift (loss of gas lift may result to potential and reserve loss), and
3) aging of the installation and obsolescence of equipment and spare part.

From the characteristic of OGPA, the major risk occurrence during operation relates to the design of the facilities. Those are, (1) Major leak on gathering network that could impact accommodation camp and office, (2) major leak on OGPA process platform that could impact control room, (3) inadequate fire or gas detection on main processing platform, gas compression platform, and liquid export platform. The installation of OGPA is displayed on figure 1.1.

Those above major risks are due to the following reasons:

1) Major fire or gas leak on OGPA platform,

2) safety distances are not well defined in the process area,
3) emergency shutdown valve (ESDV) within hazardous area, without adequate passive fire protection,
4) numerous flanges and tapping points downstream emergency shutdown valves could possibly cause major leak.

Figures 1.1 The installation of oil and gas processing area. This OGPA delivers production of hydrocarbon oil, gas and condensate.

As faced by the OGPA, those risks should be controlled. Although the risks cannot be eliminated completely, yet to ensure optimal safe operability, those risk must be minimized. The key of risks control is defined as prevention of incident and mitigation of major incident escalation. Failure to perform incident escalation can lead the minor incident to be a catastrophic accident. In many cases[1] catastrophic accidents in petroleum/petrochemical processing area begin with failure of hydrocarbon containment or inadequate to limit hydrocarbon leakage.

As mainly deal with hydrocarbon release that may lead to major fire incident, the OGPA should implement an integrated safety system that could be automatically detect the early stage of catastrophic incident such as explosion or fire blast. As incident escalation prevention, gas detector should be implemented in the process area.

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[1] as described in Chapter 2.1.

1.1.1.1. Existing Gas Detector in OGPA

The oil and gas processing area has been implemented gas detection system by utilizing catalytic technology. This type of gas detector is unlikely to detect the real gas release during several incidents occurred in the OGPA (as it will be elaborated more in chapter 1.1.1.2). The catalytic gas detector is form of gas detection technology which can only detect in the limited coverage area. It can only detect in singular point of release and not suitable for windy area. In fact, it is the cheapest gas detector available on market. The configuration of catalytic gas detector in OGPA is described on figure 1.2.

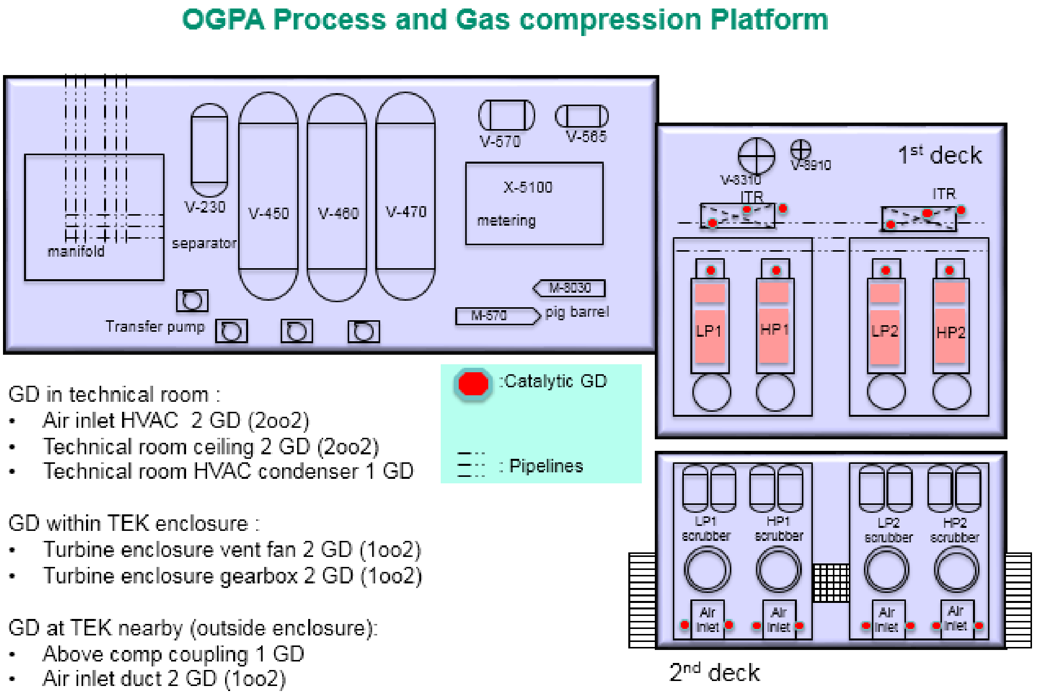
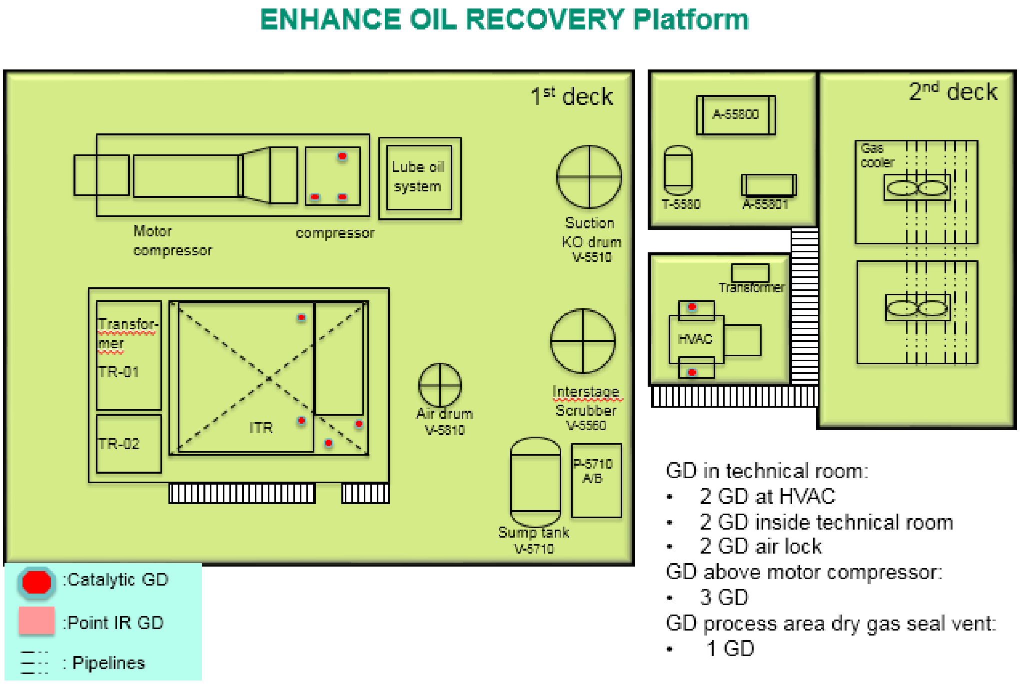


Figure 1.2a. The location of existing gas detector. It is noted that placement of gas detector does not cover all hazardous area in the OGPA



GD in technical room:
- 2 GD at HVAC
- 2 GD inside technical room
- 2 GD air lock

GD above motor compressor:
- 3 GD

GD process area dry gas seal vent:
- 1 GD

Figure 1.2b. The location of existing gas detector. It is noted that placement of gas detector does not cover all hazardous area in the OGPA

1.1.1.2. Past Incidents Review in The OGPA

During its operation, the OGPA has suffered several major or significant hydrocarbon release incidents. These incidents are mainly due to ineffective detection of existing gas detector. Eventually the process was finally shut downed by operator not automatically by system. The incidents are captured hereunder,

Significant gas leak from body of discharge scrubber compressor

- July first, 2013 at 14.25, gas leak was found from the body of discharge scrubber of Gas Compressor Low Pressure train 2. It is located on second deck above compressor unit. Vessel working pressure is 20 barg.
- The Gas Compressor was then stopped by normal stop at 15.30 for intervention.
- No gas detector was active as the 2nd deck of compressor is beyond coverage of gas detector.

Gas cloud from rupture 6” flange fuel gas inlet compressor

- November, 11st 2009 at 13.10 a high noisy sound is heard from office and control room, site operator checked on location and found gas cloud from rupture 6” flange fuel gas inlet 1 compressor. The operator was noticed before ESD.
- At 13.15 Processing platform got ESD (shut down and depressurize) initiated

Based on the situation faced by the OGPA, it is confirmed that the existing catalytic gas detector is not optimal for detecting hydrocarbon release. The existing catalytic gas detector must be re-evaluated by analyzing their benefit, cost and risk. They are even probably changed with newer technology such as, infrared or ultrasonic leak detector.

1.1.2. Fuzzy Analytic Hierarchy Process in Multi Criteria Decision Making

The selection of sensor technology based on various criteria can be regarded as a Multi criteria decision making (MCDM) problem. MCDM is methodology for modelling process of complex engineering problem (Kahraman, 2008). Multi criteria decision making based on the characteristic to evaluate complex criteria and numerous alternatives. The final goal of MCDM is to achieve the best alternatives based on given multi criteria. Two types of MCDM methods are the analytical hierarchy process (AHP) and analytical network process (ANP). Both mentioned methodology is performed by quantifying output values based on pairwise comparison matrix. The different is that AHP the criteria involved do not have correlation one to another. Whereas in ANP all the criteria involved are correlated to the others. Specifically, in this research, criteria involved is not correlated each other. Therefore, AHP based methodology is chosen.

In the conventional AHP, methodology to perform multi criteria decision making is based on single crisp number (Chen, 1996). This methodology has been criticized for handling uncertainty in the decision maker’s judgement to a number (Ayag & Ozdemir, 2006). The conventional AHP is unable to precisely process uncertainty and vagueness in performing pair-wise comparisons (Gupta et al., 2005). In addition, the factors for assessing suitability level of gas detector technology is often observed as qualitative criteria. The vagueness and uncertainty is difficult to put exact crisp number to represent the judgment, such as “environment distractive signal”. In order to overcome this limitation, fuzzy analytic hierarchy process was introduced (Laarhoven & Pedrycz, 1983). Developed based on fuzzy logic and method of MCDM, Fuzzy AHP is capable of evaluating uncertainty in human thought and preference. This method will enable AHP to adapt in the evaluation where the criteria and alternatives, are based on qualitative judgement or imprecise (Li, 2005).

Based on the advantages delivered by fuzzy AHP, this research employs this methodology to evaluate selection of gas detector technology. Expected result of fuzzy AHP is that this methodology can deliver precise result on the evaluation. The result of fuzzy AHP evaluation shall be scientifically true based on this research conclusion.

1.2. Problem Statement

Based on the intrinsic characteristic of high risk industry, oil and gas processing area (OGPA) covers several problems that need to be reinstated, those are:

1. The capability and suitability of gas detectors technology should be quantified to best applied in the oil and gas processing area.
2. The gas detector criteria are analyzed based on their benefit, cost, and risk associated. Fuzzy analytic hierarchy process is implemented for evaluation the selection. And the sub-criteria are developed and ranked based on Delphi technique.
3. Criteria defined from selection of gas detection technology shall taking into account the level of risk into the ALARP (as low as reasonable and practicable). The term of reasonable is based on capital and operational cost, and practicable is for delivering normal production. As the gas detection

technology is linked with safety shutdown system, the detection must be accurate to prevent spurious shutdown which caused by false detection.

1.3. Research Objectives

The formulated purpose of this research is defined as follow:

1. To define selection sub-criteria and alternatives attribute for the optimal operation in terms of ALARP for oil and gas processing area in selecting the gas detector technology.
2. To obtain best applicable in terms of ALARP for selecting the gas detector technology in Oil and Gas Processing Area. The selection shall take into account benefit, cost and risk analysis for the decision making. This research covers an internal factor such as: Control System Mechanism, major risk that is faced by OGPA, and practicability for production deliverability.
3. To evaluate the result category based on Fuzzy-analytic hierarchy process in selecting gas detector technology.

1.4. Research Scope

In order to make robust problem solving, the subject limitation for this research is defined as follow,

1. Implementation of this research is based on petroleum processing plant operated in east Kalimantan region. This plant has been delivering oil and gas production for more than 40 years with average production of 2500-barrel oil per day (BOPD) and 35 million standard cubic feet per day (MMSCFD)
2. The selection of gas detector technology sub-criteria is based on interview and questioner involving 10 expertise or engineer working in the oil and gas processing area. Those are: Production Method service engineer, Maintenance department engineer, head of project interface department, and head of safety concept service. The sub-criteria development is based on two-round Delphi technique.
3. Evaluation of gas detector methodology is based on fuzzy analytic hierarchy process and conventional analytic hierarchy process.

4. Typical gas detectors evaluated are: catalytic gas detector, ultrasonic gas leak detector, open-path infrared gas detector and point-type infrared gas detector.
5. This research analyzes gas detector technology based on benefit delivered by gas detector characteristic, capital and operational costs, and its capability to reduce risk into ALARP condition.

1.5. Expected Benefits

The analysis for evaluating gas detector category mainly provides several advantages as described below:

1. This research helps the company to understand the critical factors for determining gas detector technology capability and characteristic in detecting flammable gas.
2. Describe the importance of selecting suitable gas detector technology for early detection effectiveness and efficiency.
3. Result of this research would help the company management to select which gas detector technology is best applied in oil and gas processing area. Managerial implication for gas detector selection shall be based on this research. Management of Petroleum Company shall use this research as one of guidance for implementing future development of gas detector in the OGPA.
4. Obtaining the optimal safety and production deliverability within oil and gas processing area which can be implemented in all other affiliate or sites.

1.6. Structure of the Thesis

The structure of this thesis is defined into several chapters and sub-chapters as follow:

CHAPTER I	**INTROCUTION**
	This chapter consists of research background in regards to importance of selecting suitable gas detector technology, problems reinstatement, research objectives, research advantages, research limitation, and structure of the thesis.

CHAPTER II **LITERATURE REVIEW**

This chapter consists of several literature review for developing the thesis. The main literature in this research involves studies related to risk definition in oil and gas processing area: control system mechanism, fire zone principle, and hazardous area classification. Besides that, this chapter explains detail characteristic and working methodology of gas detector technology. In addition, principle of multi criteria decision making is described based on conventional analytic hierarchy process, triangular fuzzy number, and fuzzy analytic hierarchy process.

CHAPTER III **RESEARCH METHODS**

This chapter defines the methodology used in this research to analyze the selection of gas detector technology. The methodology covers working flowchart in developing Delphi technique, data collection based on interview and questionnaire for assessing the sub-criteria. In addition, this chapter describes general flowchart used in this research for determining body of research project and fuzzy analytic hierarchy design based on criteria selected.

CHAPTER IV **RESULT OF DELPHI TECHNIQUE AND EVALUATION OF FUZZY AHP**

From data and analytic hierarchy structure which is obtained from previous chapter, it is implemented an evaluation of fuzzy AHP as follow:

A. Evaluation of fuzzy AHP for **benefit** category
B. Evaluation of fuzzy AHP for **costs** category
C. Evaluation of fuzzy AHP for **risks** category

The analysis for above categories is calculated based fuzzy pairwise comparison matrix. To develop a fuzzy judgement matrix based on triangular fuzzy number which one of sub-criteria is more important to another.

CHAPTER V RESEARCH RESULT AND ANALYSIS

In this chapter explain results of the final value of fuzzy AHP methodology for alternatives are obtained for each level of categories, criteria, and alternatives. Quantified score for each gas detector technology is listed precisely.

CHAPTER VI CONCLUSION AND RESEARCH SUGGESTION

In this chapter of thesis, it is explained overall conclusion based on analysis of research in selection of gas detector technology. This chapter also suggests the OGPA management in implementation of suitable gas detector based on methodology selected in this research. This conclusion of research is expected to provide obvious understanding in order to obtain safe and productive processing plant.

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CHAPTER II

LITERATURE REVIEWS

2.1. Risk Related to Oil and Gas Processing Area

Within oil and gas processing area, fire is the main hazard which can lead to total disastrous event. Respecting to magnitude of consequence, incidents are classed into several rank, those are: Insignificant, Minor, Moderate, Major, and Catastrophic (Basu, 2017). All of those categories have consequences in respective layer: human, environment, asset, production shortfall, and company reputation. The catastrophic incident possible to occur in oil and gas process gas area is described hereunder.

2.1.1. Un-ignited gas/spray cloud

The gas cloud is formed by high pressurized system which has loss of containment of hydrocarbon. Gas cloud may be formed as spray-mist of condensate vapor or natural methane gas. The early stage of catastrophic incident escalation begins as gas cloud incident often in many cases. As described in Chevron Richmond refinery incident, the gas cloud which cannot be limited either by time or quantity is the root cause of the catastrophic incident. At this stage early gas detection is the key of incident prevention. Without existence human in the process, adequate gas detection system is able to detect and delimitate amount of gas leakage.

2.1.2. Flash Fire

“A flash fire is the non-explosive combustion of a vapor cloud resulting from a release of flammable material into the open air, which, after mixing with air, ignites” (CCPS, 1994). The flash fires occur when flammable gas is released in windy condition ignited by fire or heat. The concentration of gas is enough only to be ignited but not to create explosion. The flash fire is not likely to produce detonation; only slow deflagration is often observed.

2.1.3. Boil Over

As defined by NFPA, boil over is “an event in the burning of certain oils in an open-top tank when, after a long period of quiescent burning, there is a sudden increase in fire intensity associated with expulsion of burning oil from the tank” (NFPA, 2013). This incident occurs when there is an explosion caused by expansion of water at the bottom at tank and rapidly force out burnt liquid hydrocarbon causing massive explosion. This typical incident has occurred several times, including incident in RU V Cilacap-Indonesia, Caribbean Petroleum Tank (chemical safety board, 2010), and Milford Haven boil over incident (Persson & Lonnermark, 2014). Simulation of boil over is described in figure 2.1.

Figure 2.1. Simulation of boil over is performed in small scale. one kilogram of cooking oil was poured with 1 liter of water. *source picture: Wikipedia, 2017*

2.1.4. BLEVE

Another form of expansion liquid explosion is named BLEVE. The BLEVE is standing for boiling liquid expanding vapor explosion. The characteristic of this incident involves in closed pressurized vessel rather than open type tank which occur in boil over incidents. A BLEVE has been defined as “an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure” (CCPS, 1994). In terms of detonation, BLEVE is often gives shockwave as energy released by the explosion. In many case BLEVE is likely to be occurred in pressurized vessel (three phase separator), liquefied petroleum spherical vessel, or hydrocarbon boiler/distillation column.

Figure 2.2. Example of BLEVE during San Juanico disaster, 1984. *source picture: alchetron.com*

2.1.5. Vapor Cloud Explosion (VCE)

The vapor cloud explosion is defined “as explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure”

(CCPS,1994). Vapor cloud explosion is formed based on the release of hydrocarbon gas vaporizing from liquid or gas from pressurized vessel or tank. The release of hydrocarbon shall be sufficient so that it can be ignited by fire or heat. Flammable gas in high density is more likely to be hazardous in terms of VCE occurrence. This fact is due to high density vapor is heavier than air, and it will be accumulated and hard to disperse. For instance, propane and butane gas are likely to be easier to ignite rather than methane. As described by CCPS, vapor cloud explosion incident occurred in Port Hudson, Missouri, “On December 9, 1970, a liquefied propane pipeline ruptured near Port Hudson. About 24 minutes later, the resulting vapor cloud was ignited. The pressure effects were very severe. The blast was equivalent to that of 50,000 kg of detonating TNT.” (CCPS, 1994).

Figure 2.3. Port Hudson, Missouri disaster, this incident is resulted by vapor cloud explosion (CCPS, 1994). *Source picture: CCPS Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs page 96*

2.3. Safety Instrumented System

According to IEC 61511 (2003), safety instrumented system (SIS) is "instrumented system used to implement one or more safety instrumented functions (SIF). An SIS is composed of any combination of sensor(s), logic solvers, and final element(s)" (IEC 61511:2003). In process safety engineering, mainly safety instrumentation system is divided by:

1. Pressure protection system such as HIPPS (High-integrity pressure protection system) or pressure relieve/safety valve (PSV). This system is designed to prevent over-pressurization of plant, such as processing plant or oil refinery (API STD 521, 2014). Although the main function of HIPPS and PSV is quite similar, their working principle is different. PSV is preventing from overpressure by limiting process working pressure. This based on mechanical protection valve which will be opened and vented in safe place when there is overpressure. The HIPPS will shut off the source of the high pressure before the design pressure of the system is exceeded, thus preventing loss of containment through rupture (explosion) of a line or vessel (Wikipedia, 2017).
2. Emergency shutdown system (ESD). This system is mainly functioned to reduce the potential of escalation from unwanted event. Basically this mechanism based on limitation of hydrocarbon containment (ESDV), Eliminate source of ignition (Electrical shutdown), and reduce flammable inventory (emergency depressurization) (API STD 521, 2014).
3. Fire and gas system (F&G).as it has been named, this system is divided into fire system and gas detection system. The fire system functioned as early detection of heat source for ignition. This system is designed to prevent existence of fire-flame or heat source for a flammable gas to be ignited. The gas detection system is designed to prevent escalation of undesired event by detecting source of hazardous gas before it reached to the lower explosive level concentration (LEL). Both of fire and gas system is connected to emergency shutdown system.

4. Ultimate safety system (USS). This system is mainly functioned as back-up for essential emergency shutdown system (ESD) action. The ultimate safety system is designed based on solid state logic solver handling main function of safety shutdown system.

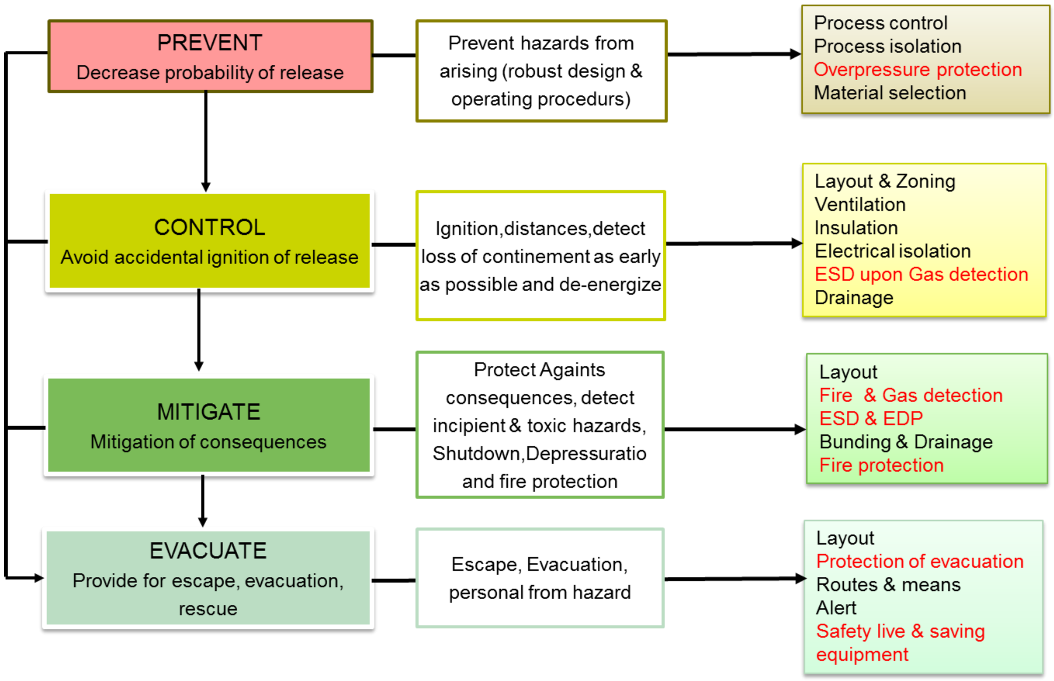


Figure 2.4. Safety critical element hierarchy. As part of safety critical element, gas detection system is included in the Control layer which avoid accidental ignition of release. Based on the safety critical element principle, Gas detection mentioned in this research are compatible with the existing process design.

As primarily designed to enhance safe condition in oil and gas processing area, the safety instrumented system, as shown in figure 2.4. is mandatory to be existed. However, the installation of safety instrumented system does not completely eliminate hazard. The controlling mechanism is more likely to reduce probability and/or severity of risks to ALARP condition.

2.3. Control System Mechanism

The OGPA control system mechanism is based on distributed control system and human-machine interface located in control room which is permanently manned and monitored by panel operator. The control system is designed to monitor and operate automatically and continuously the different modules on the oil process in several platforms (gas compression, liquid export, oil-water treatment unit, and liquid treatment process). The system controls automatically these facilities start-up, normal running, downgraded modes of operation, turndown, normal shutdown and emergency shutdown.

In principle, the OGPA control system is divided into several interconnected and redundant programmable logic controllers. In the first layer of control system is the Process Control System (PCS). This mechanism controls normal operation of process facilities. The controls include opening and closing process control valve, liquid-gas control level, and normal temperature control. The second layer of control system is Process Safety System (PSS) which working in separated core with PCS. PSS will initiate shutdown to equipment which called SD-3 (shutdown level-3). This mechanism is triggered by deviation outside operating limit process unit, such as level switch very-low, pressure switch very high, and temperature switch very high.

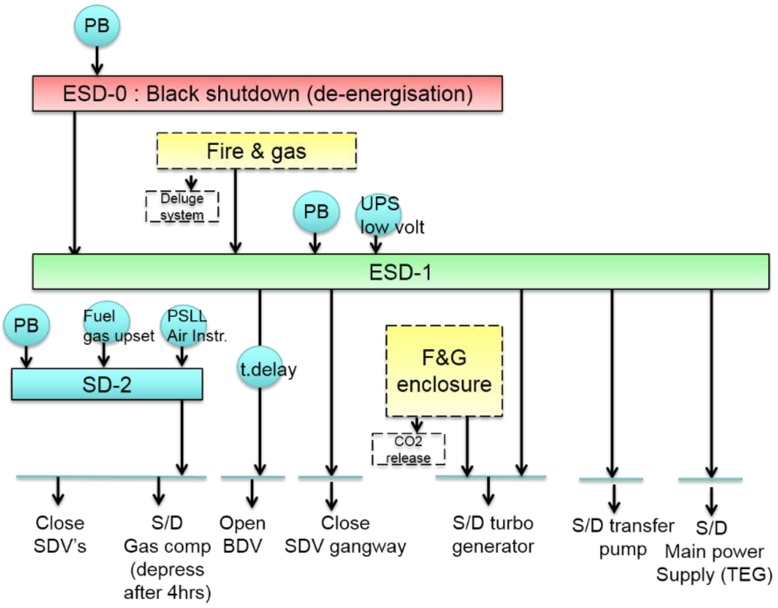


Figure 2.5. Control system diagram block. It defines hierarchical structure of safety shutdown system. Each of block diagram is defined as individual distributed control system.

The third layer of control system is called Emergency Shutdown (ESD) System. This mechanism control whole operation of shutdown system, including shutting down emergency shutdown valve, opening blow down valve (for depressurization), and triggering all process shutdown system. The fourth layer of control system is Fire and Gas (F&G) system. The Fire and Gas system is detected from gas detector, fire/flame detector, and smoke detector. It initiates fire extinguishing system, deluge system, and triggers Emergency Shutdown System. The last layer is ultimate layer called Safety Shutdown System. This system controls the shut downing mechanism of all power (high voltage and low voltage), including uninterruptable power supply for control room after triggering ESD system and F&G System. The safety shutdown system also called ESD-0 (emergency shutdown system level-0). It can be activated only by push button for processing area abandonment. The overall hierarchy of control system is described on figure 2.5.

2.3. The Fire Zone Principle

Fire zone is process area where equipments are located in similar level of risks. One fire zone to another should be separated by sufficient distance or barrier so that in one fire occurrence is not affecting the other fire zone. “The partition of an installation into fire zones results in a significant reduction of the level of risk. This implies that consequences of a fire, flammable gas leak or an explosion corresponding to the credible event likely to occur in the concerned fire zone, shall not impact other fire zones to an extent where their integrity could be put at risk” (Total S.A, GS EP SAF 253, 2012).

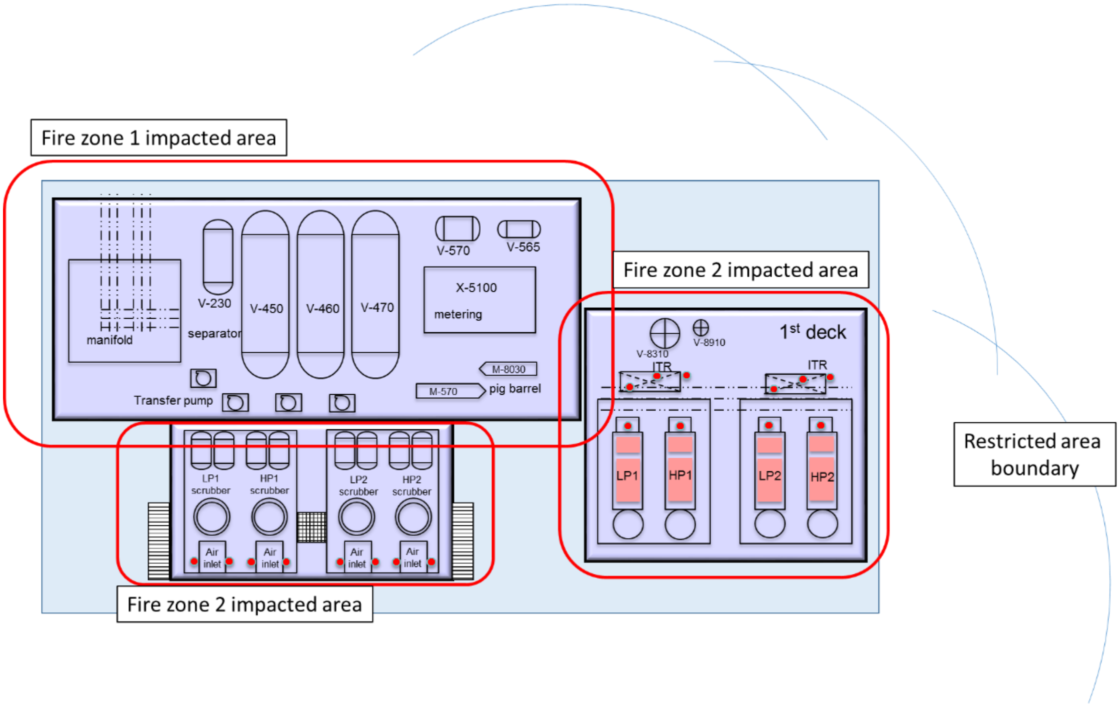


Figure 2.6. The configuration of fire zone in typical oil and gas processing area. The fire zones are located inside restricted area.

In OGPA, the considered fire zone has not been identified properly due to unavailability of safety concept. The only configuration of for determining fire zones in OGPA comes from ESD logic. In OGPA can be divided in 5 different fire zones:

1) A. Main OGPA processing platform (consist of separation vessel and settling tank)
   B. Liquid export platform (consist of 4 interchangeable export pump)
2) Gas lift compression platform (consist of 4 turbo generator compression)
3) Enhance oil recovery platform (gas compression platform with 2 electric compressor)
4) Oily water treatment unit (OWT)
5) Power platform (consist of 5 interchangeable turbine engine generator)

The fire zone layout of OGPA is described in figure 2.7.

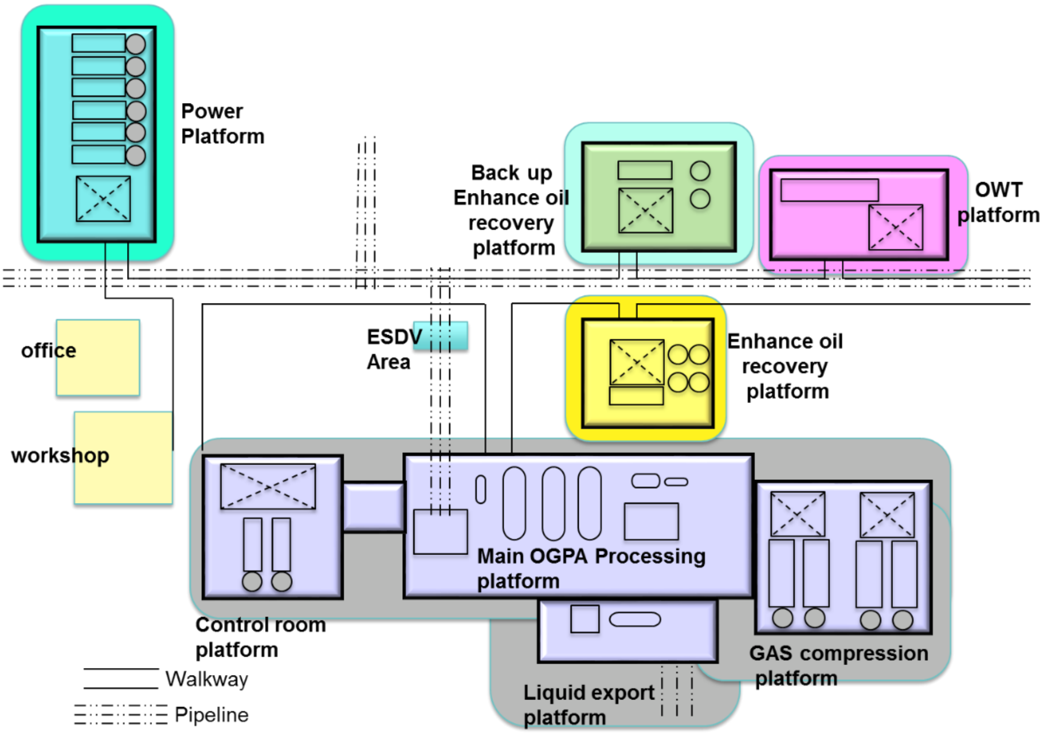


Figure 2.7. The layout of oil and gas processing area associated with its fire zone represented with different color.

2.4. Hazardous Area Classification

The hazardous area is defined according to its potentiality in generating concentration of flammable gases or vapor. In petroleum and petrochemical processing plant, potential concentration of flammable vapors is commonly occurred permanently. Flammable gas concentration is defined as lower explosive limit (LEL) and Upper explosive limit (UEL). The LEL is concentration of gas or vapor mixed with air (percentage by volume, at room temperature) that will cause the propagation of flames when it comes in contact with a source of ignition. While the UEL is the maximum concentration of gas or vapor mixed with air (percent by volume, at room temperature) that will cause the propagation of flames when it comes in contact with an ignition source (Kumar et al., 2013).

The risk of ignition source must be limited within hazardous area. As defined by recommendation practice for classification at petroleum facilities (API recommended practice 505, 1997) hazardous area classification are:

1) “Zone 0, a location in which ignitable concentration of flammable gases or vapors are present continuously or present for long period of time (more than 1000 hours per year);
2) Zone 1, a location in which ignitable concentration of flammable gases or vapors are likely to exist under normal operating condition or may exist frequently because of maintenance operations or because of leakage (10< hours/ year < 1000);
3) Zone 2, a location in which ignitable concentration of flammable gases or vapors are not likely to occur in normal operation and if they do occur will exist only for a short period (1< hour/ year< 10). The zone 2 usually includes location that would become hazardous only in case of an accident or of some unusual condition;
4) Unclassified zone, a location where considered as safe area and ignitable concentration of flammable gases and vapors is not considerable (less than 1 hour/year).”

Gas detector installation should take into account the hazardous area range. Zone 1 and Zone 2 are the most undertaken location for placement. Placement of gas detector for Zone 0 is not required because flammable gases or vapors has been expected continuously. Risk control for Zone 0 is mainly by limitation of containment. Nonetheless, gas detector placement for unclassified zone is never been a consideration since flammable gases and vapors is not expected. Risk control for unclassified zone is by installation of smoke and fire detector.

2.5. Gas Detector Technology

There are several types of detectors are commonly used for the detection of flammable gas clouds. Current technologies are catalytic, infrared sensors, and ultrasonic gas leak detector. Catalytic gas sensors detect the presence of a chemical contaminant by an oxidation-reduction reaction with the catalyst. Infrared sensors work by detecting the amount of infrared energy absorbed by a contaminant cloud at specific wavelengths. The infrared sensors possess a higher unit cost but can often detect contaminant with more accurate gas monitoring. Ultrasonic gas leak detector sense the noise change which generated by a gas leak comprises both audible and ultrasonic frequencies. The sensors are able to identify ultrasonic sound frequencies (25kHz to 100kHz), while excluding audible frequencies (0 to 25kHz) (Sizeland, 2014). This methodology delivers wider coverage of detection than catalytic gas detector and infrared gas detector. However, its characteristic of sensitivity could lead to spurious detection and it is not suitable for noisy environment, such as near compressor or high pressure-high flow well.

2.5.1. Catalytic Gas Detector

The principle of catalytic gas detector is based on catalytic combustion within an element on principle of Wheatstone bridge. Platinum coil embedded in a catalyst is the main element of censor known as catalytic beads sensor. The flammable gas measured is entered into a chamber and react with catalytic reaction and produced heat. As the heat produced is increase by the concentration of flammable gas, this cause a change of resistance within the embedded coil that is measured and monitored. The catalytic beads sensor consists of two identical beads, one as baseline reference and the other as active measuring element which oxidized flammable gas present. Baseline reference bead is then compared to the resistance of the active bead to determine the concentration of gas measured. In principle of Wheatsone bridge, comparison resistance between active beads and baseline reference bead results in a measurable voltage differential which correspond to the concentration of flammable gas.

Catalytic combustion reaction on the surface of active bead involving flammable gas and oxygen is given as:

$$CH_4 + 2O_2 + 8N_2 \longrightarrow CO_2 + 2H_2O + 8N_2 \tag{1}$$

Figure 2.8. Installation of Catalytic gas detector. Based on its characteristic, this gas detector shall be placed in redundant configuration in one coverage area

From above reaction, one parts of methane required two parts of oxygen, which mean at concentration of 20% oxygen in the air, it requires ten parts of air existence. For a sensor to detect methane, the signal output will respond linearly from 0–5% of methane. As the concentration reaches close to 9%, the signal increases very rapidly and peaks at around 10% (Kumar et al., 2013). Based on this characteristic, catalytic gas detector can only be used in oxygen sufficient environment and not suitable for detecting methane (flammable gas) above 10% concentration. This phenomenon is called sensor poisoning. In general, Sensors based on catalytic oxidation shall not be used in low oxygen atmospheres, in high air flow-rates, or in high gas concentrations.

2.5.2. Infrared Gas Detector

The developed gas detection technology is based on infrared absorption in specific wavelength when the radiation is passing through in concentration of flammable gas. The mechanism of detection is based on infrared transmitter and sensor measuring light intensity. Two infrared wavelength transmitters, one as active measuring flammable gas wavelength, and the other as reference wavelength. As the flammable gas release at the detector, it will be passed through infrared transmitter and sensor. The infrared intensity will be reduced at the active wavelength, while the infrared intensity remains steady. The difference infrared intensity is converted into electronics signal and displayed as flammable gas concentration. Figure 2.9. describe the infrared spectrum absorbed by the concentration of flammable gas.

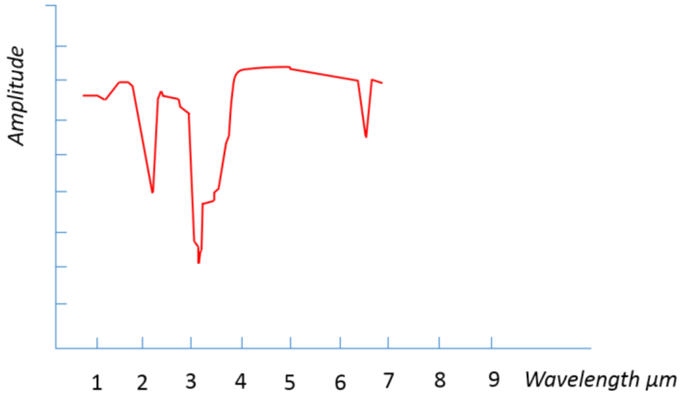


Figure 2.9. Methane absorption infrared spectrum, it has main absorption peaks at $3.37 - 3.51\mu m$ (Naranjo & Baligha, 2012).

2.5.2.1. Point-type Infrared Detector

Point-type infrared gas detector configures installation of infrared transmitter and sensor in fixed path length that last in a few inches. The gas concentration is considered as uniform disperse across this length. Point-type infrared gas detector is useful to detect flammable gas in the specific placement with accurate measurement. The coverage area of point-type infrared gas detector is typically narrow. Therefore, implementation this model of gas detector is best placed on specific gas release location and for highly accurate detection, such as gas turbine enclosure, gas compressor package, and engine air intake.

2.5.2.2. Open-Path Infrared Gas Detector

Open-path infrared gas detectors typically consist of a radiation transmitter and a physically separate, remote sensor/receiver. The detector measures the average concentration of gas along the path of the beam. Open-path infrared gas detector offers capability to cover wide open area or a process area where there is a line of potential hydrocarbon release, such as a row of pressurized vessel or turbine compressor.

Figure 2.10. Installation of open-path infrared gas detector. It involves receiver and transmitter which detect gas concentration along the beam

The unit of measurement is the concentration multiplied by path length, % LEL x m and ppm x m. The length of open-path distances is typically 25m for offshore and up to 50 m for onshore installation. The minimum alarm level is set at 0.5 LEL x 1m (50% LEL extended for one meter). It also gives an alarm if there is a flammable gas cloud of 5% LEL over a distance of 10 m. The detail calculation of concentration measurement is illustrated on figure 2.11.

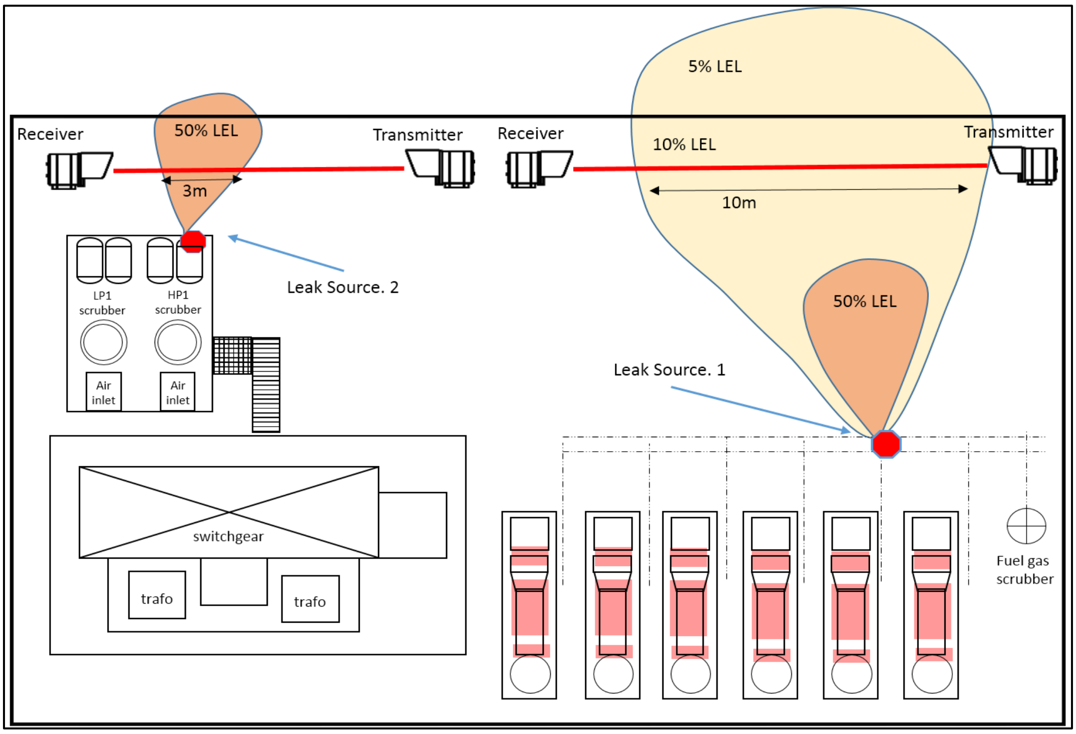


Figure 2.11. Open-path infrared gas detector LEL and length of beam calculation. Gas detector 1 measures 10% LEL x 10m = 100% LEL at leak source 1 and gas detector 2 measures 50%LEL x 3m = 150% LEL at leak source 2.

2.5.3. Ultrasonic Gas Detector

Unlike neither the catalytic nor the infrared detection system, ultrasonic gas leak detector responds to the gas leak source rather than measuring concentration of gas released. Ultrasonic gas leak detector sense the presence of gas leak by detecting sound produced by leak source as gas come out from the containment. The sound is produced as gas travels from a high-pressure situation to a low-pressure environment (Sizeland, 2014). Characteristic from the sound generated is ultrasonic sound, type of sound that the frequency above audible to human hearing. Instead of measuring gas concentration, gas leak quantification is based on leak rate measurement or commonly known as mass flowrate of the jetting gas.

As defined by Naranjo and Baligha (2009), the scale of measurement is defined as Sound Pressure Level (SPL). “The scale is based on logarithmic scale defined as decibel (dB)”. Since the sound power is directly proportional to the power generated by the gas upon expansion (Naranjo & Baligha, 2009), SPL can be expressed as:

$$SPL = 20 \log\left(\frac{RT}{M}\,\dot{m}\right) \tag{2}$$

Where m is the mass flow rate of the jetting gas, T is gas temperature at the leaking orifice, M is the molecular weight, and R is the gas constant. The mass flowrate (kg/s) is defined as equation 3:

$$\dot{m} = C_d . A . \frac{P_g}{\sqrt{\frac{8314}{M_w} . T_g}} . \sqrt{\gamma . \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{3}$$

Where,

ϒ = Isentropic expansion factor (Cp / Cv)
m = Mass flow rate, Kg/s
Cd = Discharge coefficient (between 0.8 and 1 for gases)
A = Hole area in m2
Mw = Molecular weight, Kg/mol
Tg = Temperature of the vessel in K
Pg = Absolute pressure of the gas in Pa
P = Ambient pressure in Pa

Based on the methodology of leak detection, ultrasonic gas leak detector is not defining the type of gas released. Methane, propane, or natural gas containing H2S is commonly detected as alarm triggering. At some case, ultrasonic gas detector seldom detects normal gas relieving process (e.g. pressure relief valve,) or air-actuated instrument venting. This could cause some drawbacks from the detection system, as spurious gas detection may cause unwanted shutdown that may lead to production shortfall.

Besides some drawbacks from its detection methodology, ultrasonic gas leak detector provides several advantages that distinctively other type of gas detector cannot. Wide spread area coverage and provides early detection system are the main benefit by using ultrasonic technology. Low maintenance cost, less need of calibration and long lasting sensor lifespan are also main benefits of this technology.

2.6. Delphi Technique

Delphi Technique is defined as methodology for obtaining decision based on expert judgement it is commonly formed in panelist, participants, or respondents (Dalkey & Helmer, 1963). The participant of experts is become important to perform scientific judgements. It is supposed that probability of wrong decision is more unlikely to be made by involving several experts (Hasson et.al, 2000). Features of Delphi consist of anonymity, iteration and controlled feedback from prior round to the current one, statistical aggregation of group responses, and expert panels (Zangenehmadar & Mosselhi, 2016). In short, Delphi Technique is a method of “allowing a group of individuals, as whole to deal with complex problem while avoiding their direct confrontation and retaining their interactions” (Linstone & Turoff, 1975).

In the process of research development, Delphi Technique is used for determining sub-criteria and attributes in selecting most suitable gas detector technology. Weighting in form of “Rank-type” (Zangenehmadar & Mosselhi, 2016) is used for determining important factor that applicable in selecting gas detector technology. These factors should cover advantages, costs, and risk aspects. At first, Delphi Technique process begin with problem statement and description of research objectives. Then, experts and panelist are selected based on their competencies in relevant studies and working métier. As defined by Trevelyan and Robinson (2015) to develop Delphi Technique there are several areas to consider as follow,

Selecting expert panelist:

- To consider competencies and relevant studies for the panel. Avoid labelling experts without consideration of this label

- Understand that result of Delphi might not reach in synonymous decision in term of consensus.

Iteration

- To consider number of iteration, “Three number are optimal”
- Consider the panelist to rank the importance of each choice or criteria post completion of Delphi study

First round:

- Floor to the panelist the well-structured open-ended question, or develop initial statement that might be agreed or disagreed by panelist
- Beware of trivial statement that may lead to large amount of subsequent data

Second round:

- Develop weighting in criteria based on Likert scale. “The optimum number of response lie between four to seven”
- In case panelist is not fully understanding the problems, their results might be omitted. “Consider providing No Comment Option”
- “Consider the potential pitfalls of using a Likert scale with a midpoint”

Subsequent round:

- Perform question recirculation from round two and delivering its feedback
- Avoid omitting data as it will create bias and prevent full analysis results

Participant feedback:

- Consider to deliver “visual feedback” (graphical information) to describe the distribution of data
- “Use both central tendency and a measure of dispersion to aggregate data”.

Consensus:

- Define the level of consensus. The terms of consensus are not similar with synonymous decisions. Clear level of consensus agreement is the stooping guideline of Delphi Technique
- “Differentiate between stability (consistency), agreement, and consensus”
- Measurement of data distribution as variance is “appropriate for determining consensus”

Stability of response/ consistency:

- “Stability of response should not be confused with consensus”
- “If analyzed, the Wilcoxon matched-pairs signed rank test is appropriate methods to inferentially determine stability of response. Stability could also be determined though providing data on the median and IQR across rounds or through graphical representation”

As described by Black et al. (1999) “There is no empirical relationship between the number experts and the validity of the survey and some researchers believed that the numbers of experts is subjected to the available resources and scope of the problems.” In most of research 15-35 experts panel are involved (Zangenehmadar & Mosselhi, 2016). Specifically, in this research, ten expert panelist who have background in chemical-process safety engineering are involved.

2.7. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) methodology has been used in recent decades to determine weighting factors in multi-criterion decision making. “The Analytic Hierarchy modeling and measurement process (AHP) is a scientific approach used to determine the relative importance of a set of activities or criteria” (Saaty et al., 2015). This methodology was developed by Saaty (1977), Analytical Hierarchy Process demonstrates consistent result in determining both qualitative and quantitative factors. It reduces complex decision to a series of one-to-one comparisons then synthesizes the results. AHP uses the expertise ability to compare single properties of alternatives (Novirsal & Tjakraatmadja, 2006).

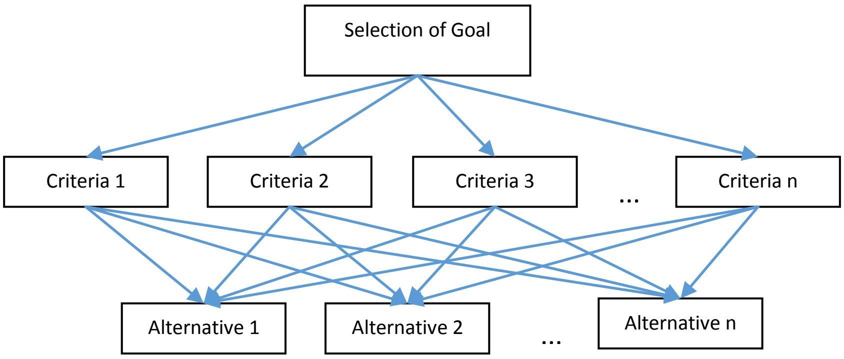


Figure 2.12. Three level of hierarchy in AHP selection methodology

The pair wise comparison is valid for reciprocal condition. It means that comparison for alternative (a) over alternative (b) is equal with 1/ (alternative (b) over alternative (a)). The equation can be written as,

$$Pc(Ai, Aj) = \frac{1}{Pc\ (Aj, Ai)} = a_{ij} = \frac{1}{a_{ji}} \tag{4}$$

Where *Pc(Ai,Aj)* is preference value of alternative *Ai* over alternative *Aj*. Therefore, for n number of alternatives, the equation can be explained by matrix, *A* = *(aij)n x n* structure,

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_n} & \frac{1}{a_{2n}} & \cdots & 1 \end{pmatrix} \tag{5}$$

“This means that, if the entries exactly represent ratios between weights, then the matrix A can be expressed in the following form” (Brunelli, 2015),

$$A = \begin{pmatrix} w1/w1 & w1/w2 & \cdots & w1/w_n \\ w2/w1 & w2/w2 & \cdots & w2/w_n \\ \vdots & \vdots & \ddots & \vdots \\ w_n/w1 & w_n/w2 & \cdots & w_n/w_n \end{pmatrix} \tag{6}$$

In developing pair wise comparison, consistency is the key value to show the reliability of AHP structure. The consistency value *(CI)* is a way to measure degree of error in judgment criteria. CI is calculated as follow:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (7)$$

Where λ_{max} is the maximum Eigen value of matrix *A* and *n* is the order.

The Consistency index (CI), then divided by Random Index (RI) to determine Consistency Ratio (CR).

$$CR = \frac{CI}{RI} \qquad (8)$$

Where *RI* is the appropriate random index from following N number of criteria.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,58	0,90	1,12	1,24	1,32	1,41	1,45	1,49

Table 2.1 Values of Random Index (RI)

Consistence and reliable AHP structure should not exceed values of CR= 0.1.

2.8. Fuzzy Logic

"The theory of fuzzy logic provides a mathematical strength to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning" (Kahraman, 2008). Fuzzy logic as a form of "truth-valued" logic ranged between 0 and 1. The applicability of fuzzy logic is often to describe application of probabilistic value related to human thinking. For instance, in terms of temperature, human thinking might describe it as Cold, Cold to warm, Warm, Warm to hot, and Hot. This description of this level can be described as figure 2.13.

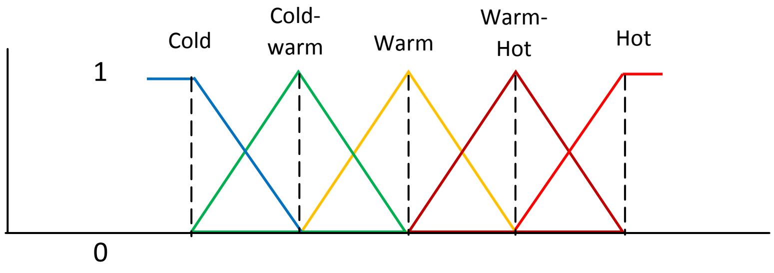


Figure 2.13. Fuzzy logic graphical explanation for temperature condition.

2.9. Triangular Fuzzy Number (TFN)

The fuzzy set theory was first introduced by Zadeh (1965) to compensate human relative thought or vagueness. The membership function in fuzzy set theory within universal set R is defined as follow

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x)) \mid x \in R\} \tag{9}$$

Where, $\mu_{\tilde{A}}$ is degree of membership of x, which represent universal set R to the interval within [0,1] Membership function of fuzzy set is described as triangle shape curve, known as triangular fuzzy number (TFN).

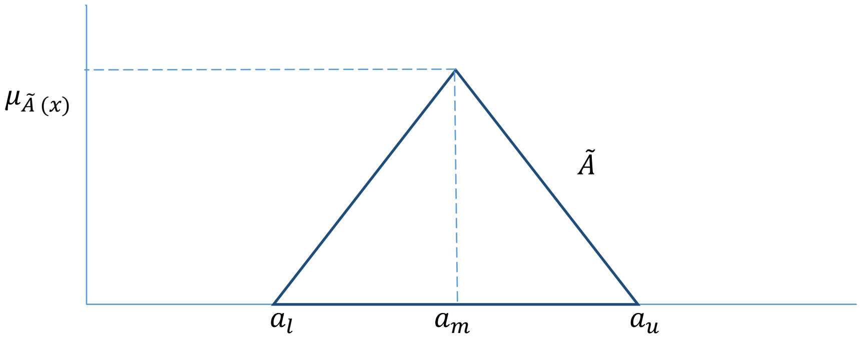


Figure 2.14 Triangular shape curve of TFN, $\tilde{A}$

A fuzzy number on universal set R to be a TFN is denoted as $\tilde{A} = a_l, a_m, a_u$ with the membership function is equal to (Kaufmann, 1991 within Kusumadewi, et.al, 2006)

$$\mu_{\tilde{A}}(x) = \begin{cases} 0; & x < a_l \\ \dfrac{x - a_l}{a_m - a_l}; & a_l \leq x \leq a_m \\ \dfrac{a_u - x}{a_u - a_m}; & a_m \leq x \leq a_u \\ 0; & x > a_u \end{cases} \tag{10}$$

Concerning the interval of confidence, showing the coefficient α, the triangular fuzzy number has a characteristic as (Kaufmann, 1991 within Kusumadewi, et al., 2006)

$$\widetilde{A^{\alpha}} = [a_l{}^{\alpha}, a_u{}^{\alpha}] = [(a_m - a_l)\alpha + a_l \,, \; a_u - (a_u - a_m)\alpha] \forall \, \alpha \in [0,1] \quad (11)$$

The mathematical operations of triangular fuzzy number include (Soheil & Kaveh, 2010):

Addition,

$$\tilde{A} \oplus \tilde{B} = (a_l, a_m, a_u) \oplus (b_l, b_m, b_u) = (a_l + b_l, a_m + b_m, a_u + b_u) \quad (12)$$

Subtraction,

$$\tilde{A} \ominus \tilde{B} = (a_l, a_m, a_u) \ominus (b_l, b_m, b_u) = (a_l - b_l, a_m - b_m, a_u - b_u) \quad (13)$$

Multiplication,

$$\tilde{A} \otimes \tilde{B} = (a_l, a_m, a_u) \otimes (b_l, b_m, b_u) = (a_l * b_l, \; a_m * b_m, \; a_u * b_u) \quad (14)$$

Division,

$$\tilde{A} \oslash \tilde{B} = (a_l, a_m, a_u) \oslash (b_l, b_m, b_u) = (a_l/b_l, \; a_m/b_m, \; a_u/b_u) \quad (15)$$

And reciprocal,

$$(\tilde{A})^{-1} = (a_l, a_m, a_u)^{-1} = \left(\frac{1}{a_l}, \frac{1}{a_m}, \frac{1}{u}\right) \quad (16)$$

2.10. Fuzzy Analytic Hierarchy Process

Fuzzy analytic Hierarchy process is the further development from analytic hierarchy process (AHP) to compensate the deficiency of vagueness in multi criteria decision making (MCDM) (Kahraman, et al., 2004). Since AHP figures incapability to overcome uncertainty and imprecision of computation, Laarhoven and Pedrycz was first developed the fuzzy analytic hierarchy process (Kahraman, 2008). This methodology involves triangular fuzzy number as triplet number (Chang, 1996) for computation in pairwise comparison, same as those crisp in AHP. In fuzzy AHP, result of computation is described in interval of values which can be evaluated according to level of confidence (index of optimism) (Kusumadewi, et al., 2006).

To perform computation in fuzzy AHP, procedures is described as follow:

Step1: Modify Saaty scale into triangular fuzzy number, including the linguistic preference scale

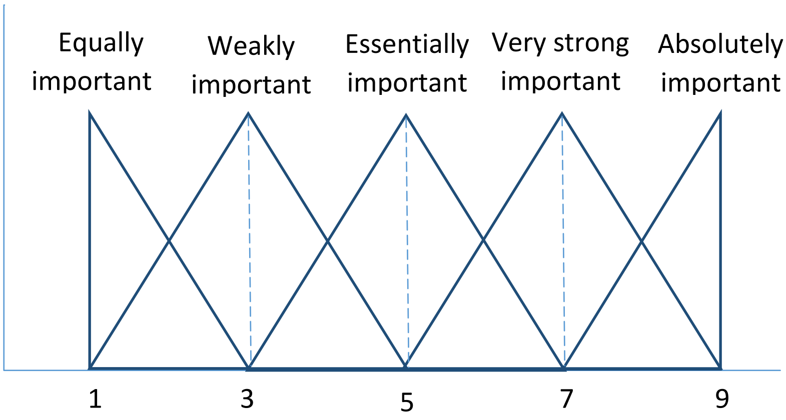


Figure 2.15. The Saaty scale in AHP described inTriangular shape curve of TFN.

Table 2.2. The membership function of Saaty scale

Fuzzy number (Saaty scale)	**Linguistic preference scale**	**Membership function**
1	Equally important	(1,1,3)
3	Weakly important	(1,3,5)
5	Essentially important	(3,5,7)
7	Very strong important	(5,7,9)
9	Absolutely important	(7,9,9)

The fuzzy membership function is listed as lower and upper value (a_l , a_m) with equation 17:

$$\widetilde{1_\alpha} = [1^\alpha, 3^\alpha] = [1 \quad , \quad 3 - 2\alpha]$$

$$\widetilde{3_\alpha} = [1^\alpha, 5^\alpha] = [1 + 2\alpha \, , 5 - 2\alpha] \quad ; \quad \widetilde{3_\alpha}^{-1} = \left[\frac{1}{5 - 2\alpha}, \frac{1}{1 + 2\alpha}\right]$$

$$\widetilde{5_\alpha} = [3^\alpha, 7^\alpha] = [3 + 2\alpha \, , 7 - 2\alpha] \quad ; \quad \widetilde{5_\alpha}^{-1} = \left[\frac{1}{7 - 2\alpha}, \frac{1}{3 + 2\alpha}\right]$$

$$\widetilde{7_\alpha} = [5^\alpha, 7^\alpha] = [5 + 2\alpha \, , 9 - 2\alpha] \quad ; \quad \widetilde{3_\alpha}^{-1} = \left[\frac{1}{9 - 2\alpha}, \frac{1}{5 + 2\alpha}\right]$$

$$\widetilde{9_\alpha} = [7^\alpha, 9^\alpha] = [7 + 2\alpha \quad , \quad 9] \quad ; \quad \widetilde{9_\alpha}^{-1} = \left[\frac{1}{9}, \frac{1}{7 + 2\alpha}\right] \qquad (17)$$

Step 2: Perform computation based on fuzzy pairwise comparison matrix. Develop a fuzzy judgement matrix $\tilde{A}$ based on triangular fuzzy number (al, am, au) which one of criteria is more important to another.

$$\widetilde{A_\alpha} = \begin{bmatrix} 1 & \tilde{a}_{\alpha_{12}} & \cdots & \tilde{a}_{\alpha_{1n}} \\ \tilde{a}_{\alpha_{21}} & 1 & \dots & \tilde{a}_{\alpha_{2n}} \\ \dots & \dots & \ddots & \dots \\ \tilde{a}_{\alpha_{n1}} & \tilde{a}_{\alpha_{n2}} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{\alpha_{12}} & \cdots & \tilde{a}_{\alpha_{1n}} \\ \tilde{a}_{\alpha_{12}}{}^{-1} & 1 & \dots & \tilde{a}_{\alpha_{2n}} \\ \dots & \dots & \ddots & \dots \\ \tilde{a}_{\alpha_{1n}}{}^{-1} & \tilde{a}_{\alpha_{2n}}{}^{-1} & \cdots & 1 \end{bmatrix} \qquad (18)$$

Where,

$$\tilde{a}_{\alpha_{ij}} = \begin{cases} \tilde{1}\,, \tilde{3}\,, \tilde{5}\,, \tilde{7}\,, \tilde{9} & , criterion\ i\ is\ reletive\ important\ to\ criterion\ j \\ \tilde{1} & , criterion\ i\ is\ equal\ important\ to\ criterion\ j \\ \tilde{1}^{-1}\,, \tilde{3}^{-1}\,, \tilde{5}^{-1}\,, \tilde{7}^{-1}\,, \tilde{9}^{-1} & , criterion\ is\ releatively\ less\ important\ to\ criterion\ j \end{cases}$$

Step 3: Calculating fuzzy weight by applying geometric mean for each criterion. As stated by Wang and Chen (Wang and Chen,2008), the fuzzy weight of each criterion are calculated by Buckley (1985) as follows:

$$\widetilde{r_i} = \left[\tilde{a}_{\alpha_{i1}} \otimes \tilde{a}_{\alpha_{i2}} \otimes \ \dots \ \tilde{a}_{\alpha_{in}}\right]^{1/n} \forall i = 1,2, \dots, n \qquad (19)$$

And determine weight of fuzzy value by normalizing each criterion

$$\widetilde{w_i} = \frac{\widetilde{r_i}}{\widetilde{r_1} \oplus \widetilde{r_2} \oplus \dots \oplus \widetilde{r_n}} \qquad (20)$$

Where, $\tilde{a}_{\alpha_{ij}}$ is the fuzzy pairwise comparison value *i* compare to *j* $\widetilde{r_i}$ is the geometric mean, and $\widetilde{w_i}$ is the fuzzy weight value of the *i*th criterion.

Step 4: Determining fuzzy final value by calculating hierarchical layer sequencing (Wang and Chen, 2008).

$$\widetilde{U_i} = \sum_{j=1}^{n} \widetilde{w_i} * \widetilde{r_{ij}} \qquad (21)$$

Where, $\widetilde{r_{ij}}$ is the fuzzy weight value of the *j*th criterion to the *i*th alternatives. The value of $\widetilde{U_i}$ is representing by triangular fuzzy number $\widetilde{U_i} = (a_l\,, a_m\,, a_u)$.

Step 5: Determining rank for each alternative by implementing defuzzyfication of triangular fuzzy number (a_l, a_m, a_u).

It is necessary to define a method for building a crisp value from the fuzzy number to choose the optimum alternative. Therefore, a defuzzification process needs to be adopted, which arranges the fuzzy numbers for ranking (Wang and Chen, 2008). The defuzzification of (a_l, a_m, a_u) is based on total integral value (Kusumadewi, et al., 2006).

$$U = \frac{1}{2}\left(\alpha\,(a_l) + a_m + (1-\alpha)a_u\right) \tag{22}$$

Where, α is the degree of optimism, which can be chosen by decision maker, valued from 0 to 1. The bigger value α, indicates more optimism of decision maker.

2.10.1. Consistency analysis

As Fuzzy AHP has been defined its crisp value, it is important to check whether the comparison matrix is consistence. The crisp value is the formed into a comparison matrix similar with conventional AHP. The value of defuzzyfication U is developed into crisp value comparison matrix as follows:

$$U = \begin{bmatrix} U_{11} & U_{12} & \cdots & U_{1n} \\ U_{21} & U_{22} & \dots & U_{2n} \\ \dots & \dots & \ddots & \dots \\ U_{n1} & U_{n2} & \cdots & U_{nn} \end{bmatrix} \tag{23}$$

The crisp consistency of matrix U is evaluated by AHP methodology consistency analysis. “when the conventional comparison matrix U is consistent, it means that fuzzy comparison matrix $\widetilde{U}$ is also consistent.” (Zheng et al., 2012). Consistency analysis is then calculated by implementing equation 7 and 8.

2.11. Past Researches and Studies

Past researches and studies are important as the baseline of this research. Several method implementations for multi criteria decision making have been continuously developed. As improvement, those methodology, especially AHP has been refined to overcome its limitation. Fuzzy analytic hierarchy process is one of the example. In past years, AHP was criticized for its incapability for handling vagueness and imprecise in human thought. Based on intrinsic characteristic of fuzzy logic which can deal with imprecision, Fuzzy AHP is developed as improvement from AHP.

First developed by Laarhoven and Pedrycz in 1983, the Fuzzy AHP study was performed by implementing triangular fuzzy number, and the computation steps are similar in crisp AHP (Kahraman, 2008). Buckley (1985) then formed methodology of Fuzzy AHP as improvement from Laarhoven and Pedrycz's. Buckley stated that on Laarhoven and Pedrycz's Fuzzy AHP consist of two problems." First, the linear equations of obtained equations do not always have a unique solution. Second, they insist on obtaining triangular fuzzy numbers for their weights" (Kahraman, 2008).

In further research, implementation of Fuzzy AHP is developed for more complex problems in real industry. For example, assessing risk and safety evaluation in coal mine industry in China (Qiaoziu et al., 2016). The summary implementation of Fuzzy AHP is described in the table 2.2. Even though the implementation from those research has been extensively use Fuzzy AHP method, an integrated with Fuzzy AHP and Delphi technique has not been identified. Therefore, particularly in this research integration of Fuzzy AHP and Delphi is implemented for assessing the selection of gas detector technology.

Table 2.3a. Previous research related to Fuzzy AHP methodology

No	Researcher	Methodology	Problems Statement	Result
1	Wang, Tien Chin and Chen, Yueh-Hsiang, 2008	Fuzzy-linguistic preference relations, Fuzzy AHP	Improvement for Fuzzy AHP based on fuzzy linguistic preference relations. To solve the problems regarding the inconsistency in decision making process. Implementation by selection optimum location of new car factory	1. The fuzzy linguistic preference relations are used to derive pairwise comparison matrices. 2. The study reveals that the proposed method yields the same result as that of Kahraman et al. (2004)., however, we can reduce the number of pairwise comparisons 3. This methodology resolves the problem of consistency of the fuzzy AHP. 4.
2	Zheng, Guozhong et.al, 2012	Trapezoidal Fuzzy AHP	Application of Fuzzy AHP study for evaluating A safety evaluation framework containing three factors (work, environment, and workers).	1. The comprehensive the comprehensive safety index, work safety index, environment safety index, human safety index, safety grade and early warning grade are determined. 2. Implementation of those safety index is best applied in coal mine industry where hot and humid environments exist.

Table 2.3b. Previous research related to Fuzzy AHP methodology

3	Qiaoxiu, Wang et.al, 2016	Non-Linear Fuzzy AHP	Nonlinear methodology to find the precedence of risk factors in coal mine in China. Implementation of logarithmic fuzzy preference programming to estimate and rank risk factors which involves managerial, environmental, operational and individual criteria.	the proposed evaluation system (logarithmic fuzzy preference programming) is found out to be more convenient, precise and complete during the evaluation process, compared to traditional AHP and FAHP based on EA method. From this research, its defined that human factor has the greatest impact among four criteria.
4	Multazam, Teuku et.al,	Fuzzy AHP	Selection of optimum location for Wind Farm power generator	Based on the calculation, it is found that the alternative location of Sukomoro has the highest weight that is, 0.2518, while the location of Nganjuk, Pace Rejoso and Lengkong are on the order of two, three, four and fifth with the resulted weights are 0.2335, 0.1361, 0.1290 and 0.2189.

CHAPTER III

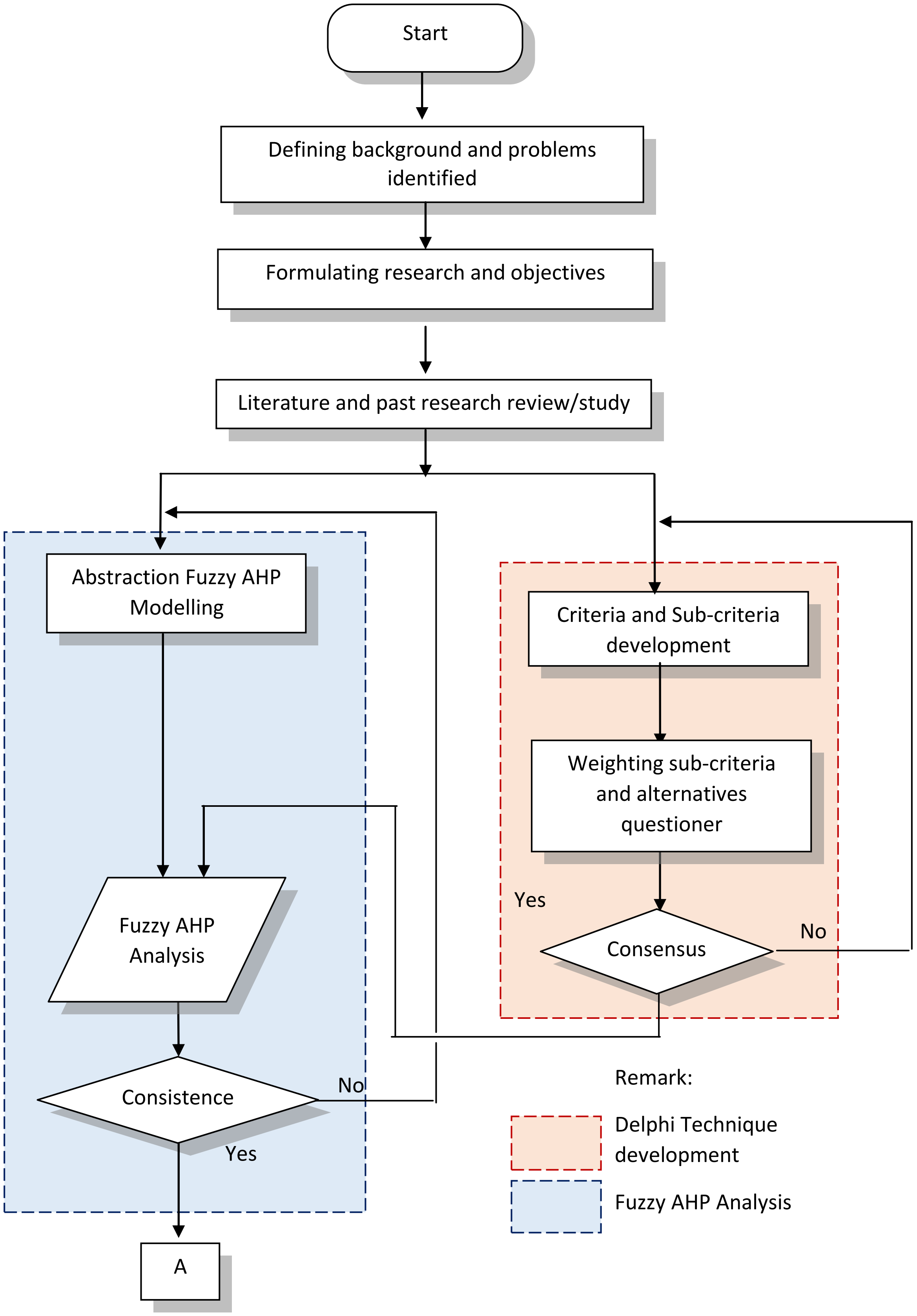
RESEARCH METHODS

This chapter describes the research design including data collection process and steps taken to analyze data. The methodology is largely developed based upon the Fuzzy AHP technique.

3.1. Research Framework and Design

As stated in the research objectives, formulated problems involved in the thesis is selection of gas detector technology. It is necessary to perform such research to ensure that gas detector chosen and implemented in oil and gas processing area (OGPA) will be suitable. This research is carried out to evaluate and quantify specific value as baseline for OGPA's management to implement gas detector technology. The criteria analyzed cover several aspects, such as: advantages delivered by the gas detector, Cost required for each gas detector technology, and gas detector latent risk based on the technology used. Result of this research is expected to deliver detail guidance for OGPA management on which technology is best applied. Comparison result of each gas detector technology is delivered as quantified value, as it can be directly compared and measured.

The structure of this research is divided into several parts which is described in figure 3.1.


Start
Defining background and problems identified
Formulating research and objectives
Literature and past research review/study
Abstraction Fuzzy AHP Modelling
Fuzzy AHP Analysis
Consistence
No
Yes
A
Criteria and Sub-criteria development
Weighting sub-criteria and alternatives questioner
Yes
Consensus
No
Remark:
Delphi Technique development
Fuzzy AHP Analysis

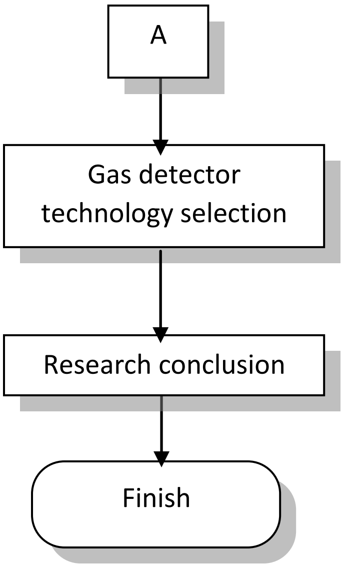


Figure 3.1 Research flowchart. It defines detail steps in developing the thesis research.

3.4. Development of Selection Criteria and Data Collection

For a Fuzzy AHP research to be precise, its criteria, sub-criteria, and alternatives should be developed based on applicable research methodology. Delphi technique has been known for its advantages to gather and conclude experts' judgment for scientific problems. Delphi technique is particularly used in this research for constructing sub-criteria of selection of gas detector technology and the alternatives attribute. Three aspects criteria of this research has been evaluated in Delphi technique: benefit, cost, and risk.

3.4.1. Implementation of Delphi Technique for Developing Research Sub-Criteria and Alternatives Attribute

The implementation of Delphi technique in this research was carried out during November-December 2017 in the petroleum company operating the OGPA. At first, Delphi technique is performed by describing problems which is encounter by the OGPA regarding selection of gas detector technology. Explanation of recent gas detector technology and working principle are delivered and prepared as the option for the panelist. Then, questionnaire is developed based on three aspects that is evaluated in selecting gas detector technology. Benefit aspect is firstly mentioned to the expert panelist. It is selected 5 sub-criteria that best mentioned by the expert panelist. Secondly, cost aspect is mentioned covering sub-criteria for Capital expenditure, maintenance cost, training and development cost. Four sub-criteria are selected from the cost aspect. Similar method is also performed for risk aspect, and 5 sub-criteria are selected accordingly. The number of sub-criteria is limited to 4-7, due to consideration of bias and consistency. Development of the Delphi technique is described in figure 3.2.

Ten expertise participants are selected accordance to their métier and working scope. The participants involved in interview and questionnaire are selected from their capability in determining sub-criteria for selecting gas detector technology. The expert panelist was contacted firstly by email, and the one that commit to perform interview was attended by the author. The interview was based on several question such as: “In terms of benefit delivered by gas detector, what factors can you identified, please mentioned?”, “what is the reason for you to choose reliability factor as determining criteria in selecting gas detector?”. Detail question is available on the appendix. The discussion in each round was performed by the author and panelist solely. It is impossible for each panelist know other panelist in name because this Delphi technique is performed anonymously. Distribution of panelist is described in figure 3.3 and 3.4.

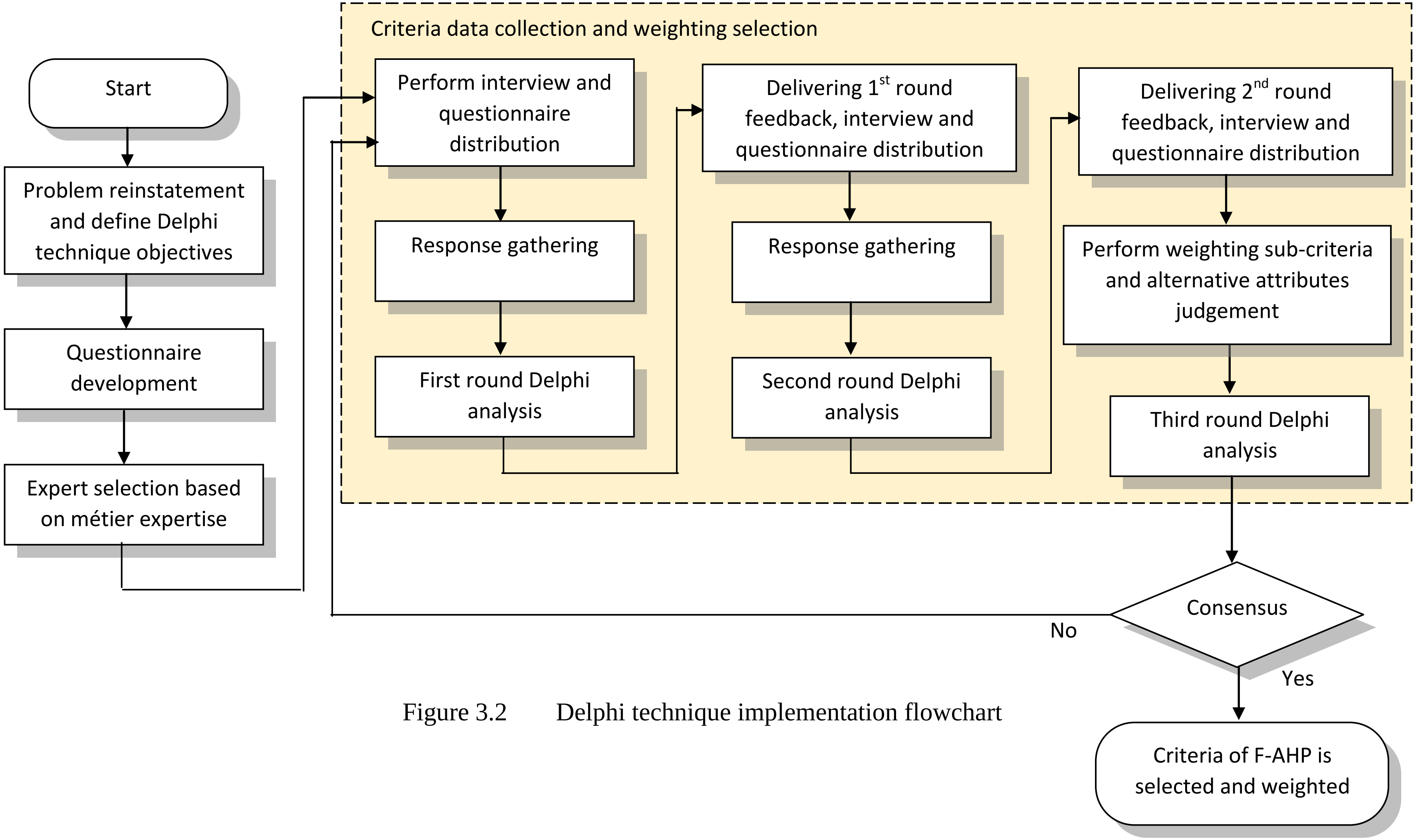


Figure 3.2 Delphi technique implementation flowchart

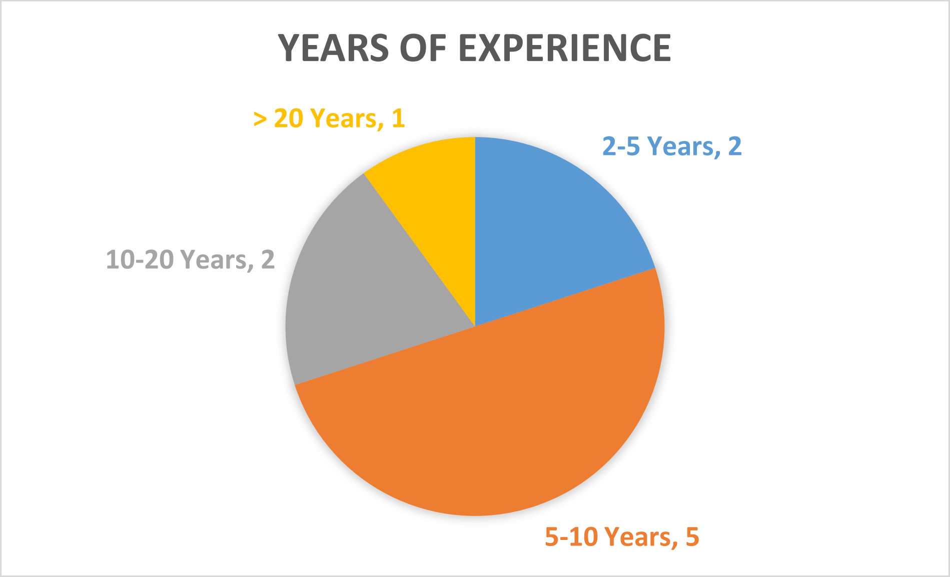


Figure 3.3 Years of experience graphic of panelists involved in the Delphi technique

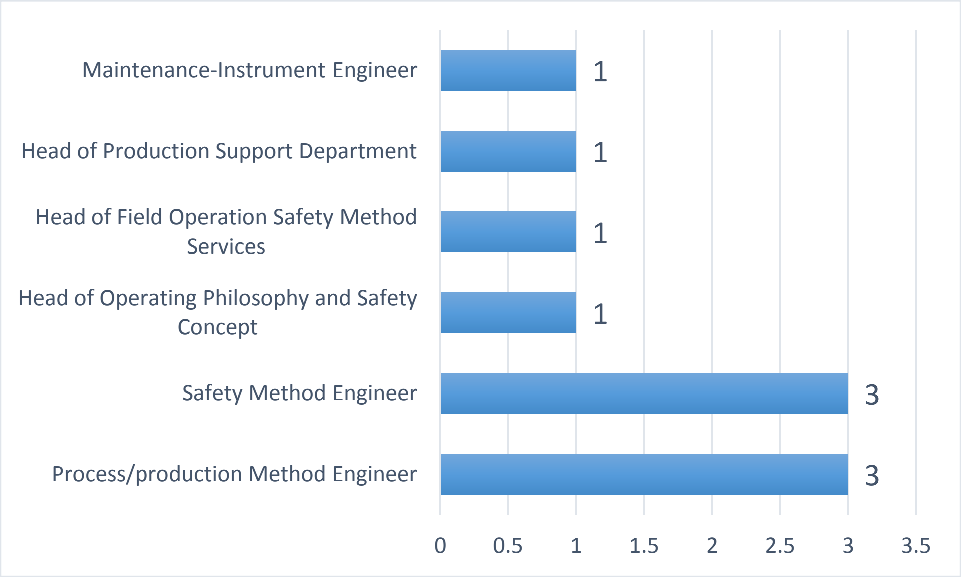


Figure 3.4 Working position of expert panelists involving in the Delphi technique

Those experts are mainly working in Field Operation division in petroleum company, East Kalimantan. Engineer panelist was most selected because they are the true front-liner to perform calculation on safety engineering factors. Some managerial positions are also selected such as, head department of production support and head of field operation safety and method services. This approach is taken because they are the key person for decision making process in the OGPA.

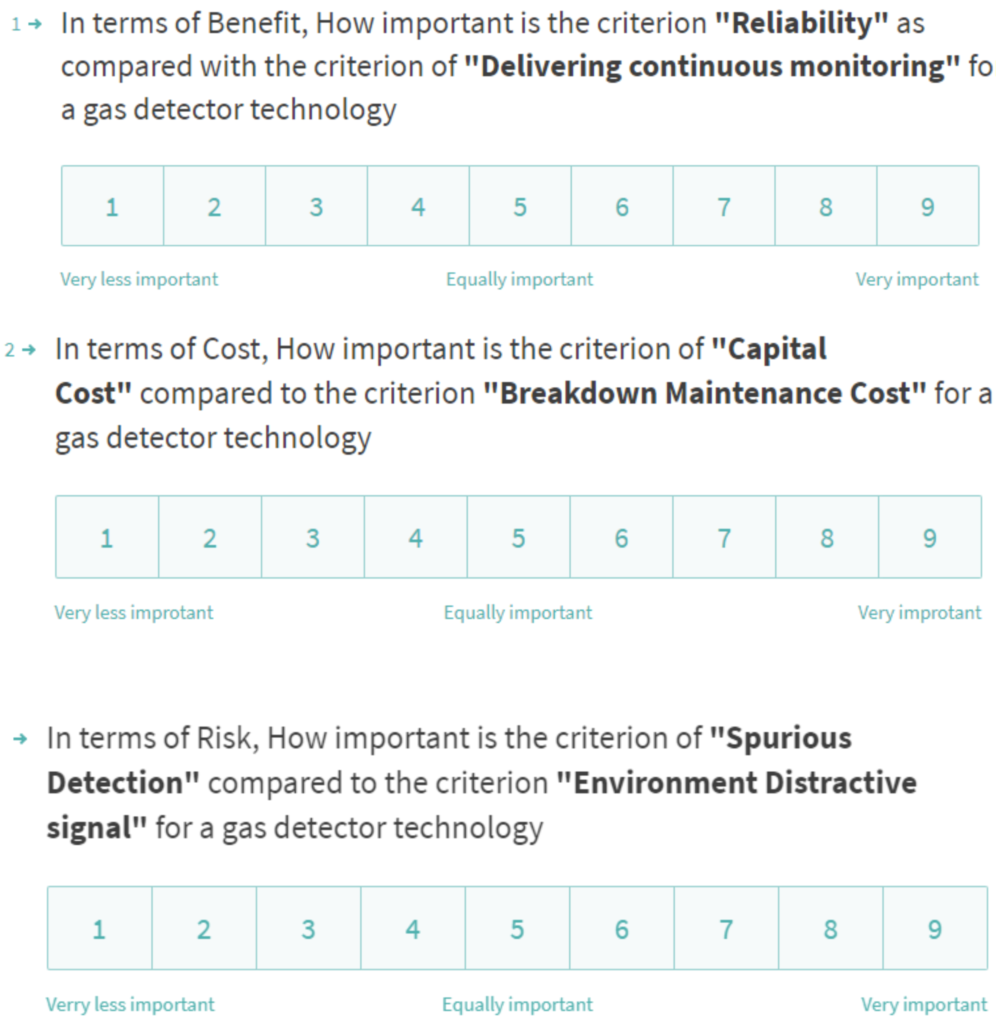
Delphi technique is carried out in three round analyses. on round one and two, the Delphi technique is performed by interviewing the expert panelists. Feedback from round one is delivered in round two. By delivering feedback, it is expected that panelist would response to a consensus understanding. Round one and two are mainly performed to construct the sub-criteria for selecting the gas detector technology. Whereas round three is specified to weight on the sub-criteria defined and the alternative attribute.

3.4.2. Weighting Sub-Criteria and Alternatives Attribute Development

The development of weighting criteria is performed by delivering questionnaire in round three Delphi technique. The data of questioner is gathered by providing pair wise comparison of criteria for selecting gas detector technology. each of criteria is developed into open-ended question describing how important a criterion compared to another criterion. The preference is collected by specially designed format as shown in figure 3.5.

The questionnaire is delivered to the expert panelists, and they could response immediately by providing their preference. The result of this questionnaire is delivered thoroughly in chapter 4.

In this chapter, it is also delivered the alternatives attributes judgment by the panelist. The alternatives attribute judgment is performed for the qualitative criteria (benefit and risk aspects). Whereas the quantitative criteria (costs) attributes judgment is based on the technical data.



1 → In terms of Benefit, How important is the criterion **"Reliability"** as compared with the criterion of **"Delivering continuous monitoring"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Very less important Equally important Very important

2 → In terms of Cost, How important is the criterion of **"Capital Cost"** compared to the criterion **"Breakdown Maintenance Cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Very less improtant Equally important Very improtant

→ In terms of Risk, How important is the criterion of **"Spurious Detection"** compared to the criterion **"Environment Distractive signal"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important Equally important Very important

Figure 3.5. Preference format data collection. This figure demonstrates the importance of one criterion to another criterion.

3.5. Development of Fuzzy Analytic Hierarchy Process

By evaluating characteristic of each gas detector technology, the implementation of fuzzy AHP is to define selection based on benefit, cost and risk analysis. All criteria for Benefit, Cost, and Risk is broken down into set of hierarchy structure.

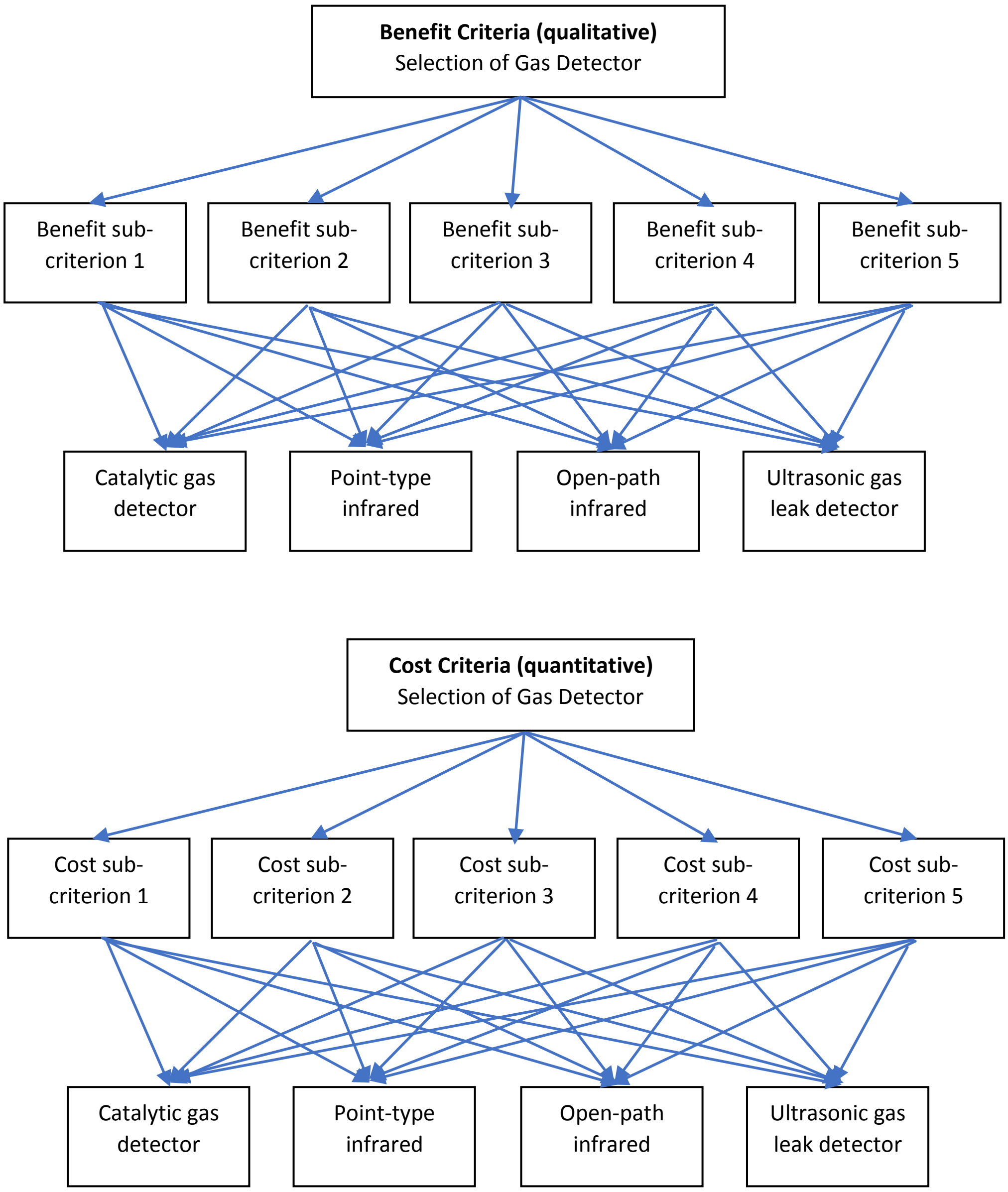


Figure 3.6a. The hierarchy of gas detector technology selection covering benefit, cost and risk criteria.

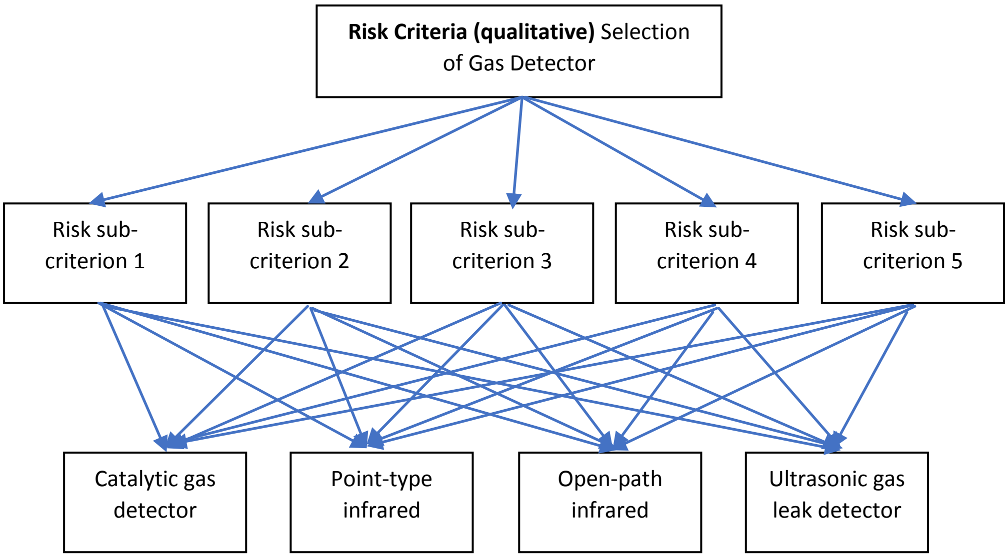


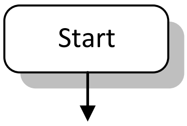
Figure 3.6b. The hierarchy of gas detector technology selection covering benefit, cost and risk criteria.

Figure 3.6. explains the structure of hierarchy process in this research. The involving criteria is divided into two aspects, which are,

- Qualitative: Benefit criteria and risk criteria
- Quantitative: Cost criteria.

For all criteria (benefit, cost and risk), associated sub-criteria will be defined as the result of Delphi method. Example of sub-criteria for "benefit" is: *reliability* and *delivering continuous monitoring*. And another example of "Risk" sub-criteria involves *environment distractive signal.* The detail sub-criteria will be explained in chapter 4 which elaborates the results of Delphi technique.

The analysis for all criteria is calculated based fuzzy pairwise comparison matrix. A fuzzy judgment matrix $\tilde{A}$ based on triangular fuzzy number (al, am, au) is developed, which one of sub-criteria is more important to another. Expected result from the Fuzzy AHP analysis are quantified weighting value of each gas detector technology. The rank priority is then developed respectively. The working flowchart to construct Fuzzy AHP method is described in figure 3.7.



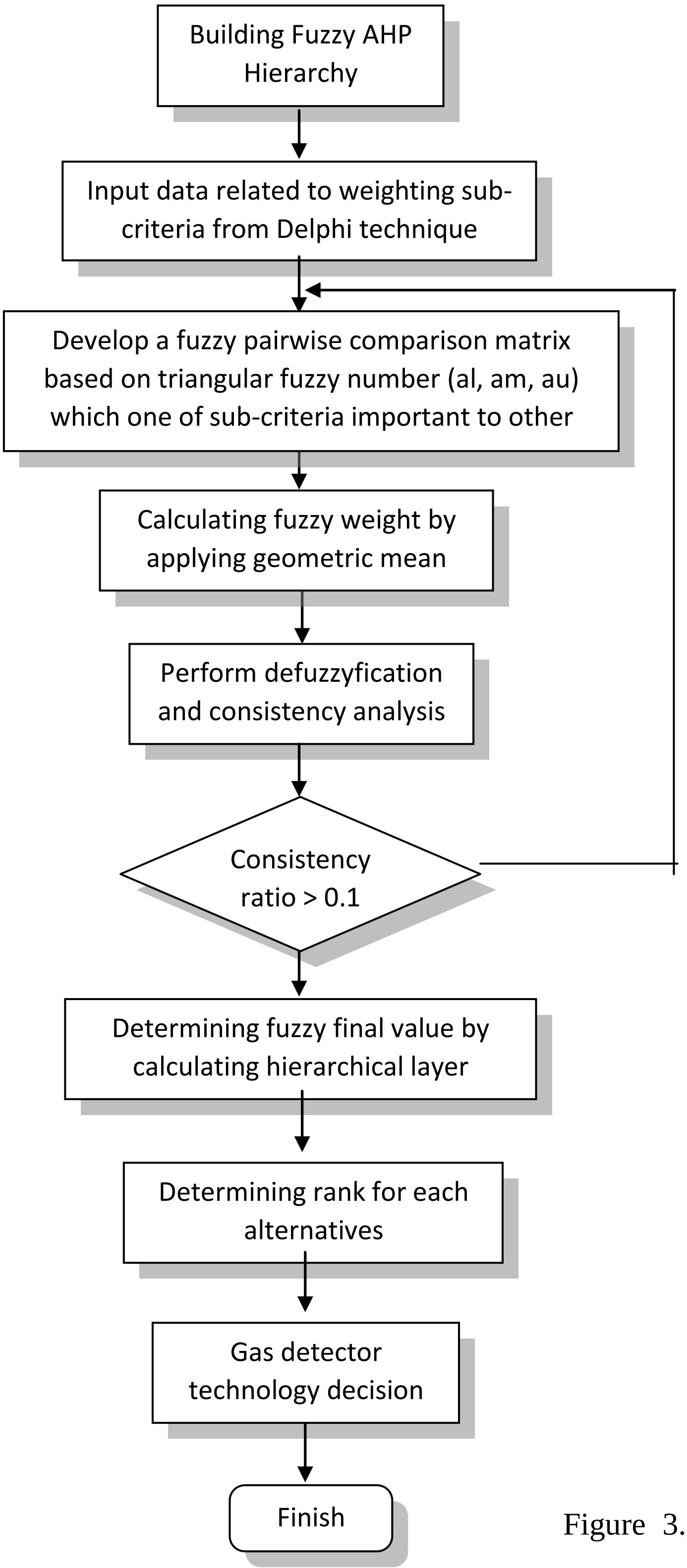


Figure 3.7. Flowchart to develop Fuzzy AHP method in selecting gas detector technology

3.5.1. Development of Hierarchy Construction

Development of hierarchy construction begins with determining the ultimate goal of the research. The Fuzzy AHP method should have capabilities to conclude which gas detector technology best applied in the OGPA. The hierarchy level is described as:

Level-1: Ultimate goal of the research is placed as the first level of hierarchy. Particularly in this research, the ultimate goal is "Selecting the best gas detector technology for the oil and gas processing area"

Level-2: The second level hierarchy is called sub-criteria level. This level explains all sub-criteria gathered from Delphi technique from respecting categories: benefit aspect, cost aspect, and risk aspect. On each category, it is applied several criteria for evaluation, such as: a. benefit aspect (5 sub-criteria), b. cost aspect (4 sub-criteria), and c. risk aspect (5 sub-criteria).

Level-3: Third level of hierarchy is called alternatives level. This level consists of four alternatives represented gas detector technology: a. open-path infrared gas detector; b. point-type infrared gas detector; c. ultrasonic gas leak detector; d. catalytic gas detector.

3.6. Sensitivity Analysis

Sensitivity analysis is aimed to detect the consistency of the fuzzy AHP analysis in this research. Sensitivity analysis is performed by changing the sub-criteria weight and observes how many changes occurs in the alternative's weight. The change of alternative's weight will be acceptable if the alternatives rank position is still same with initial rank position. The fuzzy AHP is consistent if there is no change of alternatives rank position after the sub-criteria's weight change.

CHAPTER IV

RESULT OF DELPHI TECHNIQUE AND EVALUATION OF FUZZY AHP

The chapter IV defines how the data are collected and evaluated based on the methodology chosen in this research. Data are gathered based on the three rounds Delphi technique. The first and second are intended to identify the sub-criteria which are most applicable for selecting gas detector technology. The third round elaborates judgment value for the sub-criteria and value of the alternatives over the sub-criteria. The data are then evaluated based on fuzzy AHP methodology to analyze the judgment precisely.

4.1. Gas Detector Alternatives Identification

Based on literature study, alternatives identification is performed in this research. For the time being, the OGPA have several alternatives which can be assessed accordingly. Alternatives identification is necessary based on the gas detector market availability and the OGPA capability to possess the technology.

In this research, four alternatives are available for the OGPA to implement gas detector technology. These alternatives are possible to be chosen due to their availability, after-market service, and the existence in other Company's affiliate. The alternatives are listed, *Catalytic Gas Detector, Point-type Infrared Gas Detector, Open-path Infrared Gas Detector, and Ultrasonic Leak Detector.* Table 4.1 shows main characteristics of the alternatives.

Table 4.1. Alternatives main characteristic summary in terms of Cost

No	**Specification**	**Alternatives**			
		Catalytic gas detector (CGD)	**Point-type infrared gas detector (PGD)**	**Open-path infrared gas detector (OPGD)**	**Ultrasonic gas leak detector (UGLD)**
COST					
1	Capital expenditure[2]	$844.00 (each)	$1,792.00 (each)	$10,300.45	$18,336.00
2	Maintenance cost[3]	$2,484	$1,380	$1,656	$828
3	Spare-part cost[4]	$88.62 (each)	$188.16 (each)	$1,081.55	$1,925.28

Table 4.2. Alternatives main characteristic summary in terms of Benefit

No	**Specification**	**Alternatives**			
		Catalytic gas detector (CGD)	**Point-type infrared gas detector (PGD)**	**Open-path infrared gas detector (OPGD)**	**Ultrasonic gas leak detector (UGLD)**
BENEFIT					
4	Detection technology	Combustion in chamber	Infrared	Infrared, line of sight	Ultrasonic (sound) detection
5	Coverage area	<1m (one dimensional)	<1m (one dimensional)	1.5m - 30m (two dimensional)	2m – 20m (three dimensional)
6	Feature/capability	• Continuous %LEL monitoring • 0-100% LEL range	• Continuous %LEL monitoring • Zero oxygen detection • Fail to safe • Wide range %LEL detection (0-200%)	• Continuous %LEL monitoring • Zero oxygen detection • Fail to safe • Wide range %LEL detection (0-200%)	• Zero oxygen detection • Fail to safe technology • 40-100dB range (only two types of alarm low level-high level)
7	SIL[5] (safety integrity level)	Unspecified (>SIL 1)	SIL 2 certified per IEC61508	SIL 2 certified per IEC61508	SIL 2 certified per IEC61508
8	Response time	50% LEL in 3.8 seconds 90%LEL in 8.4 seconds 60%LEL in 10 seconds	50% LEL in 4.8 seconds 90%LEL in 7.6 seconds 60%LEL in 5.1 seconds	90%LEL in 2 seconds	30 seconds delay, 30 seconds recover.

Table 4.3. Alternatives main characteristic summary in terms of Risk

No	**Specification**	**Alternatives**			
		Catalytic gas detector (CGD)	**Point-type infrared gas detector (PGD)**	**Open-path infrared gas detector (OPGD)**	**Ultrasonic gas leak detector (UGLD)**
RISK					
10	Spurious detection[6]	Very unlikely	Very unlikely	Unlikely	Possible
11	Environment signal distraction	• less oxygen (<16%) • Temperature • High concentration of flammable gas	• None	• Rain • Fog • Vibration	• Noise • Vibration • High flow of hydrocarbon • Gas / over pressure venting

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[2] The prices are based distributor price on vendor website accessed on 27 November 2017.
[3] Based on man-hour required for maintenance, maintenance frequency, and duration of maintenance, accumulatively in a year
[4] Based on assumption that spare-part cost is approximately 10-11% of Capital expenditure.
[5] Safety integrity level is defined as probability of failure on demand, SIL 2 PDF= $10^{-2} – 10^{-3}$
[6] Probability of spurious detection is defined as: Very unlikely, Unlikely, Possible, Probable

4.2. Development of Sub-Criteria based on Delphi Technique Results

The gas detector is selected based on three main criteria: benefits, costs, and risks. The sub-criteria were then developed for each three criteria. The process of sub-criteria development is deemed as the most important stage as it determines the final results. As described in previous chapter, the Delphi technique was employed to generate the sub-criteria. The Delphi technique involves ten experts from various departments (production, maintenance, instrumentation and safety), including *Maintenance-instrument engineer, Head of Production Support Department, Head of Field Operation Safety and Method Services, Head of Operating Philosophy and Safety Concept, Safety Method Engineer (3 personnel), and Process/ production engineer (3 personnel).*

. The result of Delphi technique at first and second round is described in Figure 4.1, 4.2, and 4.3. The detail results of first and second round Delphi technique are available in appendix. B.

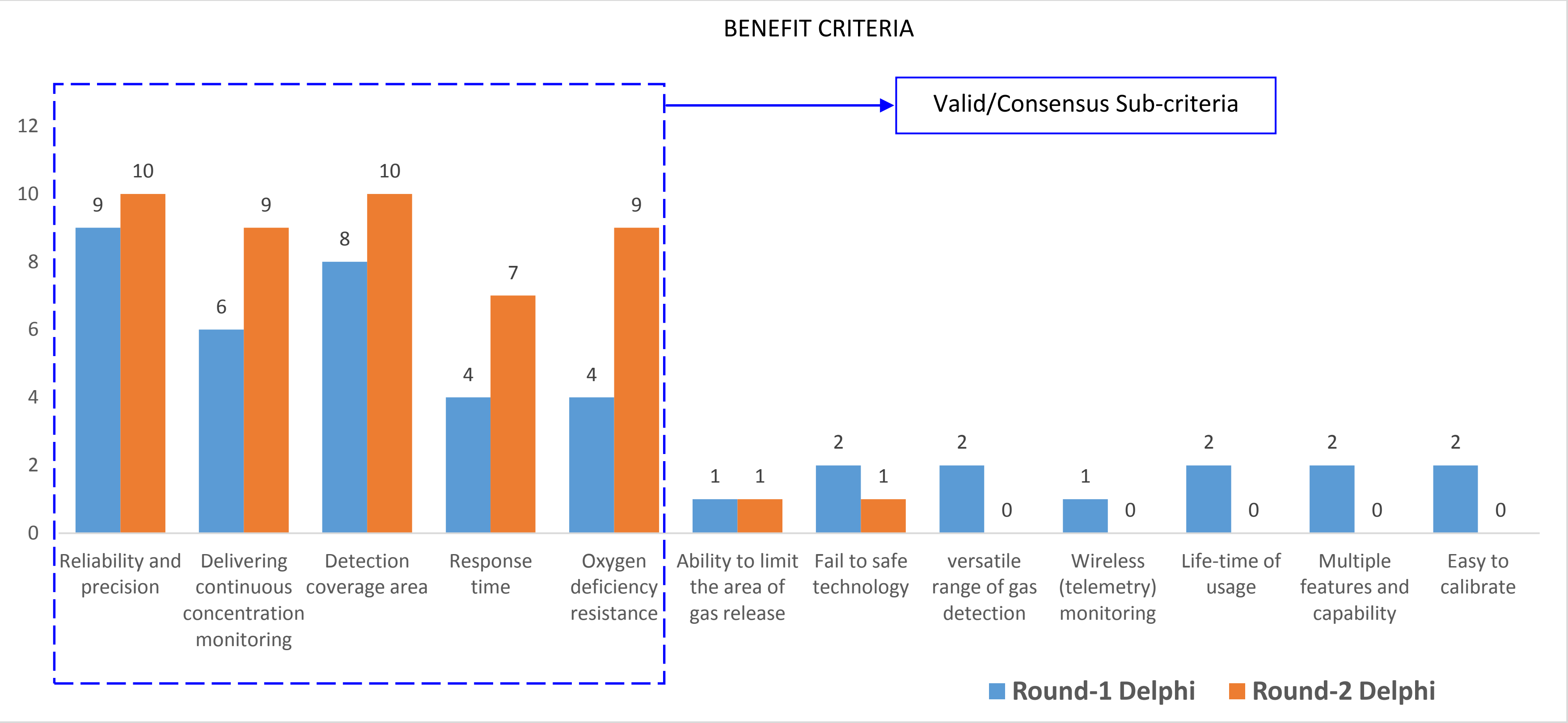


Figure 4.1. Delphi Technique result for Benefit criteria. The number of personnel devoted the sub-criteria are showed on the figure on each sub-criteria label.

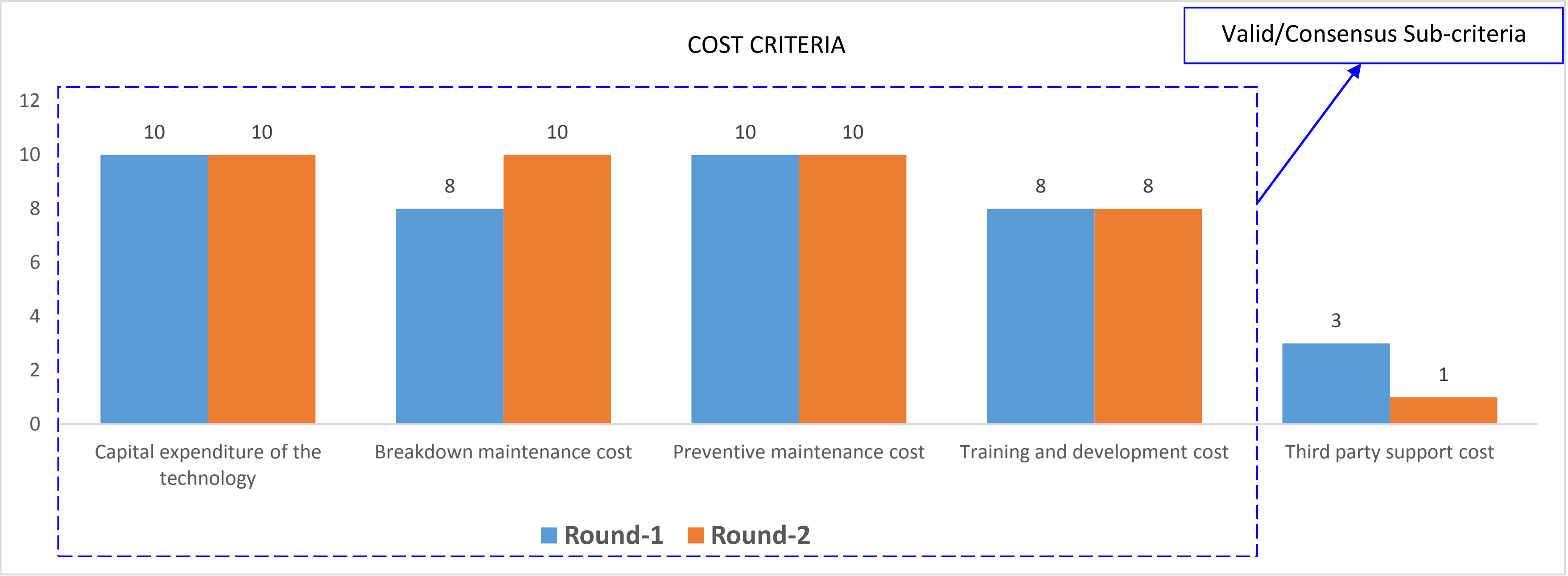


Figure 4.2. Delphi Technique result for Cost criteria. The number of personnel devoted the sub-criteria are showed on the figure on each sub-criteria label.

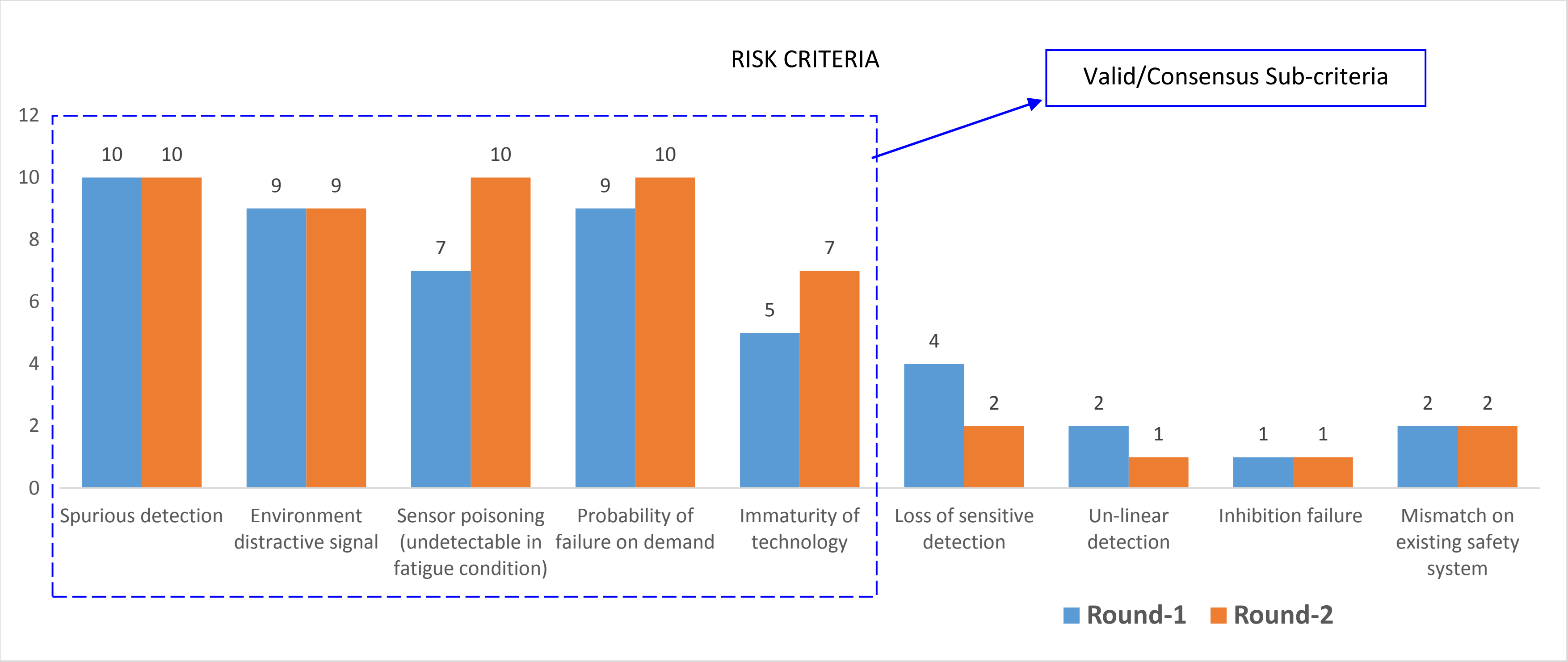


Figure 4.3. Delphi Technique result for Risk criteria. The number of personnel devoted the sub-criteria are showed on the figure on each sub-criteria label.

4.2.1. Benefit Criteria

Benefit criteria is defined as the main ability of gas detector technology deliverability. In these criteria, consensus is reached during second round of Delphi technique. It is shown that all expert panelists' answers toward to almost unanimous decision. Especially in sub-criteria *Reliability and precision* and *Detection coverage area* all panelists are agreed to choose these sub-criteria. Table 4.4. defines the definition of each sub-criterion.

Table 4.4. Sub-criteria explanation according to Delphi consensus in round-2 for benefit criteria.

No	Sub-criteria	Explanation
Criteria 1	Reliability and precision	This sub-criterion is defined as the ability of gas detector technology to deliver their intended function. As mainly function to detect gas concentration gas detector technology is considered as reliable when it can precisely detect accurate detection.
Criteria 2	Detection coverage area	As mainly linked to the number of gas detector needed, the coverage area plays important role in defining gas detector's benefit. As wider the coverage the more gas detectors are able to protect hazardous area.
Criteria 3	Delivering continuous concentration monitoring	One of benefit aspects from gas detector technology is defined by consensus: the gas detector should be able to continuously monitor gas concentration in hazardous area. The continuous monitor are defined as the ability to measure flammable gas concentration and to display the measurement into existing control panel.
Criteria 4	Oxygen deficiency resistance	There are several places in the processing area where oxygen might in deficiency condition, such as: turbine enclosure, exhaust stack, and confined space.
Criteria 5	Response time	Response time is defined as processing time for a gas detector to detect and deliver output command to shut down the processing area. As functioned to prevent hydrocarbon release escalation which can lead to a fire, quick response time is one of indispensable parameter for the goodness of gas detector.

4.2.2. Cost Criteria

Almost in all aspects of project investment analysis, cost criteria should be evaluated for the effectiveness of operation. The petroleum company operating the OGPA has determined policy of “cost culture” which means compete on cost, cash and deliverability. The operation factors delivered should consider costs aspects as the most important parameter along with safety and productivity. According to the consensus there are four sub-criteria representing the cost criteria. Table 4.5. defines the definition of each cost sub-criterion.

Table 4.5. Sub-criteria explanation according to Delphi consensus in round-2 for cost criteria

No	Sub-criteria	Explanation
Criteria 1	Capital expenditure of the technology	The capital expenditure is defined as amount of money which is spent by petroleum company to invest in the gas detector technology. Although high capital expenditure are possible to make safer process design, but the objectives is to seek the most optimum technology in terms of ALARP (as low as reasonable and practicable)
Criteria 2	Preventive maintenance cost	The preventive maintenance cost is the man-hour cost required for maintenance work, i.e. maintenance frequency and duration of maintenance. This cost is calculated based on labor man-hour to perform preventive maintenance, including calibration of gas detector equipment.
Criteria 3	Breakdown maintenance cost	This sub-criterion is directly linked to the capital expenditure. Breakdown maintenance cost is the price spent for un-repairable damage. It means that the company should replace some spare part or whole gas detector system. In the consensus, spare-part cost is approximately 10-11% of the Capital expenditure.
Criteria 4	Training and development cost	As part of continuous improvement, training and development cost should be predefined. The training cost includes the investment of maintenance technician and operator training to master the gas detector technology.

4.2.3. Risk Criteria

Table 4.6. Sub-criteria explanation according to Delphi consensus in round-2 for risk criteria

No	Sub-criteria	Explanation
Criteria 1	Spurious detection	Occasionally, gas detector often detects false gas concentration which can lead to process shutdown. Unplanned shutdown caused by spurious detection shall lead the OGPA to deserve loss of production. Often spurious detection can also lead to make the operator neglect detection signal produced by the gas detector. The real case has ever happened when one of the gas detector technology produced more than 200 times spurious detection in 3-month period, and when it detect the real gas release, the operator assume that it is false detection, and he neglect it.
Criteria 2	Probability of failure on demand	PFD is a probability of failure during expected demand of operation. It is also directly linked to the reliability of the gas detector system. As certified by IEC, gas detector must deliver a probability with SIL-2 or 10-2–10-3 probability of failure on demand.
Criteria 3	Sensor poisoning (undetectable in fatigue condition)	When a gas detector is often exposed to flammable gas concentration, there is a possibility that it does not detect real value of gas concentration. This phenomenon is called sensor poisoning, and when this happens, the gas detector must be calibrated again. The gas detector capability in handling sensor poisoning will ensure correct reading of gas concentration.
Criteria 4	Environment distractive signal	Gas detector technology should have robust feature to the environment distraction. The ability to disclose environment signal such as, noise, fog, and vibration.
Criteria 5	Immaturity of technology	When a gas detector technology is introduced to the market, the manufacturer should convince their client that the technology is mature enough. The maturity of technology includes compatibility of gas detector technology to the existing process facilities.

As mainly deal with hazardous material, the OGPA is considered as high risk industry. By the definition, risk is a condition where there is a possibility for an undesirable event (or incident) occurrence. Risk is defined as multiplication effect of *consequences-severity* by *probability* for an undesirable event. Optimal safe condition can be reached by controlling risk to an ALARP level. This means that all prevention and mitigation are devoted to reduce the consequences of an incident and/or probability of incident occurrence. The implementation of gas detector technology is a form incident consequences reduction.

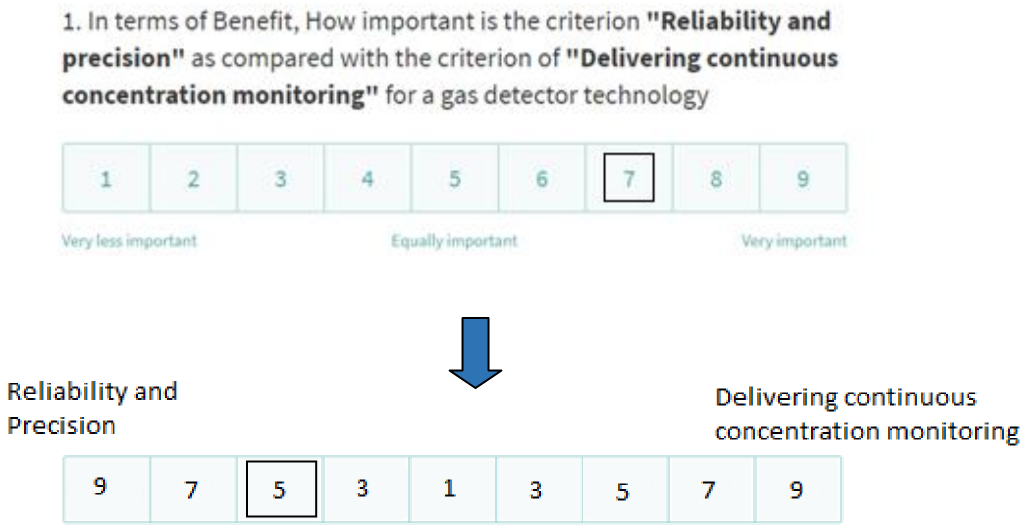
Based on the consensus in the second round of Delphi Technique, the risk sub-criteria involved in the OGPA operation is defined. The detail is described in the table 4.6.

4.3. Delphi Technique Result for Sub-Criteria Weighting

The third round of Delphi technique is intended to gather expert panelists' opinion to determine how important a sub-criterion compared to other sub-criteria. As described in chapter 3.4.2. the pairwise comparison is given to the expert panelists on the third round. This Delphi technique is pairwise comparison based on questions given to the expert panelists in figure 4.4. The result of the questionnaire will be the value fuzzy AHP pairwise comparison. The results are given respectively as follows.

4.3.1. Benefit Sub-Criteria Weighting Result

The Delphi technique consensus determines weight value of the benefit criteria. The judgment for each sub-criterion is then converted to the pairwise comparison in accordance to Saaty scale. An example of pairwise comparison table is given in figure 4.4.



1. In terms of Benefit, How important is the criterion **"Reliability and precision"** as compared with the criterion of **"Delivering continuous concentration monitoring"** for a gas detector technology

Figure 4.4. Example of questionnaire given to the panelist is converted into a Saaty scale pairwise comparison

Figure 4.4. means “Reliability and precision” is strongly important than “Delivering continuous concentration monitoring”. Overall result of the pairwise comparison is described in Table 4.5.

Table 4.7a. The summary result of Sub-criteria for Benefit criterion

Function	Safety and Method Eng II.	Production/process method Eng III.	Head of Operating Philosophy and Safety Concept	Safety and Method Eng I.	Head of Field Operation Safety and Method Services	Head of Production Support Department	Safety and Method Eng III.	Production/process method Eng II.	Production/pro-cess method Eng I.	Maintenance Instrument Eng.
Name	FDW	BJ	SS	GW	AD	RD	DS	DW	SS	AM
Question										
Benefit										
"Reliability and precision" vs "Detection coverage area"	3	1	1	1	1	3	1	3	3	1
Reliability and precision" vs "Deliviring continuous concentration monitoring"	3	3	3	3	3	3	5	5	3	3
"Reliability and precision" vs "Oxygen deficiency resistance"	5	5	5	3	3	5	5	5	5	5
"Reliability and precision" vs "Response time"	7	9	9	9	9	7	7	9	9	9
"Detection coverage area" vs "Delivering continuous concentration monitoring"	3	3	3	3	3	3	3	3	3	5
"Detection coverage area" vs "Oxygen deficiency resistance"	3	3	3	3	3	3	3	3	3	3

Table 4.7b. The summary result of Sub-criteria for Benefit criterion

"Detection coverage area" vs "Response time"	7	7	7	7	7	7	5	7	7	7
"Delivering continuous concentration monitoring" vs "Oxygen deficiency resistance"	1	1	3	3	1	1	3	3	3	3
"Delivering continuous concentration monitoring" vs "Response time"	3	3	3	3	3	3	3	3	3	3
"Oxygen deficiency resistance" vs "Response time"	3	3	5	5	3	5	5	5	3	3

This research considers that the most significant number raised by the panelist, are the represent number in pairwise comparison for a sub-criterion. It means that number of Modus will be used for the comparison value for the Fuzzy AHP.

Table 4.8. The statistical appearance of weighting pairwise comparison for benefit sub-criterion

Question	Mean	Median	Modus	Standard deviation
"Reliability and precision" vs "Delivering continuous concentration monitoring"	1.8	1	**1**	1.032796
Reliability and precision" vs "Detection coverage area	3.4	3	**3**	0.843274
"Reliability and precision" vs "Response time"	4.6	5	**5**	0.843274
"Reliability and precision" vs "Oxygen deficiency resistance"	8.4	9	**9**	0.966092
"Delivering continuous concentration monitoring" vs "Detection coverage area"	3.2	3	**3**	0.632456
"Delivering continuous concentration monitoring" v "Response time"	3	3	**3**	0
"Delivering continuous concentration monitoring" vs "Oxygen deficiency"	6.8	7	**7**	0.632456
"Detection coverage area" vs "Response time"	2.2	3	**3**	1.032796
"Detection coverage area" vs "Oxygen deficiency resistance"	3	3	**3**	0
"Response time" vs "Oxygen deficiency resistance"	4	4	**3**	1.054093

4.3.2. Cost Sub-Criteria Weighting Results

Similar methodology for the cost criteria is performed as well. The Delphi third round result for cost criteria is described on Table 4.9.

Table 4.9. The summary result of Sub-criteria for Cost criterion

Function	Safety and Method Eng II.	Production/process method Eng III.	Head of Operating Philosophy and Safety Concept	Safety and Method Eng I.	Head of Field Operation Safety and Method Services	Head of Production Support Department	Safety and Method Eng III.	Production/process method Eng II.	Production/pro-cess method Eng I.	Maintenance Instrument Eng.
Name	FDW	BJ	SS	GW	AD	RD	DS	DW	SS	AM
Question										
Cost										
"Capital expenditure of the technology" vs "Preventive maintenance cost"	3	3	5	3	3	3	3	3	3	1
"Capital expenditure of the technology" vs "Breakdown maintenance cost"	5	5	5	5	5	3	3	3	5	3
"Capital expenditure of the technology" vs "Training and development cost"	7	7	7	7	5	5	7	7	7	5
"Preventive maintenance cost" vs "Breakdown maintenance cost"	1	1	1	1	0.333333333	1	3	3	3	1
"Preventive maintenance cost" vs "Training and development cost"	3	3	3	3	3	1	3	3	3	1
"Breakdown maintenance cost" vs "Training and development cost"	1	1	1	1	1	1	1	1	1	1

The statistical result is displayed on table 4.10. represents value for determining cost criteria is resulted as follow,

Table 4.10. The statistical appearance of weighting pairwise comparison for cost sub-criterion

Question	Mean	Median	Modus	Standard deviation
"Capital expenditure of the technology" vs "Preventive maintenance cost"	3	3	**3**	0.942809
"Capital expenditure of the technology" vs "Breakdown maintenance cost"	4.2	5	**5**	1.032796
"Capital expenditure of the technology" vs "Training and development cost"	6.4	7	**7**	0.966092
"Preventive maintenance cost" vs "Breakdown maintenance cost"	1.533333	1	**1**	1.032796
"Preventive maintenance cost" vs "Training and development cost"	2.6	3	**3**	0.843274
"Breakdown maintenance cost" vs "Training and development cost"	1	1	**1**	0

4.3.3. Risk Sub-Criteria Weighting Results

Lastly, the third round of Delhi Technique present the value of pairwise comparison for the Risk sub-criteria. The result is presented in table 4.11.

Table 4.11a. The summary result of Sub-criteria for Risk criterion

Function	Safety and Method Eng II.	Production/process method Eng III.	Head of Operating Philosophy and Safety Concept	Safety and Method Eng I.	Head of Field Operation Safety and Method Services	Head of Production Support Department	Safety and Method Eng III.	Production/process method Eng II.	Production/pro-cess method Eng I.	Maintenance Instrument Eng.
Name	FDW	BJ	SS	GW	AD	RD	DS	DW	SS	AM
Question										
Risk										
"Spurious detection" vs "Probability of failure on demand"	3	3	3	3	3	3	3	3	3	
"Spurious detection" vs "Sensor poisoning (undetectable in fatigue condition)"	5	3	3	5	5	5	5	5		3
"Spurious detection" vs "Environment distractive signal"	7	7	7	7	7	7	7	7	5	9
"Spurious detection" vs "Immaturity of technology"	9	9	9	7	7	9	7	9	7	7

Table 4.11b. The summary result of Sub-criteria for Risk criterion

"Probability of failure on demand" vs "Sensor poisoning (undetectable in fatigue condition)"	3	3	3	3	3	3	3	3	3	3
"Probability of failure on demand" vs "Environment distractive signal"	5	5	5	5	3	5	5	3	3	5
"Probability of failure on demand" vs "Immaturity of technology"	7	7	7	7	7	7	7	7	7	7
"Sensor poisoning (undetectable in fatigue condition)" vs "Environment distractive signal"	3	3	3	3	5	3	1	5	5	3
"Sensor poisoning (undetectable in fatigue condition)" vs "Immaturity of technology"	3	3	3	3	3	3	3	3	3	3
"Environment distractive signal" compared to the criterion "Immaturity of technology"	1	1	1	1	3	1	3	1	1	1

Table 4.12. The statistical appearance of weighting pairwise comparison for risk sub-criterion

Question	Mean	Median	Modus	Standard deviation
"Spurious detection" vs "Probability of failure on demand"	3	3	**3**	0
"Spurious detection" vs "Sensor poisoning (undetectable in fatigue condition)"	3.6	4	**5**	1.646545
"Spurious detection" vs "Environment distractive signal"	5.2	5	**5**	1.75119
"Spurious detection" vs "Immaturity of technology"	6.6	7	**7**	0.843274
"Probability of failure on demand" vs "Sensor poisoning (undetectable in fatigue condition)"	1.6	1	**1**	0.966092
"Probability of failure on demand" vs "Environment distractive signal"	2.8	3	**3**	1.135292
"Probability of failure on demand" vs "Immaturity of technology"	5	5	**5**	0
"Sensor poisoning (undetectable in fatigue condition)" vs "Environment distractive signal"	3.4	3	**3**	1.577621
"Sensor poisoning (undetectable in fatigue condition)" vs "Immaturity of technology"	5	5	**5**	0
"Environment distractive signal" compared to the criterion "Immaturity of technology"	1.444444	1	**1**	0.881917

4.4. Delphi Technique Result for Alternatives Judgment

In the process of Fuzzy AHP development, a judgment of alternatives is performed in terms of the sub-criteria. The judgment is performed to quantify comparative value of an alternative in Saaty scale. The sub-criteria are divided into qualitative and quantitative factors. The alternatives judgment is performed to evaluate an alternative for qualitative criteria. Whereas the quantitative criteria assessment is performed by applying secondary data analysis.

4.4.1 Alternative Judgment for Qualitative Criteria

The alternative judgment for qualitative criteria is performed to analysis the importance of alternatives over the benefit and risk criteria. To assess the alternative, this research gives an evaluative format questionnaire to the expert panelists. This questionnaire is based on 5 scale scoring which is then converted into a Saaty scale according to conversion table as described in Table 4.13.

Table 4.13. Conversion scale of 5 scale scoring to the Saaty scale

Difference score from alternative *i* compare to alternative *j*	Intensity of Importance in Saaty Scale	Definition
0	1	Equal Importance
1	3	Moderate importance
2	5	Strong importance
3	7	Very strong or demonstrated importance
4	9	Extreme importance
	Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i

An implementation the conversion 5 scale scoring to the Saaty scale is given. In terms for Reliability and precision, the panelists give 5 scale scoring as stated on table 4.14:

Table 4.14. Likert scale scoring for Alternatives judgment

Alternatives	Reliability and precision Score
Catalytic (CGD)	4
Open-path infrared (OPGD)	3
Point-type infrared (PGD)	5
Ultrasonic gas leak detector (UGLD)	2

As we know from above judgment, if we compare CGD and UGLD we found the ‘2’ point difference score. Therefore, in pairwise comparison in Saaty scale means that “CGD is **strongly importance (Saaty scale 5)** in terms of reliability and precision over UGLD”. Similarly, we perform the evaluation for other sub-criteria.

The overall result of scoring judgment for Benefit criteria is described on Table 4.14 and 4.15. The detail result is attached on Appendix C and D.

Table 4.14. Expert panelist’s judgment for alternatives for Benefit criteria

Question	Mean	Median	Modus	Standard deviation
1. Reliability and Precision				
Catalytic (CGD)	3.5	3.5	**4**	0.527046
Open-path infrared (OPGD)	3.7	4	**4**	0.483046
Point-type infrared (PGD)	4.7	5	**5**	0.483046
Ultrasonic gas leak detector (UGLD)	2.4	2.5	**3**	0.699206
2. Detection coverage area				
Catalytic (CGD)	1	1	**1**	0
Open-path infrared (OPGD)	4	4	**4**	0
Point-type infrared (PGD)	1.1	1	**1**	0.316228
Ultrasonic gas leak detector (UGLD)	5	5	**5**	0
3. Delivering continuous concentration monitoring				
Catalytic (CGD)	3.7	4	**4**	0.483046
Open-path infrared (OPGD)	3.9	4	**4**	0.316228
Point-type infrared (PGD)	4.8	5	**5**	0.421637
Ultrasonic gas leak detector (UGLD)	1	1	**1**	0
4. Oxygen deficiency resistance				
Catalytic (CGD)	1	1	**1**	0
Open-path infrared (OPGD)	4.2	4	**4**	0.421637
Point-type infrared (PGD)	4.9	5	**5**	0.316228
Ultrasonic gas leak detector (UGLD)	4.9	5	**5**	0.316228
5. Response time				
Catalytic (CGD)	3	3	**3**	0
Open-path infrared (OPGD)	4.5	4.5	**5**	0.527046
Point-type infrared (PGD)	4.1	4	**4**	0.316228
Ultrasonic gas leak detector (UGLD)	1.1	1	**1**	0.316228

Table 4.15. Expert panelist's judgment for alternatives for Risk criteria

Question	Mean	Median	Modus	Standard deviation
1. Spurious Detection				
Catalytic (CGD)	2.9	3	3	0.316228
Open-path infrared (OPGD)	3.9	4	4	0.316228
Point-type infrared (PGD)	1	1	1	0
Ultrasonic gas leak detector (UGLD)	4.7	5	5	0.483046
2. Probability of Failure on Demand				
Catalytic (CGD)	2.2	2	2	0.421637
Open-path infrared (OPGD)	4.1	4	4	0.567646
Point-type infrared (PGD)	1	1	1	0
Ultrasonic gas leak detector (UGLD)	4.3	4	4	0.483046
3. Sensor Poisoning				
Catalytic (CGD)	5	5	5	0
Open-path infrared (OPGD)	1.7	2	2	0.483046
Point-type infrared (PGD)	1	1	1	0
Ultrasonic gas leak detector (UGLD)	4.1	4	4	0.567646
4. Environment Distractive Signal				
Catalytic (CGD)	2	2	2	0
Open-path infrared (OPGD)	3.2	3	3	0.421637
Point-type infrared (PGD)	1.2	1	1	0.421637
Ultrasonic gas leak detector (UGLD)	4.3	4	4	0.483046
5. Immaturity of Technology				
Catalytic (CGD)	1	1	1	0
Open-path infrared (OPGD)	3.8	4	4	0.421637
Point-type infrared (PGD)	2.3	2	2	0.483046
Ultrasonic gas leak detector (UGLD)	4.9	5	5	0.316228

4.4.2 Alternative Judgment for Quantitative Criteria

The quantitative criteria are defined as a criterion in which definite values are already obtained. In this research, quantitative criteria are defined as the cost criteria. To perform assessment for cost criteria, the second round of Delphi technique determines several cost aspects to acquire the gas detector technology. The summary of cost aspects is described on table 4.17. The cost explanation scoring is then converted into Saaty scale. Similar with chapter 4.4.1., we perform conversion with table 4.16.

Table 4.16. Conversion of cost table scale to the Saaty scale

Multiplication amount of money spent from alternative *i* compare to alternative *j*	**Intensity of Importance in Saaty Scale**	**Definition**
1 – 1.5x	1	Equal Importance
1.5 – 2x	3	Moderate importance
2 – 2.5x	5	Strong importance
2.5 – 3x	7	Very strong or demonstrated importance
> 3x	9	Extreme importance
	Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i

Table 4.17. Summary values of the cost criteria

		Catalytic gas detector (CGD)	Point-type infrared gas detector (PGD)	Open-path infrared gas detector (OPGD)	Ultrasonic gas leak detector (UGLD)
1	Capital expenditure of the technology[5]	$844.00 (each) It requires 6 UGD for redundancy $5.096 (totally)	$1,792.00 (each) It requires 6 PGD for redundancy $10.752 (totally)	$10,300.45	$18,336.00
2	Preventive Maintenance cost[6]	$2,484	$1,380	$1,656	$828
3	Breakdown Maintenance cost[7]	$560.56	$1,182.72	$1,133.00	$2,016.96
4	Training and Development cost[8]	$1,650	$1,750	$2,350	$3.500

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[5] Capital expenditure are the prices are based distributor price on vendor website accessed on 27 November 2017.

[6] Based on man-hour required for maintenance, maintenance frequency, and duration of maintenance, accumulatively in a year.

[7] Based on assumption that spare-part cost is approximately 10-11% of Capital expenditure.

[8] Training cost is assumed that the less immaturity of technology, it requires more budget on training. The price is for 1 module/person.

4.5. Developing Fuzzy Analytic Hierarchy Process

By evaluating the characteristic of each gas detector technology, the implementation of fuzzy AHP is to define selection based on benefit, cost and risk criteria analysis. All criteria for Benefit, Cost, and Risk is broken down into set of hierarchy structure.

4.5.1. Benefit Criteria

The analysis for benefit category is calculated based fuzzy pairwise comparison matrix. A fuzzy judgement matrix $\tilde{A}$ based on triangular fuzzy number (al, am, au) are developed which one of sub-criteria is more important to another. Firstly, to evaluate the benefit criteria using Fuzzy AHP, pairwise comparison matrix is performed based on Delphi Technique result on chapter 4.3.1. The pairwise comparison result is defined on Table 4.18.

Table 4.18. Pairwise comparison table for Benefit criteria

Sub-criteria	**Reliability and Precision**	**Delivering continuous concentration**	**Detection area coverage**	**Oxygen deficiency resistance**	**Response time**
Reliability and Precision	1	3	5	5	9
Delivering continuous concentration	0.3333	1	3	3	7
Detection area coverage	0.2000	0.3333	1	1	3
Oxygen deficiency resistance	0.1429	0.3333	1.0000	1	3
Response time	0.1111	0.2000	0.3333	0.3333	1

The pairwise table 4.18. is then converted into Triangular Fuzzy Number as stated on table 4.19.

Table 4.19. Converted pairwise comparison table into triangular fuzzy number for Benefit sub-criteria

Sub-criteria	Reliability and Precision	Delivering continuous concentration	Detection area coverage	Oxygen deficiency resistance	Response time
Reliability and Precision	1 ; 1 ; 1	1 ; 3 ; 5	3 ; 5 ; 7	3 ; 5 ; 7	7 ; 9 ; 9
Delivering continuous concentration	0.2 ; 0.33 ; 1	1 ; 1 ; 1	1 ; 3 ; 5	1 ; 3 ; 5	5 ; 7 ; 9
Detection area coverage	0.143 ; 0.2 ; 0.33	0.2 ; 0.33 ; 1	1 ; 1 ; 1	1 ; 1 ; 3	1 ; 3 ; 5
Oxygen deficiency resistance	0.111 ; 0.143 ; 0.2	0.2 ; 0.33 ; 1	0.333 ; 1 ; 1	1 ; 1 ; 1	1 ; 3 ; 5
Response time	0.111 ; 0.111 ; 0.143	0.143 ; 0.2 ; 0.333	0.2 ; 0.333 ; 1	0.2 ; 0.333 ; 1	1 ; 1 ; 1

Afterwards, the calculation of fuzzy weight is performed by applying geometric mean as stated in equation (19) and determine weight of fuzzy value by normalizing each criterion.

Table 4.20. The geometric mean value and normalized weight Wi

Sub-criteria	W_i	Normalized W_i
Reliability and Precision	2.2902; 3.6801; 4.6632	0.5222; 0.5096; 0.4424
Delivering continuous concentration	1.0000; 1.8384; 2.9542	0.2280; 0.2546; 0.2803
Detection area coverage	0.4911; 0.7248; 1.3797	0.1120 0.1004 0.1309
Oxygen deficiency resistance	0.3749; 0.6776; 1.0000	0.0855; 0.0938; 0.0949
Response time	0.2294; 0.3010; 0.5439	0.0523; 0.0417; 0.0516

To determine consistency of fuzzy comparison matrix, defuzzyfication process is performed by applying total integral value, in which α = 0.5 (moderate level of confidence). If the defuzzyfication matrix is compatible, then the fuzzy comparison matrix is consistence (Zheng 2012).

Table 4.21. Defuzzyfication matrix

Sub-criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**Wi**	**Normalized Wi**
Reliability and Precision	1.0000	3.0000	5.0000	5.0000	8.5000	3.5784	0.4959
Delivering continuous concentration	0.4667	1.0000	3.0000	3.0000	7.0000	1.9078	0.2543
Detection area coverage	0.2190	0.4667	1.0000	1.5000	3.0000	0.8301	0.1109
Oxygen deficiency resistance	0.1492	0.4667	0.8333	1.0000	3.0000	0.6825	0.0920
Response time	0.1190	0.2190	0.4667	0.4667	1.0000	0.3438	0.0468

The consistency analysis is performed by calculating consistency ratio as stated in equation (7) and (8). The result of CR is obtained as 0.0863 (< 0.1). It means that the matrix is consistence and applicable for analysis. The weight of each sub-criterion is represented by the number of Normalized *Wi*.

4.5.1.1. Alternatives Fuzzy AHP Computation for Benefit Criteria

The alternatives for each gas detector technology is evaluated based on the Benefit criteria. Baseline of the pairwise comparison is stated on table 4.12. Then, conversion from 5 scale scoring to the Saaty scale is performed as stated in table 4.11. The pairwise comparison for alternatives in terms of Benefit criteria is described on table 4.21-4.22.

1. Reliability and Precision

Table 4.21. Pairwise comparison alternatives for reliability and precision sub-criteria

1. Reliability and Precision				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	1.0000	0.3333	3.0000
OPGD	1.0000	1.0000	0.3333	3.0000
PGD	3.0000	3.0000	1.0000	5.0000
UGLD	0.3333	0.3333	0.2000	1.0000

Table 4.22. Fuzzy pairwise comparison and geometric mean values of alternatives for reliability and precision sub-criteria

Alternatives	CGD	OPGD	PGD	UGLD	Wi	Normalized Wi
CGD	1;1;1	1.000; 1.000; 3.000	0.2000; 0.3333; 1.0000	1.000; 3.000; 5.000	0.6687 1.0000 1.9680	0.2710; 0.2401; 0.2799
OPGD	0.333; 1.000; 1.000	1;1;1	0.2000; 0.3333; 1.0000	1.000; 3.000; 5.000	0.5081; 1.0000; 1.4953	0.2059; 0.2401; 0.2127
PGD	0.200; 0.333; 1.000	1.000; 3.000; 5.000	1;1;1	3.000; 5.000; 7.000	0.8801; 1.4953; 2.4323	0.3566; 0.3591; 0.3459
UGLD	0.200; 0.333; 1.000	1.000; 3.000; 5.000	0.143; 0.200; 0.333	1;1;1	0.4111; 0.6687; 1.1362	0.1666; 0.1606; 0.1616

Table 4.23. Defuzzification matrix and CR value indicating consistency of the matrix

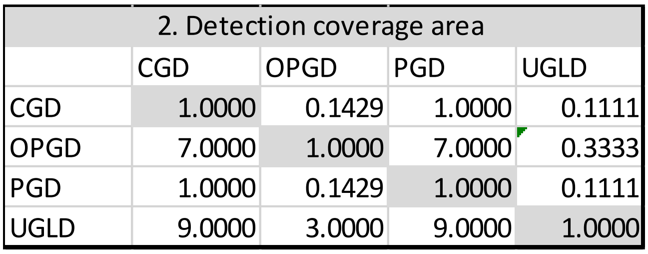
	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	1.5000	0.4667	3.0000	0.2578
OPGD	0.6667	1.0000	0.4667	3.0000	0.2247
PGD	2.1429	2.1429	1.0000	5.0000	0.3552
UGLD	0.3333	0.3333	0.2000	1.0000	0.1623

Eigen	CR
4.0399	**0.0148**

The result of CR = 0.0522 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

2. Detection coverage area

Table 4.24. Pairwise comparison alternatives for detection coverage area sub-criteria

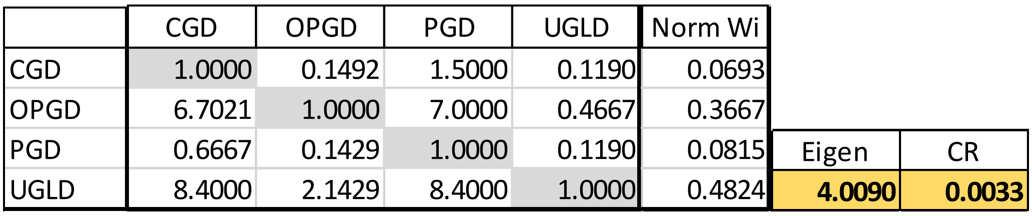


2. Detection coverage area				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.1429	1.0000	0.1111
OPGD	7.0000	1.0000	7.0000	0.3333
PGD	1.0000	0.1429	1.0000	0.1111
UGLD	9.0000	3.0000	9.0000	1.0000

Table 4.25. Fuzzy pairwise comparison and geometric mean values of alternatives for detection coverage area sub-criteria

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.1111; 0.1429; 0.2000	1.0000; 1.0000; 3.0000	0.1111; 0.1111; 0.1429	0.3333; 0.3549; 0.5411	0.0799; 0.0609; 0.0756
OPGD	5.000; 7.000; 9.000	1;1;1	5.000; 7.000; 9.000	0.2000; 0.3333; 1.0000	1.4953; 2.0103; 3.0000	0.3584; 0.3447; 0.4192
PGD	1.000; 3.000; 5.000	0.111; 0.143; 0.200	1;1;1	0.1111; 0.1111; 0.1429	0.3333; 0.4671; 0.6148	0.0799; 0.0801; 0.0859
UGLD	7.000; 9.000; 9.000	0.333; 1.000; 1.000	7.000; 9.000; 9.000	1;1;1	2.0103; 3.0000; 3.0000	0.4818; 0.5144; 0.4192

Table 4.26. Defuzzification matrix and CR value indicating consistency of the matrix



	CGD	OPGD	PGD	UGLD	Norm Wi		
CGD	1.0000	0.1492	1.5000	0.1190	0.0693		
OPGD	6.7021	1.0000	7.0000	0.4667	0.3667		
PGD	0.6667	0.1429	1.0000	0.1190	0.0815	Eigen	CR
UGLD	8.4000	2.1429	8.4000	1.0000	0.4824	**4.0090**	**0.0033**

The result of CR = 0.0033 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

3. Delivering continuous concentration monitoring

Table 4.27. Pairwise comparison alternatives for delivering continuous concentration monitoring

3. Delivering continuous concentration monitoring				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	3.0000	0.2000	5.0000
OPGD	0.3333	1.0000	0.2000	3.0000
PGD	5.0000	5.0000	1.0000	9.0000
UGLD	0.2000	0.3333	0.1111	1.0000

Table 4.28. Fuzzy pairwise comparison and geometric mean values of alternatives for delivering continuous concentration monitoring

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	1.0000; 3.0000; 5.0000	0.1429; 0.2000; 0.3333	3.0000; 5.0000; 7.0000	0.8091; 1.3161; 1.8481	0.2594; 0.2905; 0.2817
OPGD	0.200; 0.333; 1.000	1;1;1	0.1429; 0.2000; 0.3333	1.0000; 3.0000; 5.0000	0.4111; 0.6687; 1.1362	0.1318; 0.1476; 0.1732
PGD	0.200; 0.333; 1.000	3.000; 5.000; 7.000	1;1;1	7.0000; 9.0000; 9.0000	1.4316; 1.9680; 2.8173	0.4590; 0.4344; 0.4294
UGLD	0.143; 0.200; 0.333	3.000; 5.000; 7.000	0.111; 0.111; 0.143	1;1;1	0.4671; 0.5774; 0.7598	0.1498; 0.1274; 0.1158

Table 4.29. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi		
CGD	1.0000	3.0000	0.2190	5.0000	0.2805		
OPGD	0.3333	1.0000	0.2190	3.0000	0.1501		
PGD	4.5652	4.5652	1.0000	8.5000	0.4393	Eigen	CR
UGLD	0.2000	0.3333	0.1176	1.0000	0.1301	**4.2087**	**0.0773**

The result of CR = 0.0773 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

4. Oxygen deficiency resistance

Table 4.30. Pairwise comparison alternatives for oxygen deficiency resistance

4. Oxygen deficiency resistance				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.1429	0.1111	0.1111
OPGD	7.0000	1.0000	0.3333	0.2000
PGD	9.0000	3.0000	1.0000	1.0000
UGLD	9.0000	5.0000	1.0000	1.0000

Table 4.31. Fuzzy pairwise comparison and geometric mean values of alternatives for delivering oxygen deficiency resistance

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.1111; 0.1429; 0.2000	0.1111; 0.1111; 0.1429	0.1111; 0.1111; 0.1429	0.1925; 0.2049; 0.2528	0.0466; 0.0342; 0.0325
OPGD	5.000; 7.000; 9.000	1;1;1	0.2000; 0.3333; 1.0000	0.1429; 0.2000; 0.3333	0.6148; 0.8265; 1.3161	0.1487; 0.1378; 0.1694
PGD	3.000; 5.000; 7.000	1.000; 3.000; 5.000	1;1;1	1.000; 1.000; 3.000	1.3161; 1.9680; 3.2011	0.3184; 0.3280; 0.4120
UGLD	7.000; 9.000; 9.000	7.000; 9.000; 9.000	0.333; 1.000; 1.000	1;1;1	2.0103; 3.0000; 3.0000	0.4863; 0.5000; 0.3861

Table 4.32. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi		
CGD	1.0000	0.1492	0.1190	0.1190	0.0369		
OPGD	6.7021	1.0000	0.4667	0.2190	0.1484		
PGD	8.4000	2.1429	1.0000	1.5000	0.3466	Eigen	CR
UGLD	8.4000	4.5652	0.6667	1.0000	0.4681	**4.0947**	**0.0351**

The result of CR = 0.0351 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

5. Response time

Table 4.33. Pairwise comparison alternatives for response time

5. Response time				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.3333	0.3333	7.0000
OPGD	3.0000	1.0000	1.0000	9.0000
PGD	3.0000	1.0000	1.0000	7.0000
UGLD	0.1429	0.1111	0.1429	1.0000

Table 4.34. Fuzzy pairwise comparison and geometric mean values of alternatives for response time

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.200; 0.333; 1.000	0.200; 0.333; 1.000	5.000; 7.000; 9.000	0.6687; 0.9391; 1.7321	0.2036; 0.2017; 0.2520
OPGD	1.000; 3.000; 5.000	1;1;1	1.000; 1.000; 3.000	7.000; 9.000; 9.000	1.6266; 2.2795; 3.4087	0.4952; 0.4897; 0.4959
PGD	0.111; 0.111; 0.143	0.333; 1.000; 1.000	1;1;1	5.000; 7.000; 9.000	0.6560; 0.9391; 1.0648	0.1997; 0.2017; 0.1549
UGLD	0.111; 0.143; 0.200	1.000; 3.000; 5.000	0.143; 0.200; 0.333	1;1;1	0.3333; 0.4974; 0.6687	0.1015; 0.1069; 0.0973

Table 4.35. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	0.4667	0.4667	7.0000	0.2148
OPGD	2.1429	1.0000	1.5000	8.5000	0.4926
PGD	2.1429	0.6667	1.0000	7.0000	0.1895
UGLD	0.1429	0.1176	0.1429	1.0000	0.1031

Eigen	CR
4.0572	**0.0212**

The result of CR = 0.0212 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable. The final value for each alternative in benefit criteria is described by applying Fuzzy sequencing layer multiplication.

Table 4.36. Fuzzy weight calculation for Benefit alternatives

Criteria	**Sub-criteria**	**Alternatives**
Benefit	Reliability and precision 0.5222 ; 0.5096 ; 0.4424	CGD: 0.2710 0.2401 0.2799 OPGD: 0.2059 0.2401 0.2127 PGD: 0.3566 0.3591 0.3459 UGLD: 0.1666 0.1606 0.1616
	Detection area coverage 0.2280 ; 0.2546 ; 0.2803	CGD: 0.0799 0.0609 0.0756 OPGD: 0.3584 0.3447 0.4192 PGD: 0.0799 0.0801 0.0859 UGLD: 0.4818 0.5144 0.4192
	Delivering continuous concentration monitoring 0.1120 ; 0.1004 ; 0.1309	CGD: 0.2594 0.2905 0.2817 OPGD: 0.1318 0.1476 0.1732 PGD: 0.4590 0.4344 0.4294 UGLD: 0.1498 0.1274 0.1158
	Oxygen deficiency resistance 0.0855 ; 0.0938 ; 0.0949	CGD: 0.0466 0.0342 0.0325 OPGD: 0.1487 0.1378 0.1694 PGD: 0.3184 0.3280 0.4120 UGLD: 0.4863 0.5000 0.3861
	Response time 0.0523 ; 0.0417 ; 0.0516	CGD: 0.2036 0.2017 0.2520 OPGD: 0.4952 0.4897 0.4959 PGD: 0.1997 0.2017 0.1549 UGLD: 0.1015 0.1069 0.0973

Table 4.37. The final value for each alternative in benefit criteria

Alternatives	**Final Fuzzy weight**	**Final Defuzzified weight**
Catalytic gas detector (CGD)	0.1927 0.1702 0.1850	**0.1795**
Open-path gas detector(OPGD)	0.2167 0.2379 0.2503	**0.2357**
Point-type infrared gas detector (PGD)	0.2830 0.2778 0.2724	**0.2777**
Ultrasonic gas leak detector (UGLD)	0.2552 0.2725 0.2408	**0.2602**

4.5.2. Cost Criteria

The next step is to develop similar Fuzzy AHP technique for the Cost criteria. The development is described in Table 4.38 – 4.41

Table 4.38. Pairwise comparison table for Cost criteria

Sub-criteria	Capital expenditure of the technology	Preventive maintenance cost	Breakdown maintenance cost	Training and development cost
Capital expenditure of the technology	1	3	5	7
Preventive maintenance cost	0.3333	1	1	3
Breakdown maintenance cost	0.2000	1.0000	1	1
Training and development cost	0.1429	0.3333	1.0000	1

Table 4.39. Converted pairwise comparison table into triangular fuzzy number for cost criteria

Sub-criteria	Capital expenditure of the technology	Preventive maintenance cost	Breakdown maintenance cost	Training and development cost
Capital expenditure of the technology	1 ; 1 ; 1	1 ; 3 ; 5	3 ; 5 ; 7	5 ; 7 ; 9
Preventive maintenance cost	0.2 ; 0.333 ; 1	1 ; 1 ; 1	1 ; 1 ; 3	1 ; 3 ; 5
Breakdown maintenance cost	0.2 ; 0.333 ; 1	0.333 ; 1 ; 1	1 ; 1 ; 1	1 ; 1 ; 3
Training and development cost	0.111 ; 0.143 ; 0.2	0.143 ; 0.2 ; 0.333	0.333 ; 1 ; 1	1 ; 1 ; 1

Table 4.40. The geometric mean values and normalized weight Wi

Sub-criteria	W_i	Normalized W_i
Capital expenditure of the technology	1.9680 3.2011 4.2129	0.5764 0.5959 0.5263
Preventive maintenance cost	0.6687 1.0000 1.9680	0.1958 0.1861 0.2458
Breakdown maintenance cost	0.5081 0.7598 1.3161	0.1488 0.1414 0.1644
Training and development cost	0.2697 0.4111 0.5081	0.0790 0.0765 0.0635

Table 4.41. Defuzzyfication matrix

Sub-criteria	C1	C2	C3	C4	Wi	Normalized Wi
Capital expenditure of the technology	1.0000	3.0000	5.0000	7.0000	3.1458	0.5736
Preventive maintenance cost	0.4667	1.0000	1.5000	3.0000	1.1592	0.2035
Breakdown maintenance cost	0.4667	0.8333	1.0000	1.5000	0.8360	0.1490
Training and development cost	0.1492	0.2190	0.8333	1.0000	0.4000	0.0739

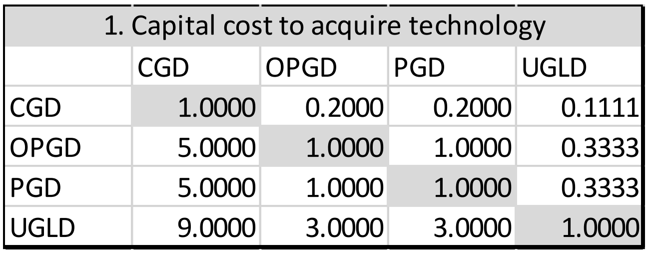
The calculation of consistency ratio obtained is 0.0981 (< 0.1). By the result, it is confirmed that the matrix is consistence and applicable for analysis.

4.5.2.1. Alternatives Fuzzy AHP Computation for Cost criteria

The alternatives for cost criteria is evaluated based on conversion from different amount of money spent by the company for an alternative to another alternative. The pairwise comparison matrix and Fuzzy AHP calculation is described on table 4.42 – 4.44.

1. Capital expenditure of the technology

Table 4.42. Pairwise comparison alternatives in terms of Capital expenditure of the technology



1. Capital cost to acquire technology

	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.2000	0.2000	0.1111
OPGD	5.0000	1.0000	1.0000	0.3333
PGD	5.0000	1.0000	1.0000	0.3333
UGLD	9.0000	3.0000	3.0000	1.0000

Table 4.43. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of Capital expenditure of the technology

Alternatives	CGD	OPGD	PGD	UGLD	Wi	Normalized Wi
CGD	1;1;1	0.1429; 0.2000; 0.3333	0.1429; 0.2000; 0.3333	0.1111; 0.1111; 0.1429	0.2182; 0.2582; 0.3549	0.0582; 0.0445; 0.0433
OPGD	3.000; 5.000; 7.000	1;1;1	1.000; 1.000; 3.000	0.2000; 0.3333; 1.0000	0.8801; 1.1362; 2.1407	0.2349; 0.1958; 0.2609
PGD	1.000; 3.000; 5.000	0.333; 1.000; 1.000	1;1;1	0.2000; 0.3333; 1.0000	0.5081; 1.0000; 1.4953	0.1356; 0.1723; 0.1823
UGLD	7.000; 9.000; 9.000	3.000; 5.000; 7.000	1.000; 3.000; 5.000	1;1;1	2.1407; 3.4087; 4.2129	0.5713; 0.5874; 0.5135

Table 4.44. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	0.2190	0.2190	0.1190	0.0476
OPGD	4.5652	1.0000	1.5000	0.4667	0.2219
PGD	4.5652	0.6667	1.0000	0.4667	0.1656
UGLD	8.4000	2.1429	2.1429	1.0000	0.5649

Eigen	CR
4.1945	**0.0720**

The result of CR = 0.0720 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

2. Preventive maintenance cost

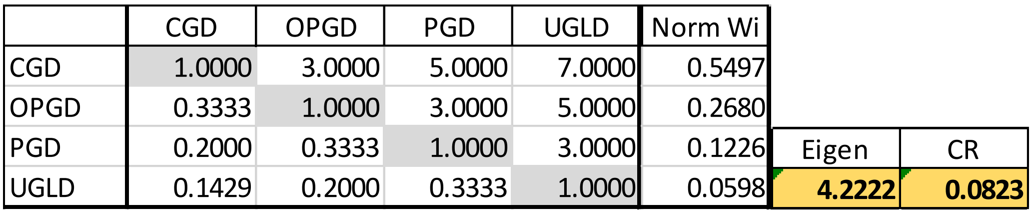
Table 4.45. Pairwise comparison alternatives in terms of preventive maintenance cost

2. Preventive maintenance				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	3.0000	5.0000	7.0000
OPGD	0.3333	1.0000	3.0000	5.0000
PGD	0.2000	0.3333	1.0000	3.0000
UGLD	0.1429	0.2000	0.3333	1.0000

Table 4.46. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of preventive maintenance cost

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	1.000; 3.000; 5.000	3.000; 5.000; 7.000	3.000; 5.000; 7.000	0.2182; 0.2582; 0.3549	0.0582; 0.0445; 0.0433
OPGD	0.2000; 0.3333; 1.0000	1;1;1	1.000; 1.000; 3.000	1.000; 3.000; 5.000	0.8801; 1.1362; 2.1407	0.2349; 0.1958; 0.2609
PGD	0.1429; 0.2000; 0.3333	0.2000; 0.3333; 1.0000	1;1;1	1.000; 3.000; 5.000	0.5081; 1.0000; 1.4953	0.1356; 0.1723; 0.1823
UGLD	0.111; 0.143; 0.200	3.000; 5.000; 7.000	0.143; 0.200; 0.333	1;1;1	2.1407; 3.4087; 4.2129	0.5713; 0.5874; 0.5135

Table 4.47. Defuzzification matrix and CR value indicating consistency of the matrix



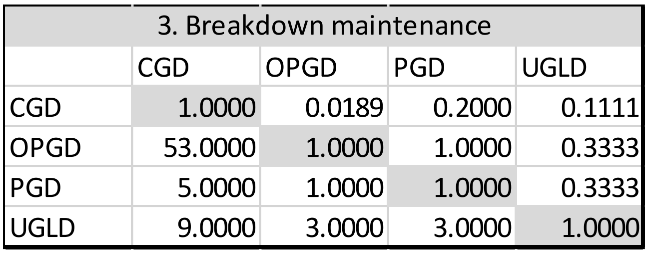
	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	3.0000	5.0000	7.0000	0.5497
OPGD	0.3333	1.0000	3.0000	5.0000	0.2680
PGD	0.2000	0.3333	1.0000	3.0000	0.1226
UGLD	0.1429	0.2000	0.3333	1.0000	0.0598

Eigen	CR
4.2222	**0.0823**

The result of CR = 0.0823 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

3. Breakdown maintenance

Table 4.48. Pairwise comparison alternatives in terms of breakdown maintenance cost



3. Breakdown maintenance				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.0189	0.2000	0.1111
OPGD	53.0000	1.0000	1.0000	0.3333
PGD	5.0000	1.0000	1.0000	0.3333
UGLD	9.0000	3.0000	3.0000	1.0000

Table 4.49. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of breakdown maintenance cost

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.2000; 0.3333; 1.0000	0.1429; 0.2000; 0.3333	0.1111; 0.1111; 0.1429	0.2182; 0.2582; 0.3549	0.0582; 0.0445; 0.0433
OPGD	3.000; 5.000; 7.000	1;1;1	1.000; 1.000; 3.000	0.2000; 0.3333; 1.0000	0.8801; 1.1362; 2.1407	0.2349; 0.1958; 0.2609
PGD	1.000; 3.000; 5.000	0.333; 1.000; 1.000	1;1;1	0.2000; 0.3333; 1.0000	0.5081; 1.0000; 1.4953	0.1356; 0.1723; 0.1823
UGLD	7.000; 9.000; 9.000	3.000; 5.000; 7.000	1.000; 3.000; 5.000	1;1;1	2.1407; 3.4087; 4.2129	0.5713; 0.5874; 0.5135

Table 4.50. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi		
CGD	1.0000	0.4667	0.2190	0.1190	0.0568		
OPGD	2.1429	1.0000	1.5000	0.4667	0.1951		
PGD	4.5652	0.6667	1.0000	0.4667	0.1693	Eigen	CR
UGLD	8.4000	2.1429	2.1429	1.0000	0.5788	**4.0794**	**0.0294**

The result of CR = 0.0294 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

4. Training and development cost

Table 4.51. Pairwise comparison alternatives in terms of training and development cost

4. Training and development cost				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.2000	0.3333	0.1111
OPGD	5.0000	1.0000	1.0000	0.3333
PGD	3.0000	1.0000	1.0000	0.3333
UGLD	9.0000	3.0000	3.0000	1.0000

Table 4.52. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of training and development cost

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.1429; 0.2000; 0.3333	0.2000; 0.3333; 1.0000	0.1111; 0.1111; 0.1429	0.2182; 0.2582; 0.3549	0.0582; 0.0445; 0.0433
OPGD	3.000; 5.000; 7.000	1;1;1	1.000; 1.000; 3.000	0.2000; 0.3333; 1.0000	0.8801; 1.1362; 2.1407	0.2349; 0.1958; 0.2609
PGD	1.000; 3.000; 5.000	0.333; 1.000; 1.000	1;1;1	0.2000; 0.3333; 1.0000	0.5081; 1.0000; 1.4953	0.1356; 0.1723; 0.1823
UGLD	7.000; 9.000; 9.000	3.000; 5.000; 7.000	1.000; 3.000; 5.000	1;1;1	2.1407; 3.4087; 4.2129	0.5713; 0.5874; 0.5135

Table 4.53. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi		
CGD	1.0000	0.2190	0.4667	0.1190	0.0599		
OPGD	4.5652	1.0000	1.5000	0.4667	0.2394		
PGD	2.1429	0.6667	1.0000	0.4667	0.1780	Eigen	CR
UGLD	8.4000	2.1429	2.1429	1.0000	0.5227	**4.0123**	**0.0046**

The result of CR = 0.0046 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

Table 4.54. Fuzzy weight calculation for alternatives in cost criteria

Criteria	**Sub-criteria**	**Alternatives**
Benefit	Capital expenditure of the technology 0.5764 0.5959 0.5263	CGD: 0.0582 0.0445 0.0433 OPGD: 0.2349 0.1958 0.2609 PGD: 0.1356 0.1723 0.1823 UGLD: 0.5713 0.5874 0.5135
	Preventive maintenance cost 0.1958 0.1861 0.2458	CGD: 0.5628 0.5638 0.5082 OPGD: 0.2517 0.2634 0.2934 PGD: 0.1176 0.1178 0.1371 UGLD: 0.0679 0.0550 0.0613
	Breakdown maintenance 0.1488 0.1414 0.1644	CGD: 0.0668 0.0515 0.0574 OPGD: 0.1881 0.1754 0.2417 PGD: 0.1429 0.1754 0.1836 UGLD: 0.6022 0.5978 0.5173
	Training and development cost 0.0790 0.0765 0.0635	CGD: 0.0730 0.0540 0.0586 OPGD: 0.2706 0.2093 0.2684 PGD: 0.1562 0.1842 0.1875 UGLD: 0.5001 0.5525 0.4856

Table 4.55. The final value for each alternative in cost criteria

Alternatives	**Final Fuzzy weight**	**Final Defuzzified weight**
Catalytic gas detector (CGD)	0.1595 0.1429 0.1609	**0.1515**
Open-path gas detector(OPGD)	0.2340 0.2065 0.2662	**0.2283**
Point-type infrared gas detector (PGD)	0.1348 0.1635 0.1717	**0.1584**
Ultrasonic gas leak detector (UGLD)	0.4717 0.4871 0.4012	**0.4618**

4.5.3. Risk Criteria

Lastly similar approach is applicable for Risk criteria. The development is described in Table 4.56 – 4.59.

Table 4.56. Pairwise comparison table for Risk criteria

Sub-criteria	Spurious detection	Probability of failure on demand	Sensor poisoning	Environment distractive signal	Immaturity of technology
Spurious detection	1	3	5	7	9
Probability of failure on demand	0.3333	1	3	5	7
Sensor poisoning	0.2000	0.3333	1	3	3
Environment distractive signal	0.1429	0.2000	0.3333	1	1
Immaturity of technology	0.1111	0.1429	0.3333	1.0000	1

Table 4.57. Converted pairwise comparison table into triangular fuzzy number for Risk criteria

Sub-criteria	Reliability and Precision	Delivering continuous concentration	Detection area coverage	Oxygen deficiency resistance	Response time
Spurious detection	1 ; 1 ; 1	1 ; 3 ; 5	3 ; 5 ; 7	5 ; 7 ; 9	7 ; 9 ; 9
Probability of failure on demand	0.2 ; 0.333 ; 1	1 ; 1 ; 1	1 ; 3 ; 5	3 ; 5 ; 7	5 ; 7 ; 9
Sensor poisoning	0.143 ; 0.2 ; 333	0.2 ; 0.333 ; 1	1 ; 1 ; 1	1 ; 3 ; 5	1 ; 3 ; 5
Environment distractive signal	0.111 ; 0.143 ; 0.2	0.111 ; 0.143 ; 0.2	0.2 ; 0.333 ; 1	1 ; 1 ; 1	1 ; 1 ; 3
Immaturity of technology	0.111 ; 0.111 ; 0.143 ;	0.111 ; 0.143 ; 0.2	0.2 ; 0.333 ; 1	0.333 ; 1 ; 1	1 ; 1 ; 1

Table 4.58. The geometric mean values and normalized weight Wi

Sub-criteria	W_i	Normalized W_i
Spurious detection	2.5365 3.9363 4.9036	0.5250 0.5166 0.4537
Probability of failure on demand	1.2457 2.0362 3.1598	0.2578 0.2672 0.2924
Sensor poisoning	0.4911 0.9029 1.5281	0.1017 0.1185 0.1414
Environment distractive signal	0.3165 0.3942 0.7248	0.0655 0.0517 0.0671
Immaturity of technology	0.2416 0.3505 0.4911	0.0500 0.0460 0.0454

Table 4.59. Defuzzyfication matrix

Sub-criteria	C1	C2	C3	C4	C5	Wi	Normalized Wi
Spurious detection	1.0000	3.0000	5.0000	7.0000	8.5000	3.8282	0.5030
Probability of failure on demand	0.4667	1.0000	3.0000	5.0000	7.0000	2.1195	0.2712
Sensor poisoning	0.2190	0.4667	1.0000	3.0000	3.0000	0.9563	0.1200
Environment distractive signal	0.1492	0.2190	0.4667	1.0000	1.5000	0.4574	0.0590
Immaturity of technology	0.1190	0.1492	0.4667	0.8333	1.0000	0.3584	0.0469

The calculation of consistency ratio obtained is 0.0945 (< 0.1). By the result, it is confirmed that the matrix is consistence and applicable for analysis.

4.5.3.1. Alternatives Fuzzy AHP Computation for Risk Criteria

Similar technique is applied for alternatives in terms of risk criteria. As qualitative criteria, Fuzzy AHP computation for risk criteria is similar with benefit criteria.

1. Spurious detection

Table 4.60. Pairwise comparison alternatives in terms of spurious detection

1. Spurious detection				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.3333	3.0000	0.2000
OPGD	3.0000	1.0000	5.0000	0.3333
PGD	0.3333	0.2000	1.0000	0.1111
UGLD	5.0000	3.0000	9.0000	1.0000

Table 4.61. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of spurious detection

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.200; 0.333; 1.000	1.000; 3.000; 5.000	0.143; 0.2000; 0.333	0.4111; 0.6687; 1.1362	0.1336; 0.1441; 0.1604
OPGD	1.000; 3.000; 5.000	1;1;1	3.000; 5.000; 7.000	0.200; 0.3333; 1.000	0.8801; 1.4953; 2.4323	0.2860; 0.3223; 0.3433
PGD	1.000; 3.000; 5.000	0.143; 0.200; 0.333	1;1;1	0.111; 0.1111; 0.143	0.3549; 0.5081; 0.6985	0.1153; 0.1095; 0.0986
UGLD	3.000; 5.000; 7.000	0.200; 0.333; 1.000	7.000; 7.000; 9.000	1;1;1	1.4316; 1.9680; 2.8173	0.4651; 0.4241; 0.3977

Table 4.62. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	0.4667	3.0000	0.2190	0.1456
OPGD	2.1429	1.0000	5.0000	0.4667	0.3185
PGD	0.3333	0.2000	1.0000	0.1190	0.1082
UGLD	4.5652	2.1429	8.4000	1.0000	0.4278

Eigen	CR
4.0121	**0.0045**

The result of CR = 0.0045 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

2. Probability of failure on demand

Table 4.63. Pairwise comparison alternatives in terms of probability of failure on demand

2. Probability of failure on demand				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.2000	3.0000	0.2000
OPGD	5.0000	1.0000	7.0000	1.0000
PGD	0.3333	0.1429	1.0000	0.1429
UGLD	5.0000	1.0000	7.0000	1.0000

Table 4.64. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of probability of failure on demand

Alternatives	CGD	OPGD	PGD	UGLD	Wi	Normalized Wi
CGD	1;1;1	0.1429; 0.2000; 0.3333	1.000; 3.000; 5.000	0.1429; 0.2000; 0.3333	0.3780; 0.5886; 0.8633	0.0965; 0.1122; 0.1102
OPGD	3.000; 5.000; 7.000	1;1;1	5.000; 7.000; 9.000	1.0000; 1.0000; 3.0000	1.9680; 2.4323; 3.7078	0.5026; 0.4636; 0.4732
PGD	0.333; 1.000; 1.000	0.111; 0.143; 0.200	1;1;1	0.1111; 0.1429; 0.2000	0.2533; 0.3780; 0.4472	0.0647; 0.0720; 0.0571
UGLD	3.000; 5.000; 7.000	0.200; 0.333; 1.000	5.000; 7.000; 9.000	1;1;1	1.3161; 1.8481; 2.8173	0.3361; 0.3522; 0.3596

Table 4.65. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	0.2190	3.0000	0.2190	0.1078
OPGD	4.5652	1.0000	7.0000	1.5000	0.4757
PGD	0.3333	0.1429	1.0000	0.1492	0.0665
UGLD	4.5652	0.6667	6.7021	1.0000	0.3500

Eigen	CR
4.0351	**0.0130**

The result of CR = 0.0130 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

3. Sensor poisoning

Table 4.66. Pairwise comparison alternatives in terms of sensor poisoning

3. Sensor poisoning				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	5.0000	9.0000	3.0000
OPGD	0.2000	1.0000	3.0000	0.3333
PGD	0.1111	0.3333	1.0000	0.1429
UGLD	0.3333	3.0000	7.0000	1.0000

Table 4.67. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of probability of sensor poisoning

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	3.0000; 5.0000; 7.0000	7.000; 9.000; 9.000	1.000; 3.000; 5.000	2.1407; 3.4087; 4.2129	0.6090; 0.6306; 0.5682
OPGD	0.143; 0.200; 0.333	1;1;1	1.000; 3.000; 5.000	0.2000; 0.3333; 1.0000	0.4111; 0.6687; 1.1362	0.1170; 0.1237; 0.1533
PGD	1.000; 3.000; 5.000	0.200; 0.333; 1.000	1;1;1	0.1111; 0.1429; 0.2000	0.3861; 0.6148; 1.0000	0.1098; 0.1137; 0.1349
UGLD	0.200; 0.333; 1.000	0.111; 0.111; 0.143	5.000; 7.000; 9.000	1;1;1	0.5774; 0.7136; 1.0648	0.1642; 0.1320; 0.1436

Table 4.68. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi		
CGD	1.0000	5.0000	8.5000	3.0000	0.6096		
OPGD	0.2000	1.0000	3.0000	0.4667	0.1294		
PGD	0.1176	0.3333	1.0000	0.1492	0.1180	Eigen	CR
UGLD	0.3333	2.1429	6.7021	1.0000	0.1430	**4.1470**	**0.0544**

The result of CR = 0.0544 (<0.1) is confirms that the matrix is consistence. Therefore, the analysis is applicable.

4. Environment distractive signal

Table 4.69. Pairwise comparison alternatives in terms of environment distractive signal

4. Environment distractive signal				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.3333	3.0000	0.2000
OPGD	3.0000	1.0000	5.0000	0.3333
PGD	0.3333	0.2000	1.0000	0.1429
UGLD	5.0000	3.0000	7.0000	1.0000

Table 4.70. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of environment distractive signal

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.2000; 0.3333; 1.0000	1.000; 3.000; 5.000	0.1429; 0.2000; 0.3333	0.4111; 0.6687; 1.1362	0.1388; 0.1469; 0.1590
OPGD	1.000; 3.000; 5.000	1;1;1	3.0000; 5.0000; 7.0000	0.2000; 0.3333; 1.0000	0.8801; 1.4953; 2.4323	0.2971; 0.3284; 0.3404
PGD	1.000; 3.000; 5.000	0.143; 0.200; 0.333	1;1;1	0.1111; 0.1429; 0.2000	0.3549; 0.5411; 0.7598	0.1198; 0.1188; 0.1063
UGLD	3.0000; 5.0000; 7.0000	0.200; 0.333; 1.000	5.000; 7.000; 9.000	1;1;1	1.3161; 1.8481; 2.8173	0.4443; 0.4059; 0.3943

Table 4.71. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Norm Wi
CGD	1.0000	0.4667	3.0000	0.2190	0.1479
OPGD	2.1429	1.0000	5.0000	0.4667	0.3236
PGD	0.3333	0.2000	1.0000	0.1492	0.1160
UGLD	4.5652	2.1429	6.7021	1.0000	0.4126

Eigen	CR
4.0351	**0.0130**

The result of CR = 0.0130 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

5. Immaturity technology

Table 4.72. Pairwise comparison alternatives in terms of immaturity technology

5. Immaturity of technology				
	CGD	OPGD	PGD	UGLD
CGD	1.0000	0.1429	0.3333	0.1111
OPGD	7.0000	1.0000	5.0000	0.3333
PGD	3.0000	0.2000	1.0000	0.1429
UGLD	9.0000	3.0000	7.0000	1.0000

Table 4.73. Fuzzy pairwise comparison and geometric mean values of alternatives in terms of immaturity technology

Alternatives	**CGD**	**OPGD**	**PGD**	**UGLD**	**Wi**	**Normalized Wi**
CGD	1;1;1	0.1111; 0.1429; 0.2000	0.2000; 0.3333; 1.0000	0.1111; 0.1111; 0.1429	0.2229; 0.2697; 0.4111	0.0515; 0.0424; 0.0485
OPGD	5.000; 7.000; 9.000	1;1;1	3.000; 5.000; 7.000	0.2000; 0.3333; 1.0000	1.3161; 1.8481; 2.8173	0.3042; 0.2903; 0.3325
PGD	1.000; 3.000; 5.000	0.143; 0.200; 0.333	1;1;1	0.1111; 0.1429; 0.2000	0.3549; 0.5411; 0.7598	0.0820; 0.0850; 0.0897
UGLD	7.000; 9.000; 9.000	1.000; 3.000; 5.000	5.000; 7.000; 9.000	1;1;1	2.4323; 3.7078; 4.4860	0.5622; 0.5824; 0.5294

Table 4.74. Defuzzification matrix and CR value indicating consistency of the matrix

	CGD	OPGD	PGD	UGLD	Wi		
CGD	1.0000	0.1492	0.4667	0.1190	0.2934		
OPGD	6.7021	1.0000	5.0000	0.4667	1.9574		
PGD	2.1429	0.2000	1.0000	0.1492	0.5492	Eigen	CR
UGLD	8.4000	2.1429	6.7021	1.0000	3.5835	**4.0185**	**0.0068**

The result of CR = 0.0068 (<0.1) confirms that the matrix is consistence. Therefore, the analysis is applicable.

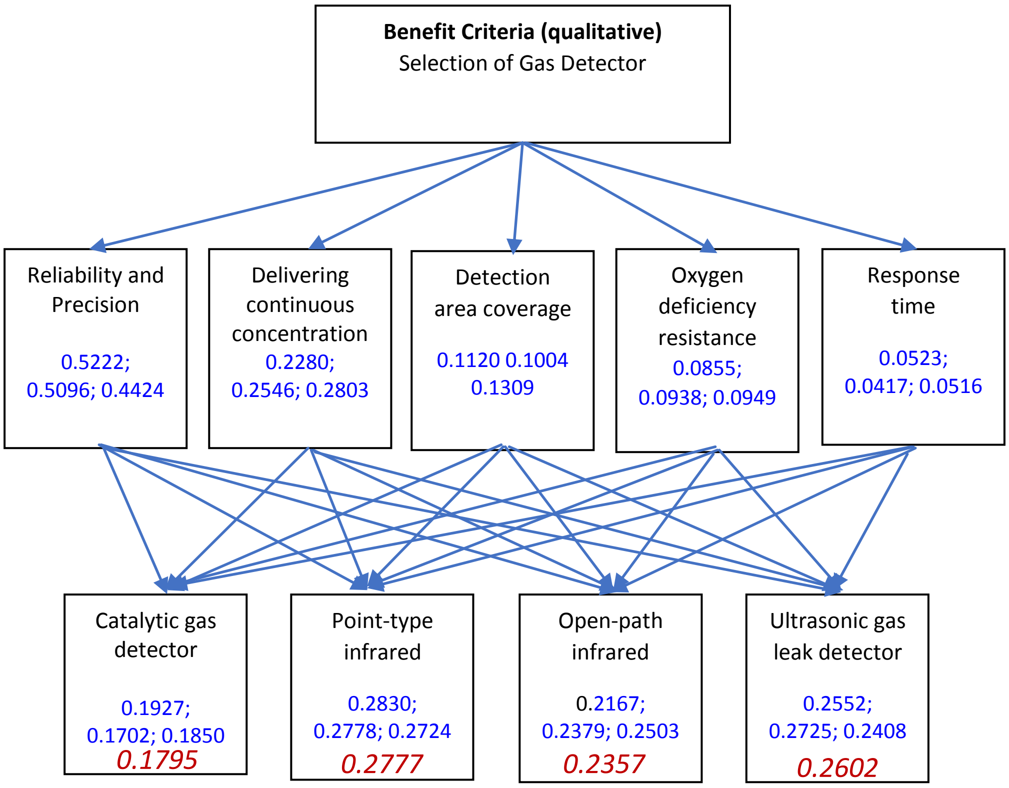
Table 4.75. Fuzzy weight calculation for Risk alternatives

Criteria	**Sub-criteria**	**Alternatives**
Risk	Spurious detection 0.5250 0.5166 0.4537	CGD: 0.1336 0.1441 0.1604 OPGD: 0.2860 0.3223 0.3433 PGD: 0.1153 0.1095 0.0986 UGLD: 0.4651 0.4241 0.3977
	Probability of failure on demand 0.2578 0.2672 0.2924	CGD: 0.0965 0.1122 0.1102 OPGD: 0.5026 0.4636 0.4732 PGD: 0.0647 0.0720 0.0571 UGLD: 0.3361 0.3522 0.3596
	Sensor poisoning 0.1017 0.1185 0.1414	CGD: 0.6090 0.6306 0.5682 OPGD: 0.1170 0.1237 0.1533 PGD: 0.1098 0.1137 0.1349 UGLD: 0.1642 0.1320 0.1436
	Environment distractive signal 0.0655 0.0517 0.0671	CGD: 0.1388 0.1469 0.1590 OPGD: 0.2971 0.3284 0.3404 PGD: 0.1198 0.1188 0.1063 UGLD: 0.4443 0.4059 0.3943
	Immaturity of technology 0.0500 0.0460 0.0454	CGD: 0.0515 0.0424 0.0485 OPGD: 0.3042 0.2903 0.3325 PGD: 0.0820 0.0850 0.0897 UGLD: 0.5622 0.5824 0.5294

Table 4.76. The final value for each alternative in risk criteria

Alternatives	**Final Fuzzy weight**	**Final Defuzzified weight**
Catalytic gas detector (CGD)	0.1660 0.1867 0.1960	**0.1839**
Open-path gas detector(OPGD)	0.3111 0.3220 0.3386	**0.3234**
Point-type infrared gas detector (PGD)	0.0962 0.0954 0.0876	**0.0937**
Ultrasonic gas leak detector (UGLD)	0.3767 0.3498 0.3323	**0.3522**

The calculation of fuzzy AHP for each sub-criterion and alternatives is presented in this chapter. The final calculation is summarized in the figure 4.5. which describes the whole value number in the fuzzy analysis. All value in the previous calculation is listed on figure 4.5.



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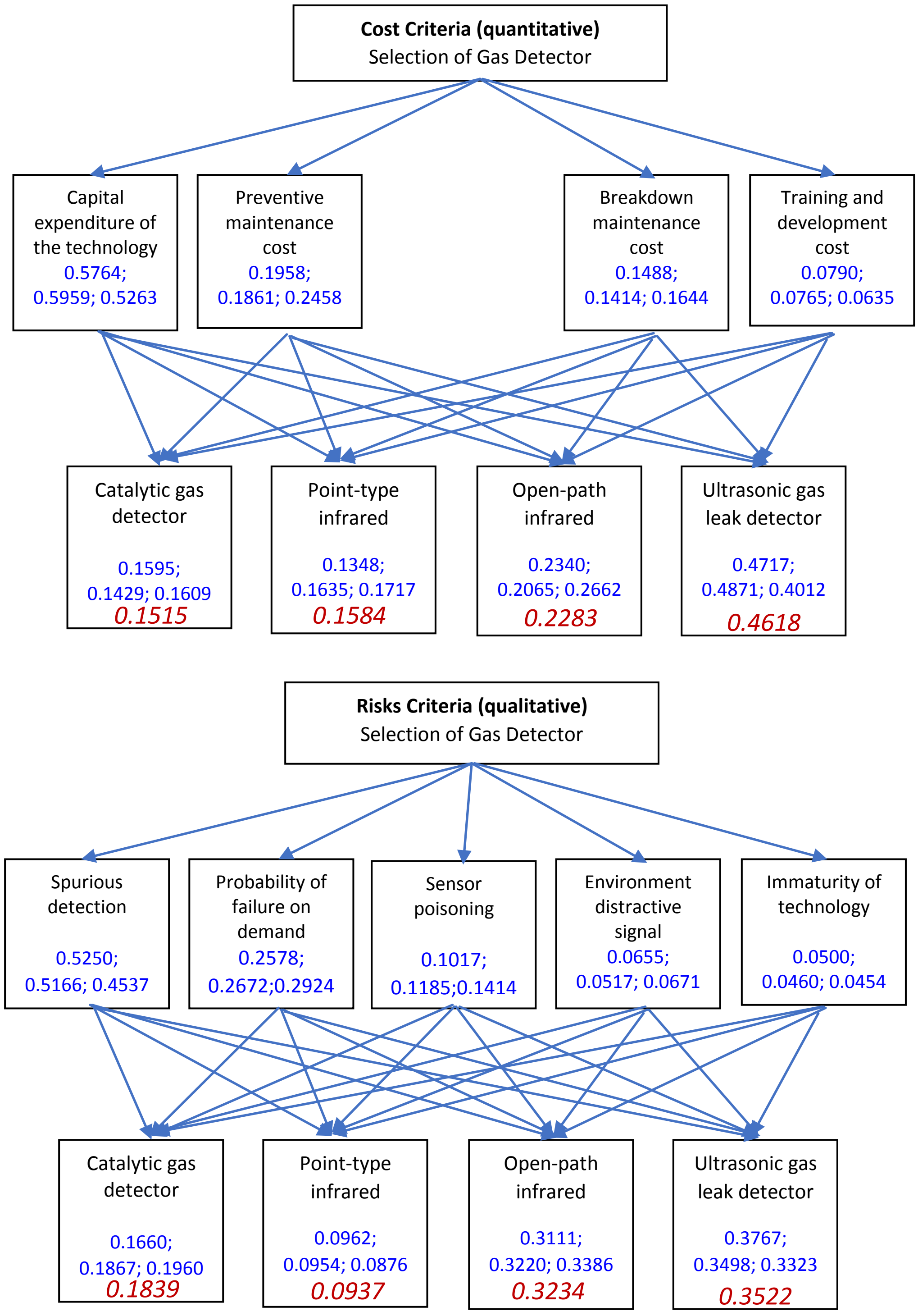
Defuzzified value

Figure 4.5a. The summary result of fuzzy AHP calculation involved in this research. The values are defined based on each sub-criterion and alternatives weight.



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Defuzzified value

Figure 4.5b. The summary result of fuzzy AHP calculation involved in this research. The values are defined based on each sub-criterion and alternatives weight.

CHAPTER V

RESULTS AND ANALYSIS

This chapter discusses the results of the research and describes the systematic analysis. After we performed complex computation of Fuzzy AHP in chapter IV, it is necessary to explain the result of those computation.

5.1. Research Result

The fuzzy AHP final values are obtained for each level of criteria, sub-criteria, and alternatives. Specifically, for Risk criteria, language preference is necessary to be predefined. In correspondence to the risk criteria, the risk is quantified as:

$$\begin{array}{lcl} r \leq 0.1 & \rightarrow & Acceptable \\ 0.1 < r \leq 0.5 & \rightarrow & Tolerable \\ r > 0.5 & \rightarrow & Unacceptable \end{array} \qquad (24)$$

Where r is the fuzzy final value for risk criteria.

As defined in the Chapter 4, all calculation result of fuzzy AHP has been obtained. Figure 4.5, defined the summary result of all calculations. The defuzzified value for all alternatives in figure 4.5. are then listed in Table 5.1 in order to simplified the appearance of calculation.

Table 5.1. Benefit and cost ratio of fuzzy AHP result in accordance with risk

Alternatives	**Benefit**	**Cost**	**Benefit/Cost Ratio**	**Risk**
Catalytic gas detector (CGD)	0.1795	0.1515	1.1848	0.1839 (Tolerable)
Open-path gas detector(OPGD)	0.2357	0.2283	1.0324	0.3234 (Tolerable)
Point-type infrared gas detector (PGD)	**0.2777**	**0.1584**	**1.7532**	**0.0937 (Acceptable)**
Ultrasonic gas leak detector (UGLD)	0.2602	0.4618	0.5634	0.3522 (Tolerable)

Benefit/Cost ratio is derived based on value of benefit divided by cost values. The division is applicable for all alternatives respectively. The language preference of risk criteria is applied based on equation 24. The final result of this research reveals that point-type infrared gas detector is the most suitable gas detector technology implemented in the OGPA.

As a comparison, we calculate the weight of each alternative by conventional AHP method. In general, the results of fuzzy AHP and conventional AHP are quite similar. The ranking of sub-criteria and alternatives between fuzzy AHP and conventional AHP are identical. Conventional AHP shows that all consistency ratio below 0.1. On the other hand, consistency ratio of fuzzy AHP is calculated by transforming the fuzzy pairwise comparison matrix to crisp number matrix through defuzzification process. It is confirmed that all the defuzzified pairwise comparison matrices are consistent.

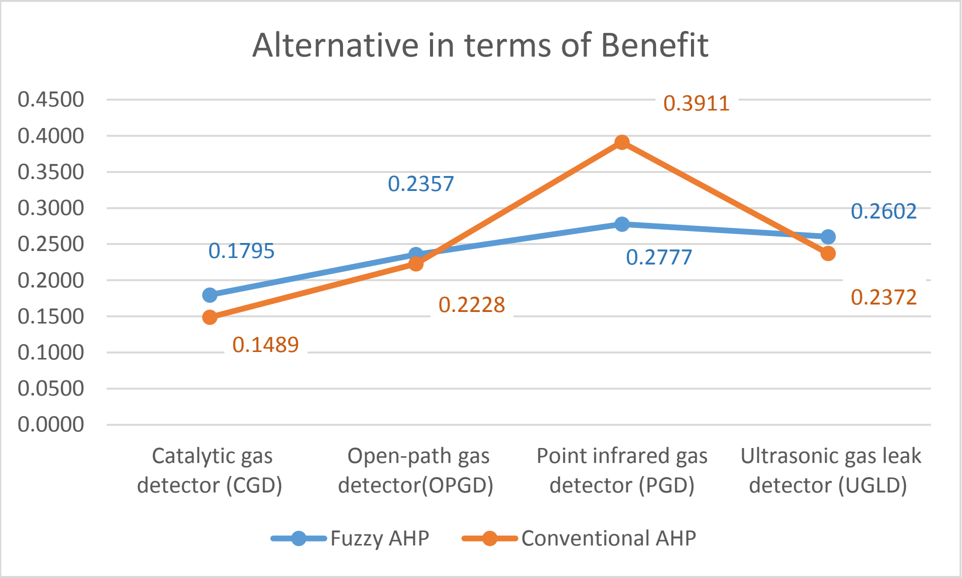

Figure 5.1. Alternatives final value comparison between fuzzy AHP and conventional AHP Method for benefit criteria.

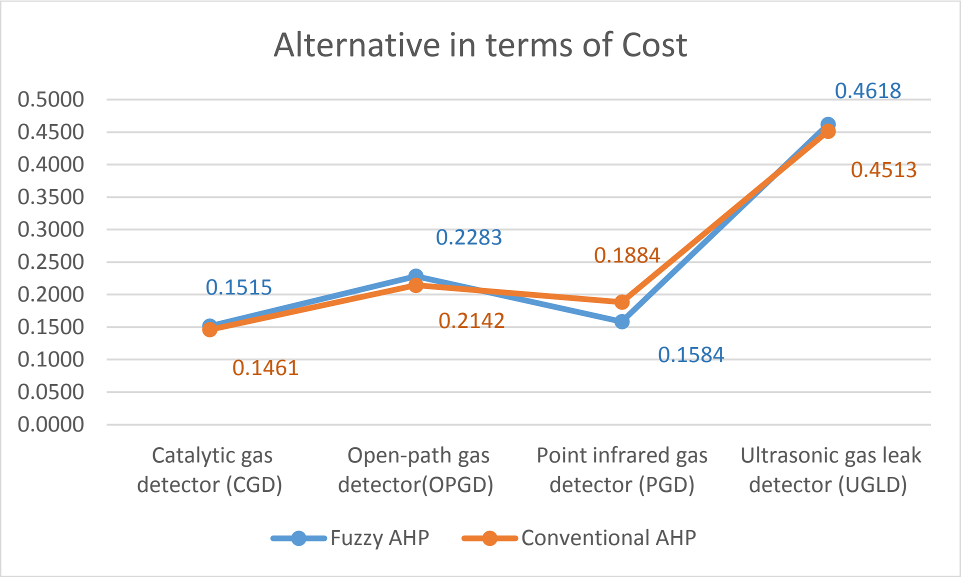

Figure 5.2. Alternatives final value comparison between fuzzy AHP and conventional AHP Method for cost criteria.

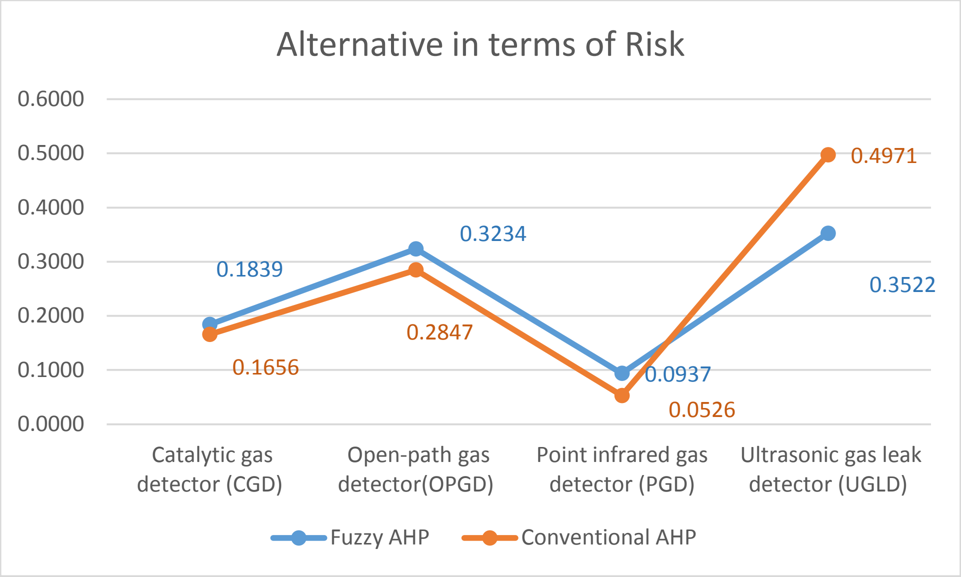

Figure 5.3. Alternatives final value comparison between fuzzy AHP and conventional AHP Method for risk criteria.

5.2. Sensitivity Analysis

It is necessary to perform such a sensitivity analysis to evaluate how input change could lead to output change. This means that if we perform a change in the input by adding or lowering the sub-criteria values, how far the expected output values in the alternatives will change. The sensitivity analysis is performed by changing the rank of importance of benefit, cost, and risk sub-criteria. For instance, we change the least important sub-criteria to become the most important sub-criteria. This analysis foresees if the alternative output value remains same or it may change. The sensitivity analysis foresees if there is a change on the expert panelists or the OGPA management's perspective in regards to sub-criteria weight, the alternatives ranking remains same. Descriptive graphics and chart will be displayed as the result of the sensitivity analysis.

5.2.1. Benefit criteria

Based on calculation in chapter 3, the most significant sub-criterion is reliability and precision followed by delivering continuous concentration; whereas the least significant sub-criterion is response time followed by oxygen deficiency resistance. The sensitivity analysis is performed by lowering 50% weight of reliability and precision as well as delivering continuous concentration sub-criteria. It is also performed an addition of 50% weight to the least significant sub-criteria, response time and oxygen deficiency resistance. Figure 5.4 describes the result of sensitivity analysis.

Table 5.2. The sub-criteria's weight change in the benefit criteria.

Sub-criteria	*Initial Weight*	*Sensitivity Analysis Weight*
1. Reliability and precision	0.5222; 0.5096; 0.4424	0.2611; 0.2548; 0.2212
2.Detection area coverage	0.2280; 0.2546; 0.2803	0.1140; 0.1273; 0.1401
3. Delivering continuous concentration monitoring	0.1120; 0.1004; 0.1309	0.1120; 0.1004; 0.1309
4. Oxygen deficiency resistance	0.0855; 0.0938; 0.0949	0.1282; 0.1407; 0.1423
5. Response time	0.0523; 0.0417; 0.0516	0.0785; 0.0625; 0.0774

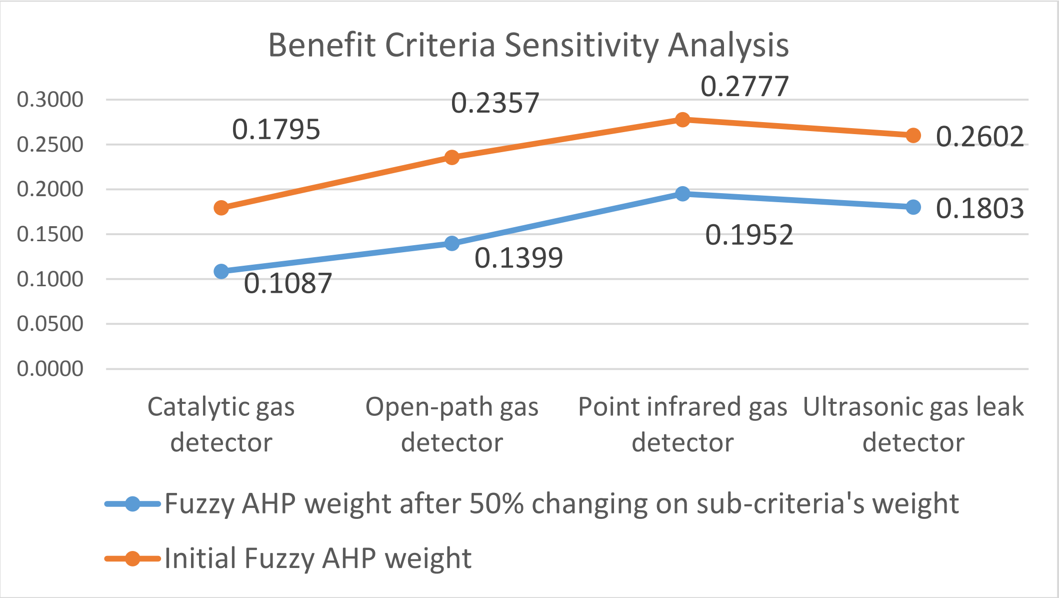

Figure 5.4. Sensitivity analysis result for benefit sub-criteria.

It is observed that there is no ranking change of alternatives. The result is still consistent, revealing that point infrared gas detector still the most beneficial gas detector technology, and catalytic gas detector brings the least beneficial gas detector technology.

5.2.3. Cost Criteria

The similar method of sensitivity analysis is implemented for Cost criteria. The most significant factor in Cost criteria, capital expenditure of the technology and preventive maintenance cost are lowered by 50%. Similarly, as the least significant sub-criteria, training and development cost and breakdown maintenance cost are added by 50% weight. As described in figure 5.5, the result of sensitivity analysis for Cost criteria confirms that the ranking of alternatives does not change. The ranking structure is consistent, following the values of each alternative.

Table 5.3. The sub-criteria's weight change in the cost criteria.

Sub-criteria	***Initial Weight***	***Sensitivity Analysis Weight***
1. Capital expenditure of the technology	0.5764; 0.5959; 0.5263	0.2882; 0.2979; 0.2631
2. Preventive maintenance cost	0.1958; 0.1861; 0.2458	0.0979; 0.0931; 0.1229
3. Breakdown maintenance cost	0.1488; 0.1414; 0.1644	0.2232; 0.2122; 0.2466
4. Training and development cost	0.0790; 0.0765; 0.0635	0.1185; 0.1148; 0.0952

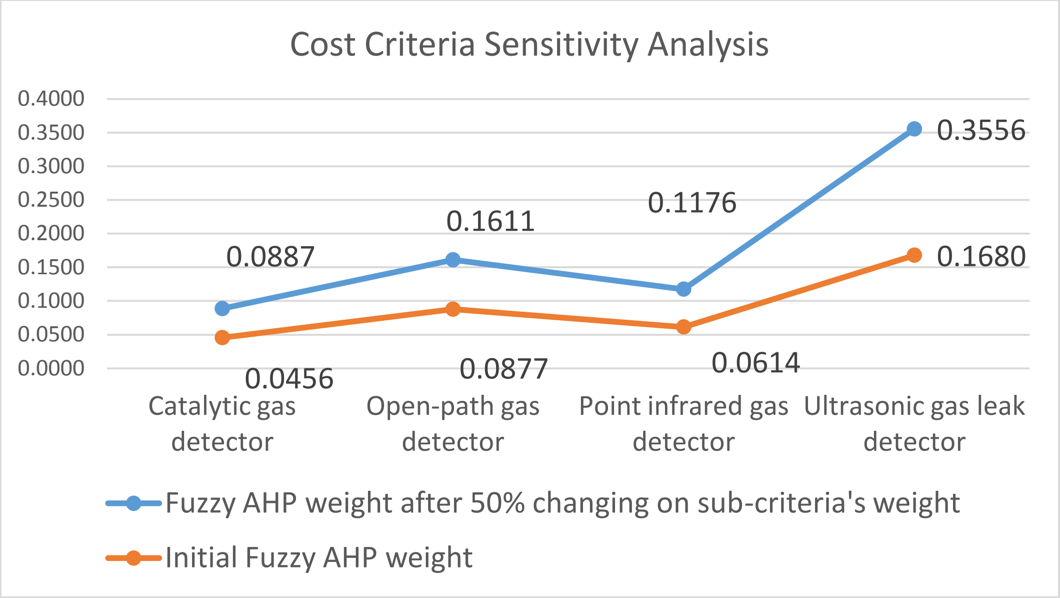

Figure 5.5. Sensitivity analysis result for cost sub-criteria.

Risk Criteria

Lastly, the sensitivity analysis is performed for Risk criteria. We perform weight reduction to the most significant sub-criteria by 50% and addition for the least significant sub-criteria by 50%. Consistent result is also obtained for risk criteria. The alternatives ranking position remains same with those in the initial fuzzy AHP.

Table 5.4. The sub-criteria's weight change in the risk criteria.

Sub-criteria	*Initial Weight*	*Sensitivity Analysis Weight*
1. Spurious detection	0.5250; 0.5166; 0.4537	0.2625; 0.2583; 0.2269
2. Probability of failure on demand	0.2578; 0.2672; 0.2924	0.1289; 0.1336; 0.1462
3. Sensor poisoning	0.1017; 0.1185; 0.1414	0.1017; 0.1185; 0.1414
4. Environment distractive signal	0.0655; 0.0517; 0.0671	0.0983; 0.0776; 0.1006
5. Immaturity of technology	0.0500; 0.0460; 0.0454	0.0750; 0.0690; 0.0682

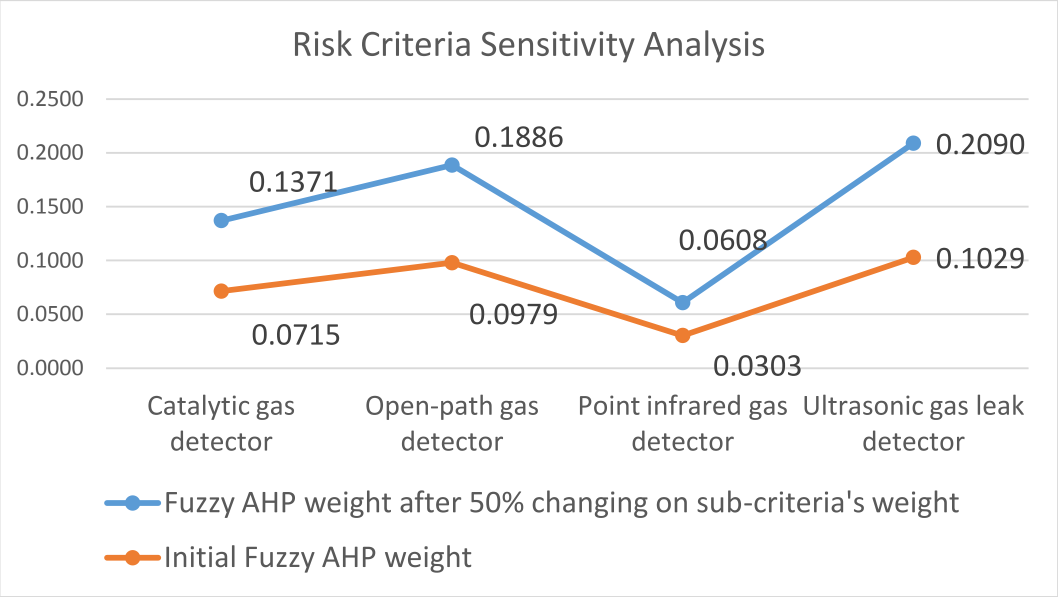

Figure 5.6. Sensitivity analysis result for risk sub-criteria.

Based on the result of sensitivity analysis, it is confirmed that the alternatives rank position does not change in spite of sub-criteria weight change for all criteria. Therefore, the evaluation of this research is able to a give consistent guidance to select the gas detector technology.

5.3. Managerial Implication

As mentioned in this research, point-type infrared gas detector brings the highest value in terms of benefits and risk criteria. It means that point-type infrared gas detector is the best option for the OGPA management to implement the gas detector technology. it is explained the elaboration of each gas detector technology benefit, cost and risk managerial implication for the OGPA. Based on the research analysis and evaluation that has been performed in previous chapter, we believe that this research has a managerial implication to Petroleum Company owned the OGPA as follow:

1. Petroleum Company obtains clear description of quantitative value for each gas detector technology in terms of their capability and applicability in OGPA.
2. Petroleum Company is able to determine the best applicable technology in terms of ALARP for selecting the gas detector in the OGPA. The selection takes into account benefit, cost and risk analysis for the decision making.
3. Petroleum Company can use this research as scientific guidance for implementing future development of gas detector technology in the OGPA or other affiliates and sites.

5.4. Scientific Implication

This research involves two analysis of consistency. Firstly, consistency ratio method is applied to the defuzzified pairwise comparison matrix. The obtained result of consistency ratio is always below 0.1 (CR<0.1). By this terms, the fuzzy AHP is consistent and applicable. Secondly, the consistency analysis is performed by the sensitivity analysis, a method to detect any change in alternatives rank if there is a change in weight of sub-criteria. By changing 50% amount of weight in all sub-criteria, there is no alternatives rank position change. The sensitivity analysis proves that the fuzzy AHP evaluation in the research is consistent irrespectively of the sub-criteria change. In short, fuzzy AHP is reliable as the scientific method for gas detector technology selection and evaluation.

The development of sub-criteria is derived by Delphi technique, a scientific method that has been developed and implemented since 1950’s. The most beneficial aspects for determining sub-criteria is the consensus obtained in the Delphi technique. The integration of Delphi technique and fuzzy AHP in this research generates comprehensive studies for determining the most optimum gas detector technology implemented in the OGPA.

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6.1. Conclusion

This research has identified key selection criteria for selecting gas decector technology using the Delphi Technique. Based on the Delphi technique, 5 sub-criteria in terms of benefit and risk, as well 4 sub-criteria for cost have been obtained with consensus decision in the first and second round. The third round is intended to measure the importance of all sub-criteria and alternatives. The result of third round is then converted to Saaty’s scale as pairwise comparison based for the fuzzy AHP procedure.

The fuzzy AHP analysis for benefit, cost, and risk analysis reveals that point infrared gas detector has the highest score (1.753). This means that point infrared technology has efficient value in delivering service to the process safety operation. Point infrared gas detector also reveals the best value in risk category analysis, which means its technology is capable of delivering reliable safety system. The fuzzy AHP evaluation in this research involves two analysis of consistency, i.e. consistency ratio and sensitivity analysis. The consistency ratio method is applied to the defuzzified pairwise comparison matrix. The obtained result of consistency ratio is always below 0.1 (CR<0.1). By this terms, the fuzzy AHP is consistent and applicable. On the other hand, sensitivity analysis shows no alternatives rank position change when 50% amount of weight in all sub-criteria has been changed.

The methodology involved in the research, integration of Delphi technique and fuzzy AHP, provides scientific guidance for gas detector technology selection. Concisely, the fuzzy AHP analysis would lead the management to select which technology is best applied in OGPA.

6.2. Recommendation

Further research can be applicable to determine correlation for each sub-criterion. As stated by Saaty (2008) that analytic network process is more appropriate to determine decision problems which cannot be structured hierarchically because they involve the interaction and dependence of higher-level elements. Therefore, Fuzzy ANP shall be applicable for the improvement of this research.

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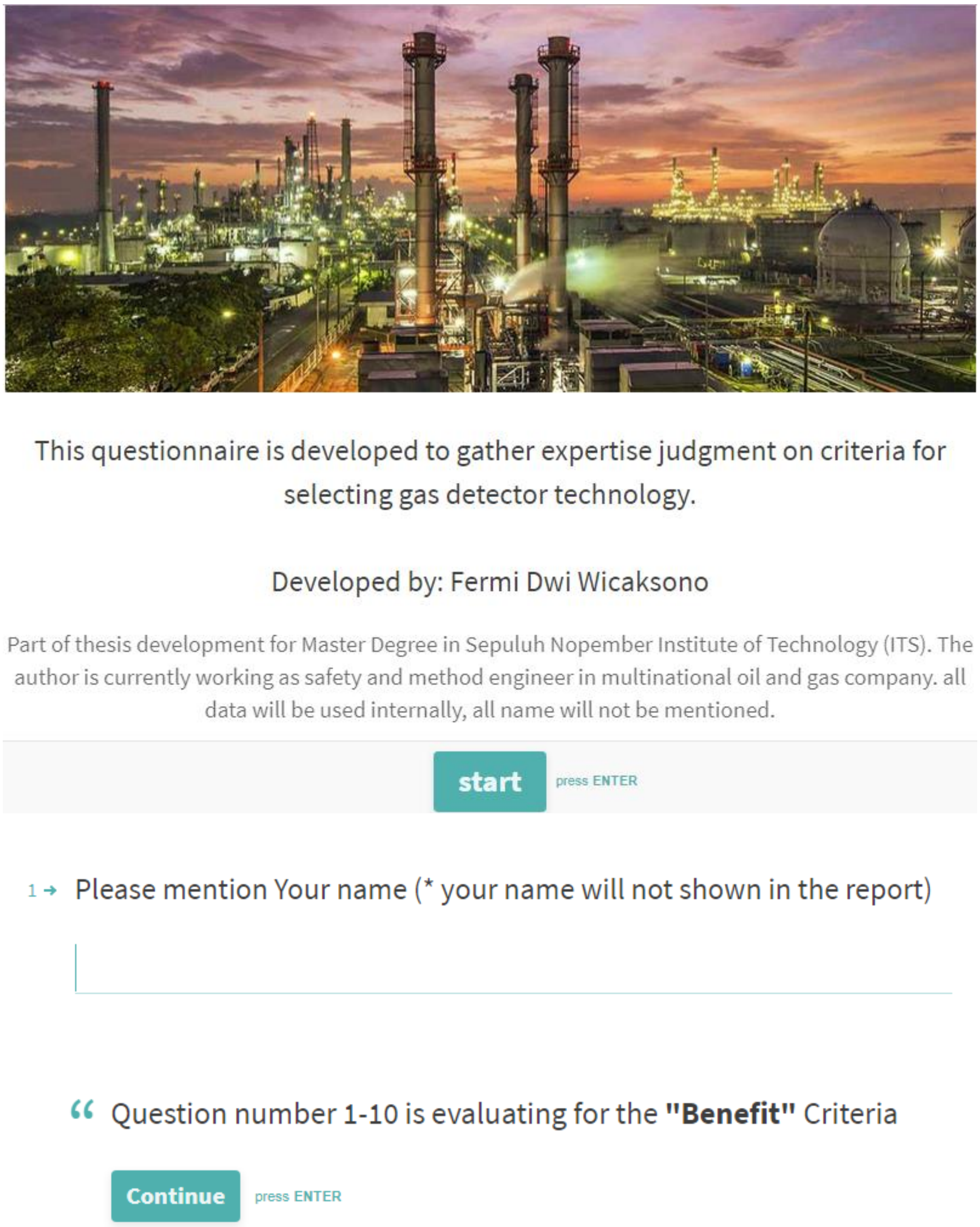
APPENDICES

Appendix A. Questionnaire



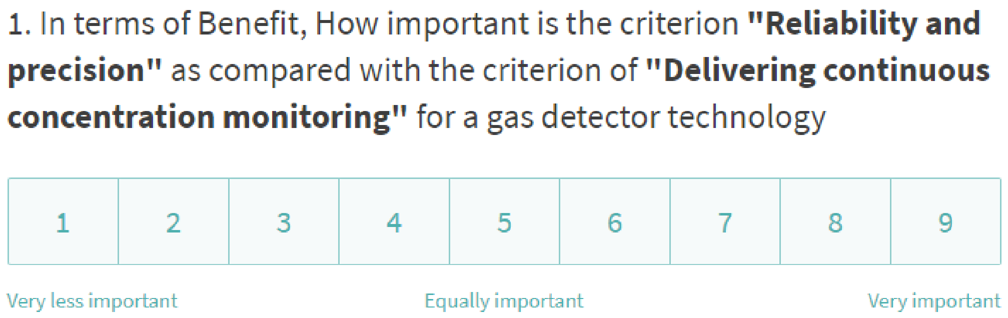
This questionnaire is developed to gather expertise judgment on criteria for selecting gas detector technology.

Developed by: Fermi Dwi Wicaksono

Part of thesis development for Master Degree in Sepuluh Nopember Institute of Technology (ITS). The author is currently working as safety and method engineer in multinational oil and gas company. all data will be used internally, all name will not be mentioned.

1 → Please mention Your name (* your name will not shown in the report)

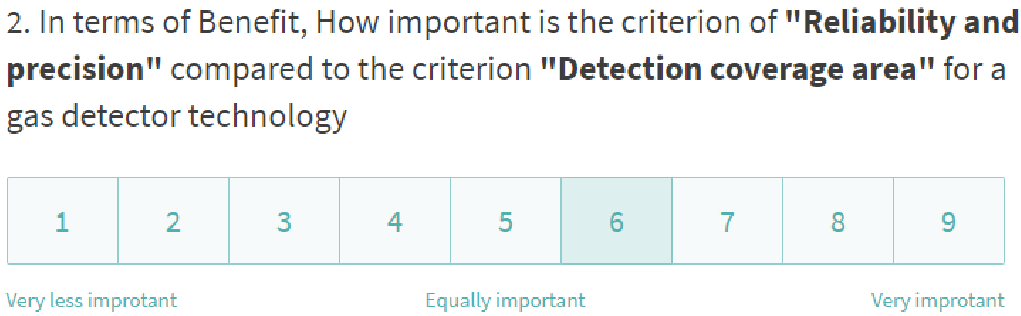
“ Question number 1-10 is evaluating for the **"Benefit"** Criteria



1. In terms of Benefit, How important is the criterion **"Reliability and precision"** as compared with the criterion of **"Delivering continuous concentration monitoring"** for a gas detector technology

1	2	3	4	5	6	7	8	9

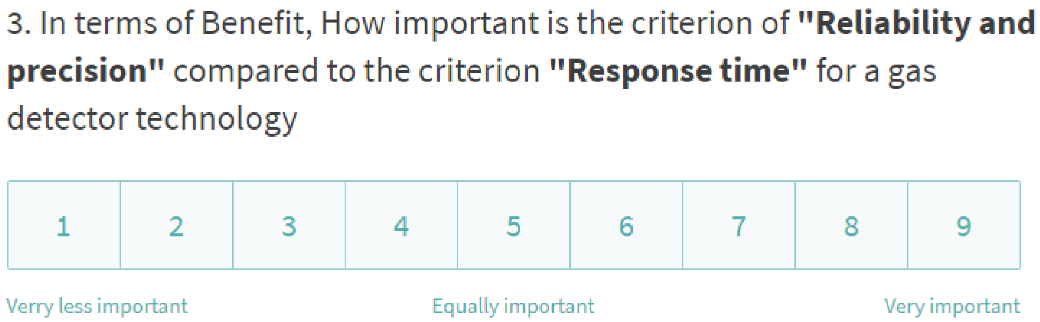
Very less important
Equally important
Very important



2. In terms of Benefit, How important is the criterion of **"Reliability and precision"** compared to the criterion **"Detection coverage area"** for a gas detector technology

1	2	3	4	5	[✓ 6]	7	8	9

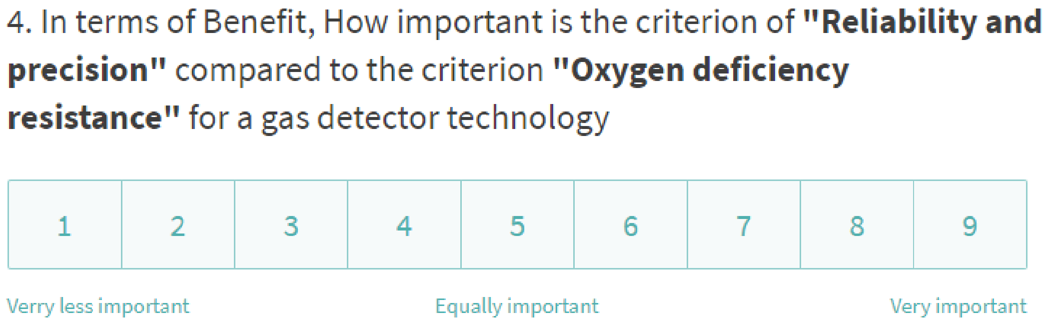
Very less improtant
Equally important
Very improtant



3. In terms of Benefit, How important is the criterion of **"Reliability and precision"** compared to the criterion **"Response time"** for a gas detector technology

1	2	3	4	5	6	7	8	9

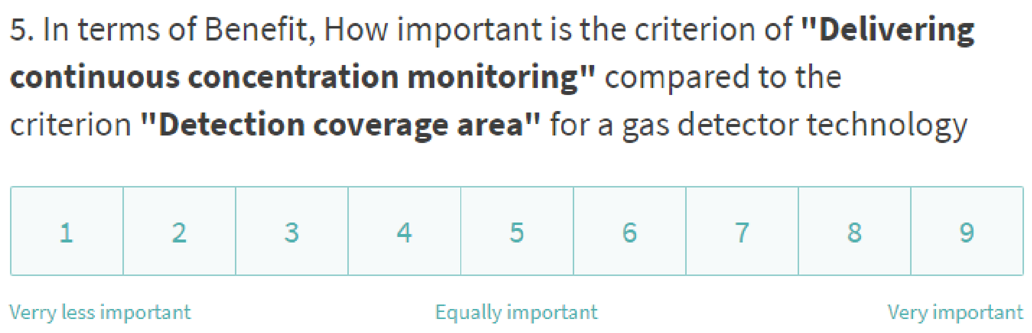
Verry less important
Equally important
Very important



4. In terms of Benefit, How important is the criterion of **"Reliability and precision"** compared to the criterion **"Oxygen deficiency resistance"** for a gas detector technology

1	2	3	4	5	6	7	8	9

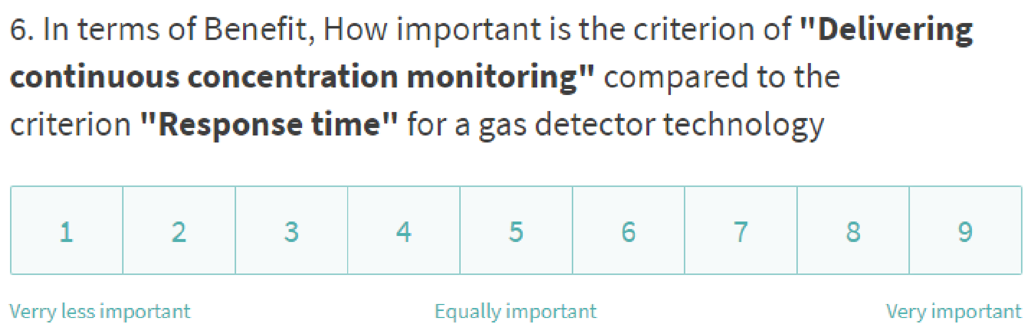
Verry less important
Equally important
Very important



5. In terms of Benefit, How important is the criterion of **"Delivering continuous concentration monitoring"** compared to the criterion **"Detection coverage area"** for a gas detector technology

1	2	3	4	5	6	7	8	9

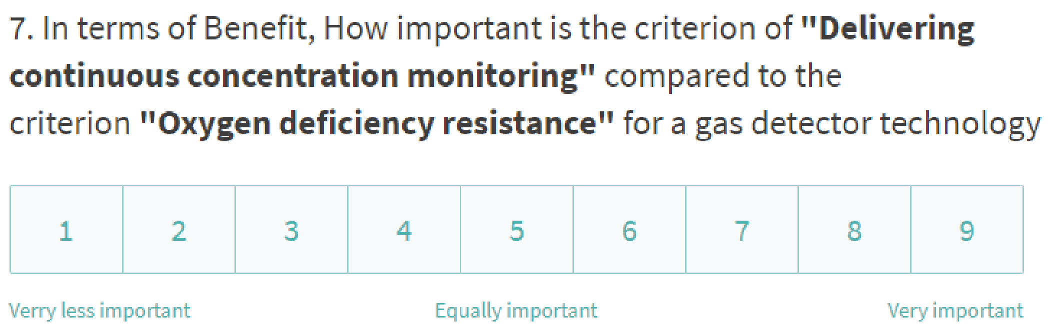
Verry less important　Equally important　Very important



6. In terms of Benefit, How important is the criterion of **"Delivering continuous concentration monitoring"** compared to the criterion **"Response time"** for a gas detector technology

1	2	3	4	5	6	7	8	9

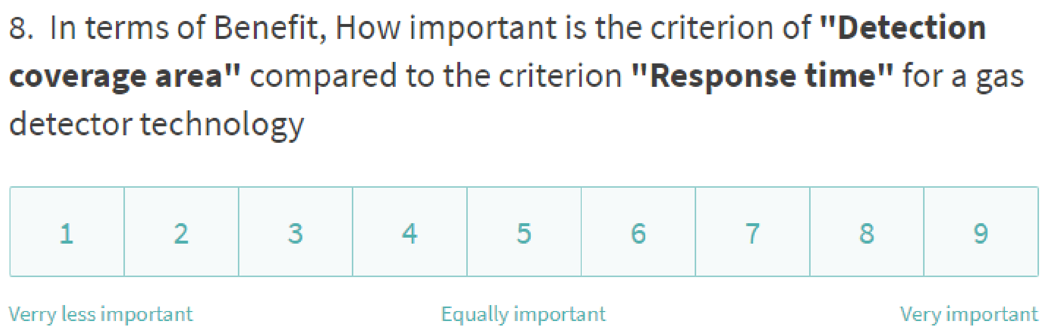
Verry less important　Equally important　Very important



7. In terms of Benefit, How important is the criterion of **"Delivering continuous concentration monitoring"** compared to the criterion **"Oxygen deficiency resistance"** for a gas detector technology

1	2	3	4	5	6	7	8	9

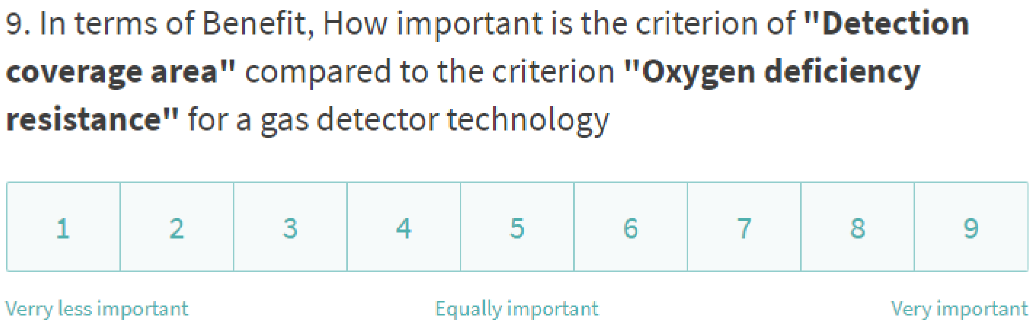
Verry less important　Equally important　Very important



8. In terms of Benefit, How important is the criterion of **"Detection coverage area"** compared to the criterion **"Response time"** for a gas detector technology

1	2	3	4	5	6	7	8	9

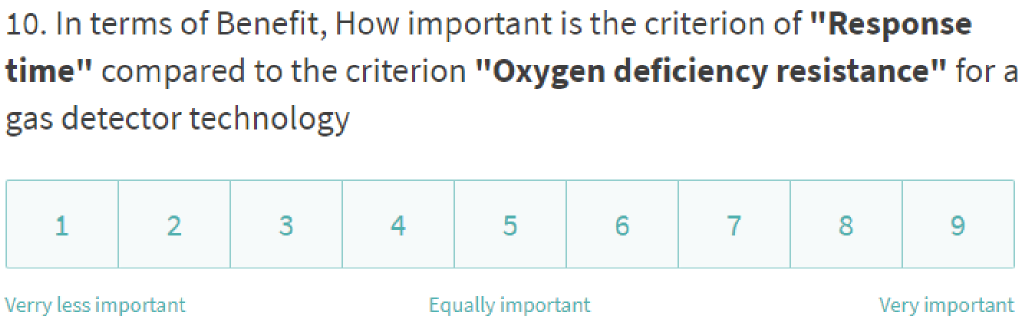
Verry less important　Equally important　Very important



9. In terms of Benefit, How important is the criterion of **"Detection coverage area"** compared to the criterion **"Oxygen deficiency resistance"** for a gas detector technology

1	2	3	4	5	6	7	8	9

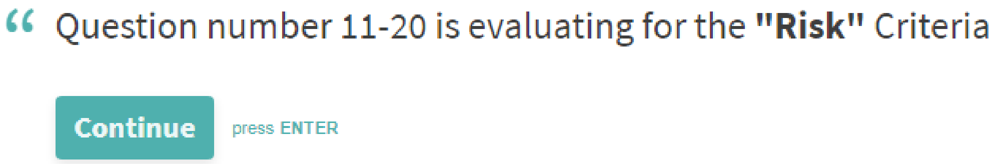
Verry less important　Equally important　Very important



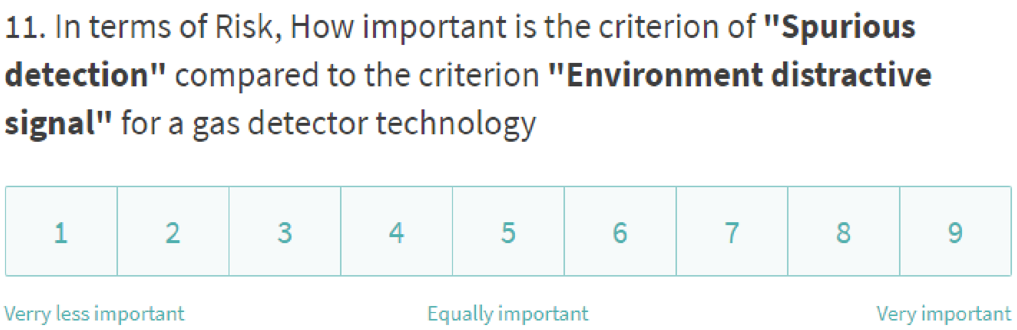
10. In terms of Benefit, How important is the criterion of **"Response time"** compared to the criterion **"Oxygen deficiency resistance"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important　Equally important　Very important



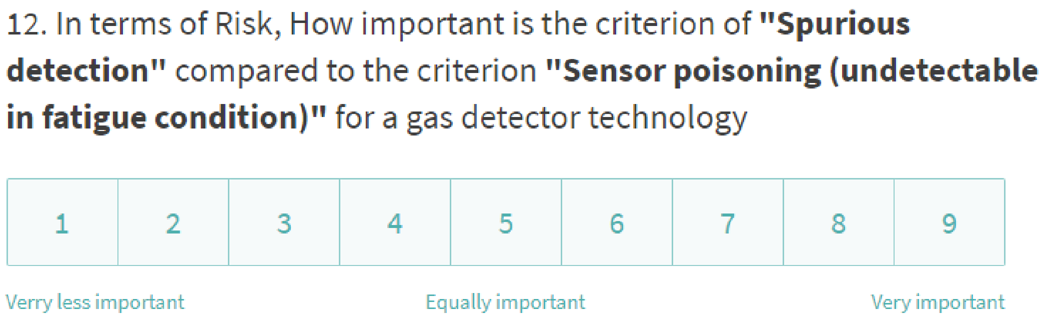
Question number 11-20 is evaluating for the **"Risk"** Criteria



11. In terms of Risk, How important is the criterion of **"Spurious detection"** compared to the criterion **"Environment distractive signal"** for a gas detector technology

1	2	3	4	5	6	7	8	9

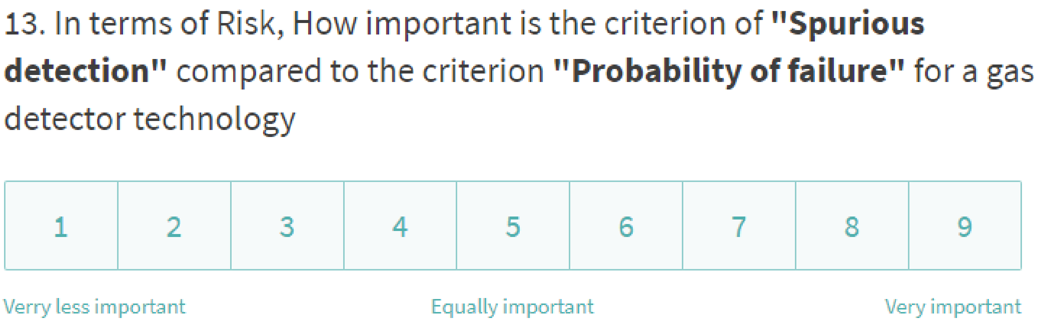
Verry less important　Equally important　Very important



12. In terms of Risk, How important is the criterion of **"Spurious detection"** compared to the criterion **"Sensor poisoning (undetectable in fatigue condition)"** for a gas detector technology

1	2	3	4	5	6	7	8	9

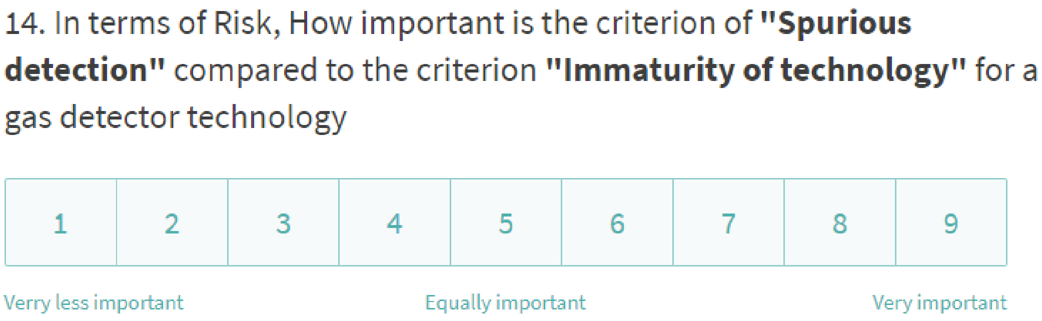
Verry less important　Equally important　Very important



13. In terms of Risk, How important is the criterion of **"Spurious detection"** compared to the criterion **"Probability of failure"** for a gas detector technology

1	2	3	4	5	6	7	8	9

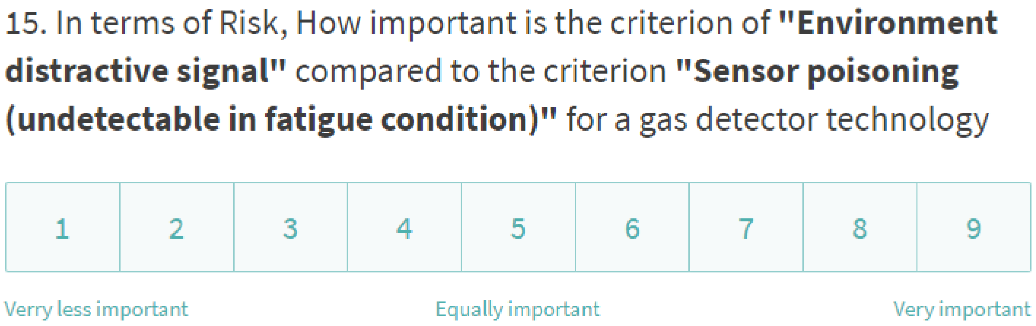
Verry less important — Equally important — Very important



14. In terms of Risk, How important is the criterion of **"Spurious detection"** compared to the criterion **"Immaturity of technology"** for a gas detector technology

1	2	3	4	5	6	7	8	9

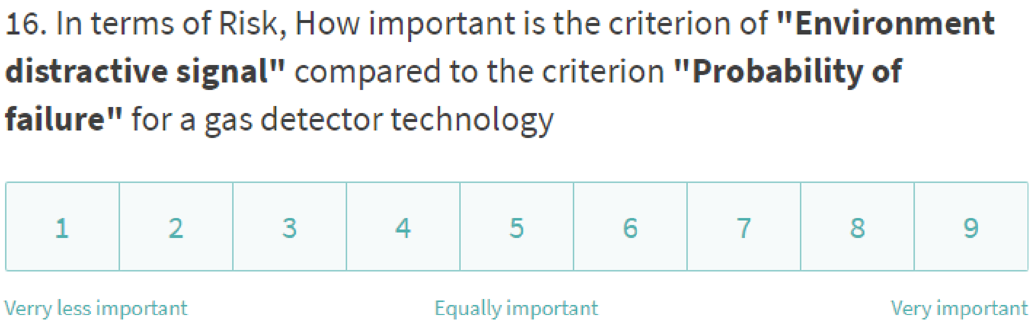
Verry less important — Equally important — Very important



15. In terms of Risk, How important is the criterion of **"Environment distractive signal"** compared to the criterion **"Sensor poisoning (undetectable in fatigue condition)"** for a gas detector technology

1	2	3	4	5	6	7	8	9

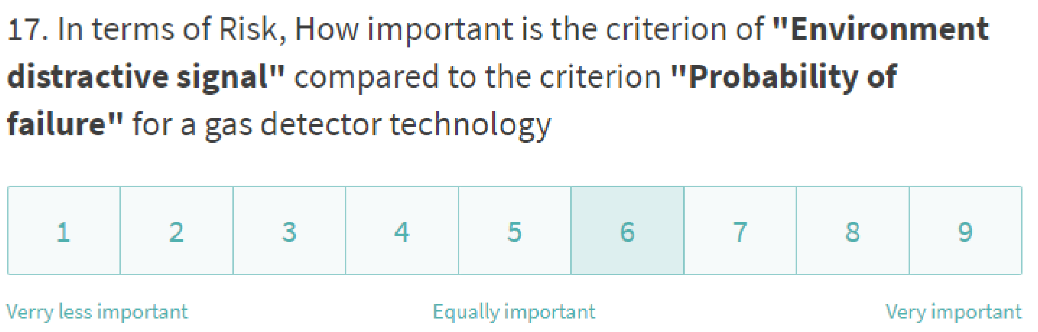
Verry less important — Equally important — Very important



16. In terms of Risk, How important is the criterion of **"Environment distractive signal"** compared to the criterion **"Probability of failure"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important — Equally important — Very important



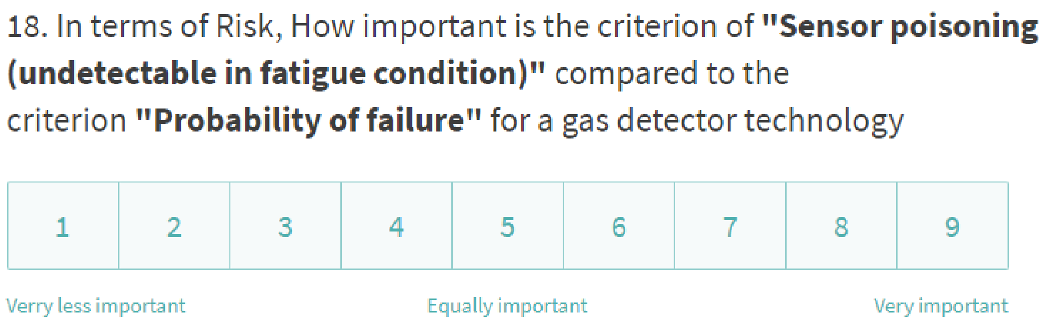
17. In terms of Risk, How important is the criterion of **"Environment distractive signal"** compared to the criterion **"Probability of failure"** for a gas detector technology

1	2	3	4	5	[✓ 6]	7	8	9

Verry less important

Equally important

Very important



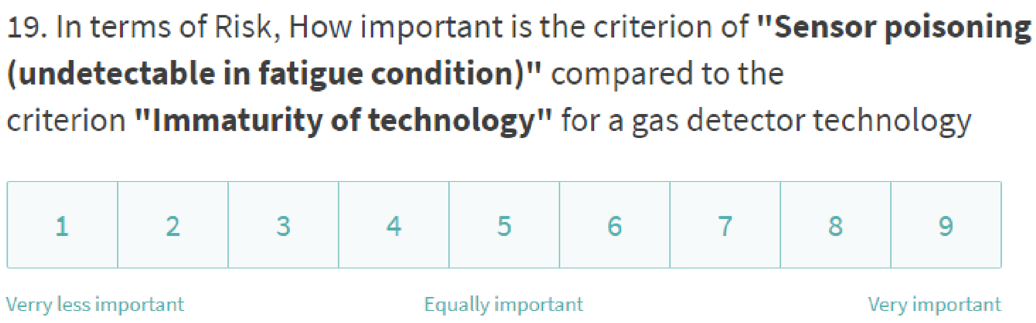
18. In terms of Risk, How important is the criterion of **"Sensor poisoning (undetectable in fatigue condition)"** compared to the criterion **"Probability of failure"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important

Equally important

Very important



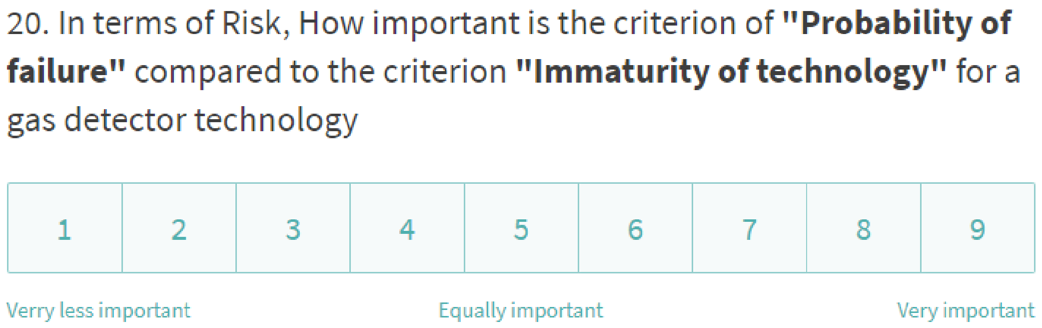
19. In terms of Risk, How important is the criterion of **"Sensor poisoning (undetectable in fatigue condition)"** compared to the criterion **"Immaturity of technology"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important

Equally important

Very important



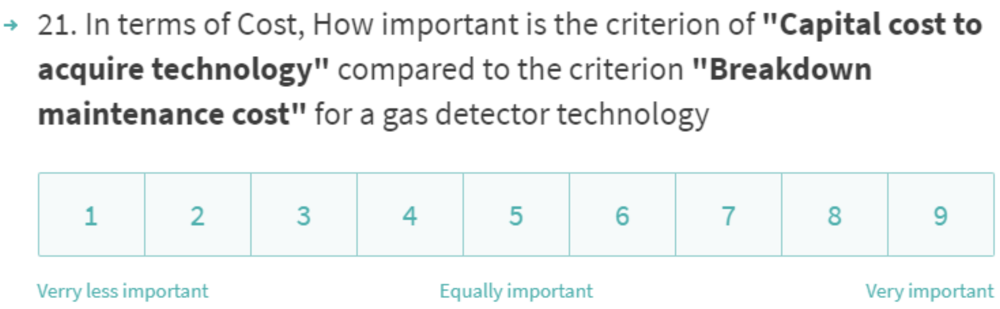
20. In terms of Risk, How important is the criterion of **"Probability of failure"** compared to the criterion **"Immaturity of technology"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important

Equally important

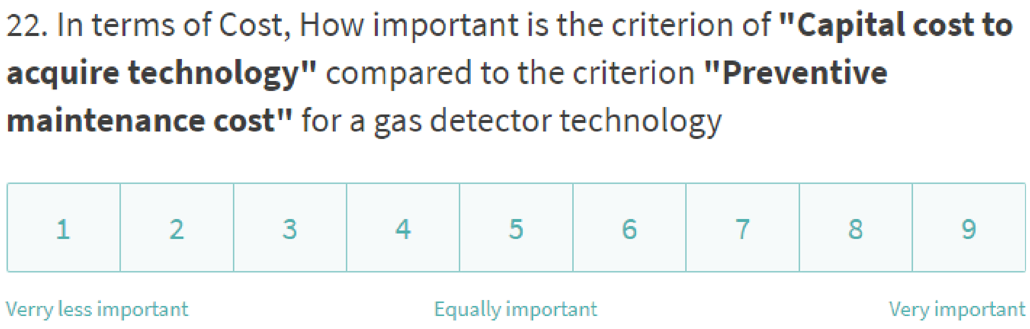
Very important



21. In terms of Cost, How important is the criterion of **"Capital cost to acquire technology"** compared to the criterion **"Breakdown maintenance cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

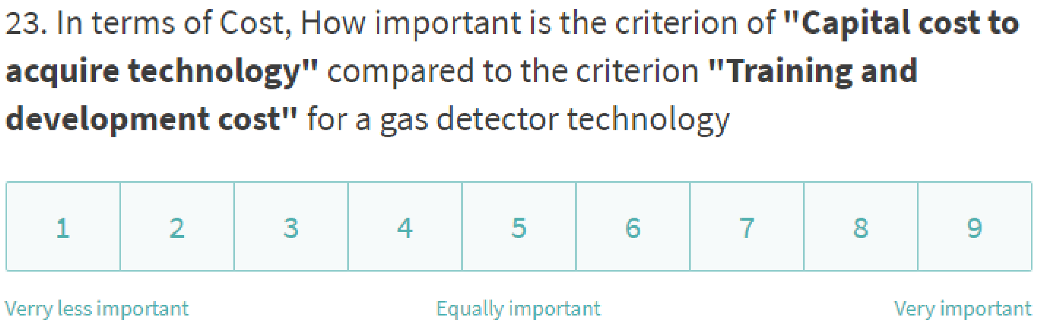
Verry less important Equally important Very important



22. In terms of Cost, How important is the criterion of **"Capital cost to acquire technology"** compared to the criterion **"Preventive maintenance cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

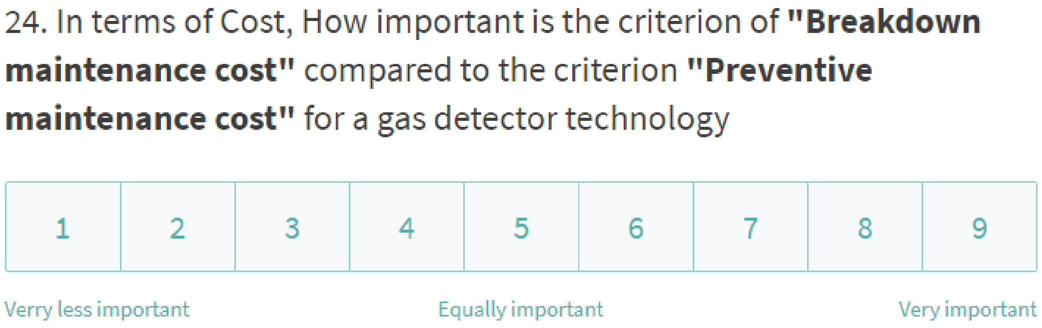
Verry less important Equally important Very important



23. In terms of Cost, How important is the criterion of **"Capital cost to acquire technology"** compared to the criterion **"Training and development cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important Equally important Very important



24. In terms of Cost, How important is the criterion of **"Breakdown maintenance cost"** compared to the criterion **"Preventive maintenance cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important Equally important Very important

25. In terms of Cost, How important is the criterion of **"Breakdown maintenance cost"** compared to the criterion **"Training and development cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important Equally important Very important

26. In terms of Cost, How important is the criterion of **"Preventive maintenance cost"** compared to the criterion **"Training and development cost"** for a gas detector technology

1	2	3	4	5	6	7	8	9

Verry less important Equally important Very important

Appendix B. Detail result of Delphi Technique Round-1 and Round-2

No.	Expert Panelists	Delphi Round-1 Result Sub-criteria	Delphi Round-2 Result Sub-criteria
1	Maintenance-instrument engineer	Benefit: - Reliability and precision - Versatile range of gas detection - Detection coverage area - Oxygen deficiency resistance - Life-time of usage Costs: - Capital expenditure of the technology - Breakdown maintenance cost - Preventive maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Probability of failure on demand - Mismatch on existing safety system	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance - Response time Costs: - Capital expenditure of the technology - Breakdown maintenance cost - Preventive maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Immaturity of technology
2	Head of Production Support Department	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Life-time of usage Costs:	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance - Response time

		- Capital expenditure of the technology - Breakdown maintenance cost - Preventive maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Probability of failure on demand	Costs: - Capital expenditure of the technology - Breakdown maintenance cost - Preventive maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Mismatch on existing safety system
3	Head of Field Operation Safety and Method Services	Benefit: - Reliability and precision - Fail to safe technology - Detection coverage area - Wireless (telemetry) monitoring Costs: - Capital expenditure of the technology - Preventive maintenance cost - Third party support cost Risks: - Spurious detection - Sensor poisoning (undetectable in fatigue condition) - Probability of failure on demand - Immaturity of technology	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance - Response time Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Capital expenditure of the technology Risks: - Spurious detection - Sensor poisoning (undetectable in fatigue condition) - Loss of sensitive detection - Mismatch on existing safety system
4	Head of Operating Philosophy and Safety Concept	Benefit: - Reliability and precision	Benefit: - Reliability and precision

		- Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Probability of failure on demand - Immaturity of technology	- Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Immaturity of technology
5	Safety Method Engineer I	Benefit: - Versatile range of gas detection - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance Costs: - Capital expenditure of the technology - Breakdown maintenance cost - Preventive maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal

		- Sensor poisoning (undetectable in fatigue condition) - Probability of failure on demand - Immaturity of technology	- Sensor poisoning (undetectable in fatigue condition) - Immaturity of technology
6	Safety Method Engineer II	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Multiple features and capability Costs: - Capital expenditure of the technology - Preventive maintenance cost - Third party support cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Immaturity of technology - Mismatch on existing safety system	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Loss of sensitive detection
7	Safety Method Engineer III	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Fail to safe technology - Multiple features and capability Costs: - Capital expenditure of the technology	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Oxygen deficiency resistance - Response time Costs: - Capital expenditure of the technology

		- Preventive maintenance cost - Breakdown maintenance cost - Third party support cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Probability of failure on demand - Un-linear detection	- Preventive maintenance cost - Breakdown maintenance cost - Training and development cost - Immaturity of technology Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Un-linear detection
8	Process/ production engineer I	Benefit: - Reliability and precision - Detection coverage area - Oxygen deficiency resistance - Easy to calibrate Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Probability of failure on demand - Un-linear detection	Benefit: - Reliability and precision - Detection coverage area - Oxygen deficiency resistance - Response time Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Immaturity of technology - Inhibition failure
9	Process/ production engineer II	Benefit: - Reliability and precision - Delivering continuous concentration	Benefit: - Reliability and precision - Delivering continuous concentration monitoring

		monitoring - Detection coverage area - Fail to safe technology Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Probability of failure on demand	- Detection coverage area - Response time Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition) - Immaturity of technology
10	Process/ production engineer III	Benefit: - Reliability and precision - Ability to limit the area of gas release - Easy to calibrate Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Probability of failure on demand - Inhibition failure	Benefit: - Reliability and precision - Delivering continuous concentration monitoring - Detection coverage area - Response time Costs: - Capital expenditure of the technology - Preventive maintenance cost - Breakdown maintenance cost - Training and development cost Risks: - Spurious detection - Environment distractive signal - Sensor poisoning (undetectable in fatigue condition)

			- Immaturity of technology

Appendix C. Detail result of alternative Judgment for Benefit Criteria

Function	Safety and Method Eng II.	Production/process method Eng III.	Head of Operating Philosophy and Safety Concept	Safety and Method Eng I.	Head of Field Operation Safety and Method Services	Head of Production Support Department	Safety and Method Eng III.	Production/process method Eng II.	Production/process method Eng I.	Maintenance Instrument Eng.
Name	FDW	BJ	SS	GW	AD	RD	DS	DW	SS	AM
1. Reliability and Precision										
Catalytic (CGD)	4	4	3	4	3	4	3	3	4	3
Open-path infrared (OPGD)	4	3	4	4	3	3	4	4	4	4
Point type infrared (PGD)	5	5	4	5	4	5	5	5	5	4
Ultrasonic gas leak detector (UGLD)	3	3	2	3	1	3	3	2	2	2
2. Delivering continuous concentration monitoring										
Catalytic (CGD)	4	3	4	4	4	4	3	4	4	3
Open-path infrared (OPGD)	4	4	4	4	4	4	4	4	3	4
Point type infrared (PGD)	5	5	4	5	5	5	5	5	5	4
Ultrasonic gas leak detector (UGLD)	1	1	1	1	1	1	1	1	1	1
3. Detection coverage area										
Catalytic (CGD)	1	1	1	1	1	1	1	1	1	1
Open-path infrared (OPGD)	4	4	4	4	4	4	4	4	4	4
Point type infrared (PGD)	1	1	1	1	1	2	1	1	1	1
Ultrasonic gas leak detector (UGLD)	5	5	5	5	5	5	5	5	5	5

4. Response time										
Catalytic (CGD)	3	3	3	3	3	3	3	3	3	3
Open-path infrared (OPGD)	4	5	5	5	5	4	4	5	4	4
Point type infrared (PGD)	5	4	4	4	4	4	4	4	4	4
Ultrasonic gas leak detector (UGLD)	1	2	1	1	1	1	1	1	1	1
5. Oxygen deficiency resistance										
Catalytic (CGD)	1	1	1	1	1	1	1	1	1	1
Open-path infrared (OPGD)	4	4	4	5	4	4	4	5	4	4
Point type infrared (PGD)	5	5	4	5	5	5	5	5	5	5
Ultrasonic gas leak detector (UGLD)	5	5	4	5	5	5	5	5	5	5

Appendix D. Detail result of alternative Judgment for Risk Criteria

Function	Safety and Method Eng II.	Production/process method Eng III.	Head of Operating Philosophy and Safety Concept	Safety and Method Eng I.	Head of Field Operation Safety and Method Services	Head of Production Support Department	Safety and Method Eng III.	Production/process method Eng II.	Production/process method Eng I.	Maintenance Instrument Eng.
Name	FDW	BJ	SS	GW	AD	RD	DS	DW	SS	AM
1. Spurious detection										
Catalytic (CGD)	4	4	4	4	4	4	4	4	4	4
Open-path infrared (OPGD)	3	2	2	3	3	2	3	3	3	4
Point type infrared (PGD)	5	4	5	5	5	4	4	4	4	2
Ultrasonic gas leak detector (UGLD)	2	1	1	2	2	1	2	2	2	2
2. Environment distractive signal										
Catalytic (CGD)	2	2	3	3	3	3	3	3	3	3
Open-path infrared (OPGD)	2	3	2	3	3	3	2	3	3	3
Point type infrared (PGD)	5	5	5	5	5	5	5	5	5	4
Ultrasonic gas leak detector (UGLD)	2	2	1	2	1	2	1	2	2	2
3. Sensor poisoning (undetectable in fatigue condition)										
Catalytic (CGD)	1	1	1	1	1	1	1	1	1	1
Open-path infrared (OPGD)	4	4	4	4	4	4	4	4	4	4
Point type infrared (PGD)	5	5	5	4	4	4	5	4	4	4
Ultrasonic gas leak detector (UGLD)	5	4	5	4	4	4	4	4	3	4

Catalytic (CGD)	4	2	3	3	3	3	3	3	3	3
Open-path infrared (OPGD)	3	3	4	4	4	4	3	3	3	3
Point type infrared (PGD)	5	4	4	4	4	4	4	4	4	4
Ultrasonic gas leak detector (UGLD)	1	1	1	2	2	2	2	2	2	1
5. Immaturity of technology										
Catalytic (CGD)	5	5	5	5	5	5	5	5	5	5
Open-path infrared (OPGD)	3	3	3	3	4	3	2	2	2	2
Point type infrared (PGD)	4	4	4	4	4	4	4	3	4	4
Ultrasonic gas leak detector (UGLD)	2	1	2	1	2	1	2	1	1	1