CRANFIELD UNIVERSITY

RAYMOND EE TZE SIONG

DERIVATION OF A METHODOLOGY TO COMPARE C, B AND R DETECTION CAPABILITY IN URBAN EVENTS

CRANFIELD FORENSIC INSTITUTE
MSc by Research

Academic Year: 2014 - 2015

Supervisor: Dr Matthew Healy
Oct 2015

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ABSTRACT

Many comparisons have been made between Chemical detectors (C), between Biological (B) detectors, and between Radiological detectors (R), providing insights to the best C, B and R equipment for a given purpose. However, no comparison has been made between C, B and R systems to appraise how C, B and R detectors perform against each other and where capability gaps lie. The dissertation generates a method to achieve an inter-comparison between C, B and R detection capabilities and identifies where to invest resources to achieve a more effective overall CBR detection architecture.

The inter-comparison methodology is based on an operational analysis tool (SMARTS). The overall CBR detection architecture is illustrated through detect to warn and detect to treat mechanisms across the timeline of a realistic scenario. The scenario has been created to be non-prejudicial to C, B or R incidents, deconstructed into four frames to accommodate SMARTS. The most suitable deconstruction is into early warning, personnel security screening, initial response and definitive identification frames. The most suitable detector Key Performance Characteristics (KPCs) are identified for each frame. SMARTS is performed by analysing the current performance of the C, B and R detection systems drawn from the literature and the target requirements determined by defensible logic. The desire to improve each capability from its current state to target requirement is subjectively determined by the author. A sensitivity analysis is applied to mitigate the effect of a limited pool of opinion.

Applying the methodology to published CBR detection capability data and the author's appraisal of the target requirement reveals that B detection requires the greatest development and R the least, and that detection in the security screening and initial response frames falls short of capability compared to early warning and definitive identification frames. Selectivity is a challenge across a broad range of frames and agents.

This work provides a methodology that is modular and transparent so that it can be repopulated should new data or alternative perception arises.

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Last but definitely not least, my family is my greatest motivation in Cranfield. I would like to thank them for their emotional support throughout my stay in Swindon. In particular, my wife has supported me selflessly by accompanying me throughout my stay in UK.

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LIST OF ABBREVIATIONS

ACPLA	Agent Containing Particles per Litre of Air
AHP	Analytic Hierarchy Process
ATP	Adenosine Triphosphate
CB	Chemical and Biological
CBR	Chemical, Biological and Radiological
CBRN	Chemical, Biological, Radiological and Nuclear
CBRNE	Chemical, Biological, Radiological, Nuclear and Explosives
CWA	Chemical Warfare Agent
DR	Desire Ratings
DSTO	Defence Science and Technology Office
FOV	Field of View
FTIR	Fourier Transform Infrared
GCMS	Gas Chromatography
GCMS	Gas Chromatography and Mass Spectrometry
GM	Geiger Muller
HPGE	High Purity Geranium
IDLH	Immediately Dangerous to Life or Health
IMS	Ion Mobility Spectroscopy
IPE	Individual Protection Ensemble
KPC	Key Performance Characteristics
LWIR	Long Wavelength Infrared
MCDA	Multi Criteria Decision Analysis
P2P	Person to Person
PMT	Photomultiplier Tube
PPL	Particles per Litre of Air
RTG	Radioisotope Thermoelectric generator
SMART	Simple Multi Attribute Rating Techniques
SMARTS	Simple Multi Attribute Rating Techniques with Swing Methods
STEL	Short Term Exposure Limit
TIC	Toxic Industrial Chemical

1 : INTRODUCTION

1.1 Chapter Introduction

The aim of this chapter is to provide an overview of the research. It outlines the motivation of the research, and the objectives and methodologies involved in achieving the aim. This chapter also summarises the dissertation by simplifying the proposed methodology in a chronological fashion.

1.2 Research Motivation

Sensing has always been a pivotal aspect in Chemical, Biological and Radiological (CBR) defence architecture. Especially since the onset of post 9-11 incidents, several government agencies [1, 2], independent laboratories [3], commercially interested companies [4], and independent researchers have been studying and analysing detection technologies within each of the CBR domains. These studies seem to always anchor on a specific domain (C, B or R), and leverage on the subject matter experts' experiences and knowledge in an attempt to close the gap between the current capabilities and the ideal situations. None of these efforts seem to have a direct comparison between C, B and R detection capabilities. This comparison may be crucial in providing a holistic understanding of the current CBR detection as a subject, and potentially could identify the main gap in a comprehensive manner. Coupled with a good comparison methodology, this analysis may also point to a research direction that requires more attention.

1.3 The Research Objectives

The objective of this dissertation is to contribute to the understanding of the current CBR detection capability gap, and to provide future potential research focal points with the aim to develop a more effective overall CBR detection architecture, aligned with the operators' needs and requirement.

In order to achieve the aims and objectives, the main tasks for this work are:

- Development of a sound methodology as a platform to compare the C, B and R detection capability.
- Preliminary comparison and analysis of the C, B and R detection capability.

The methodology discussed in this dissertation involves subjective judgements in several aspects of the C, B and R detection capabilities. Unless explicitly stated in the dissertation, the analysis on the C, B and R capabilities are purely based on the author's perceptions and interpretation of the current technological strength and limitations.

1.4 Methodology Summary

This section provides an overall summary of analysis approach, and aims to give the reader a concise expectation of this dissertation. The strategy for the comparison is presented in a chronological fashion in Table 1.

Table 1: Summary of comparison methodology.

Steps	Description	Chapter
1	Defining the scenario A realistic scenario comprising four discrete frames of detection architecture is created.	7
2	Selection of C, B and R representative agents The comparison of C, B and R detection capability is aimed to be as encompassing as possible, but due to the time limit of this dissertation, certain criteria are compared by representative agents of the C, B and R domain. The agents are selected via Analytic Hierarchy Process, a decision modelling tool.	6
3	Defining the Key Performance Characteristics The KPC of a detection system are discussed and selected.	3, 7

4	Defining the hierarchy The comparison is modelled as a hierarchy tree with the goal of ranking the relative C, B and R detection capability in terms of their detection system criteria. The overall comparison is modelled using SMARTS method.	4, 5
5	Define the target value of each criterion The ideal target of each criterion for the CBR detection systems in each frame of the overall scenario is rationalised.	7
6	Defining the current performance for each detection system in each frame The current performance of each criterion is discussed.	3
7	Criterion performance measurement The desire of each criterion to be improved from its current value to the ideal target is compared for each C, B and R detection system.	8
8	Deriving weights of criteria in each frame The weights of the criteria in each frame are derived using the same method.	8
9	Deriving the weights of frame towards the success of overall detection architecture The importance of each frame towards achieving the goal is discussed.	8
10	Summation of weights The weights of the criteria are normalised and summated for the C, B and R systems to derive an overall ranking for the capability.	8
11	Analysis Sanity checks are performed, and the results are discussed.	9

1.5 Report Structure

The dissertation is structured into 10 chapters as follows:

Literature Review

Chapter 2 – CBR Sensing Capabilities

Chapter 2 provides an introduction to C, B and R agents and the overall CBR defence strategies.

Chapter 3 – Detection Architecture

Chapter 3 discusses the CBR detection architecture by decomposing them into their different elemental components.

Chapter 4 – Multi Criteria Decision Analysis

Chapter 4 introduces the application of multi criteria decision analysis to complex problems, and discusses some critical models that are used in this dissertation.

Methodology

Chapter 5 – Methodology Discussion

Chapter 5 describes the overall strategy and procedure to compare the C, B and R detection capabilities.

Chapter 6 – Selection of a Chemical, Biological, and Radiological Agent

Chapter 6 summarises the selection of a specific C, B and R agent via one of the decision analysis models. These agents are required in the comparison of the capabilities with respect to specific criteria.

Chapter 7 – Scenario Planning and Analysis of Scenario

Chapter 7 details the analysis of the four frames that directly impact the success of the specific scenario in this dissertation.

Results

Chapter 8 – Results Generation

Chapter 8 details the generation of the results using the proposed SMARTS method.

Chapter 9 – Results and Discussion.

The results are analysed, and sanity checks are performed in Chapter 9. Discussions on the framework approach and recommendations are also detailed.

Conclusion

Chapter 10 – Conclusion

Chapter 10 summarises the dissertation, covers the conclusions that have been reached and indicates the potential for further studies.

2 CBR SENSING CAPABILITIES

2.1 Chapter Summary

This Chapter introduces the different CBR threats, and discusses the CBR warfare from a historical perspective. It then sets a prelude for detection technology concepts (Chapter 3) by elaborating on the overall CBR defence architecture.

2.2 Chapter Introduction

In the First World War[1], chemical threats are used to incapacitate and intoxicate enemy forces. In Second World War, the Japanese considered the large-scale usage of biological warfare, where tests were performed in laboratories with prisoners as the subjects to study the outbreak of cholera and typhus. Although there were not many incidents of large-scale intentional radiological attacks, several civil accidents has demonstrated the physical and social impacts radiological fallouts could have in the event of a deliberate release. For instance, the Chernobyl nuclear power plant accident in 1986 released radiation that is estimated to cause 27,000 deaths due to cancers [5], and more than half of the adult population in Ukraine appeared to be still concerned about the radiation consequences 17 years on [6].

While state actors' continued research and possession of CBRN agents pose an undeniable threat to the world today, increasing efforts were also diverted to counter CBRN operations from non-state actors. These include terrorist organisations capable of inflicting economic and social damages through small and unpredictable covert operations. One such example is the notorious Sarin attack in Tokyo Subway [7], where 12 fatalities and 50 casualties occurred. It is

[1] Chemical attacks were dated even before the First World War. An example is the Chlorine attacks by the Germans in Ypres. [226]

evident that such non-state actors target social morale and economic impact rather than catastrophic physical damages. For instance, the white powder incident where *Bacillus anthracis* dispersed in the form of powders through the US post office mail delivery system, caused immediate and long lasting effects of fear, and response cost yielding in excess of hundreds of millions of dollars [8]. Despite signing the treaty to ban research and production of nuclear warfare facilities, North Korea continued to pursue their desire of offset threats from South Korea and US in numerous nuclear studies [9].

The evolution of CBR threats from conventional to asymmetric theatres heightens the potential of increased widespread. Perpetrators leverage on the relatively low cost of weaponisation and high availability of these agents to send psychological messages to the rest of the populace into thinking that they might be next [10].

2.3 CBRN vs CBR

CBRN differs from CBR with the inclusion of nuclear (N) threats. The term CBRN has often been used loosely to describe any incident that has chemical, biological, radiological or nuclear elements. However, the effects and consequences of N differ significantly from that of CBR. In the case of a nuclear incident (intentional or accidental), it is often catastrophic and on an extreme scale. The Fukushima Daiichi Nuclear power plant accident in Japan was described by many as a disaster, affecting tens of thousands of a displaced population and resulting in an economic loss of $250 to $500 billion [11]. In intentional nuclear conflicts, the overwhelming blast effects of the nuclear bomb almost brings the destruction level several tiers above that of CBR effect, requiring responses similar to massive scale natural disasters [12]. However, the effects of C, B and R vary according to the intent of the perpetrators and availability of agents, amongst many other factors. Especially in recent incidents, they are often seen in smaller scale attacks that cause more emotional and psychological harm compared to physical damages. Also, the reliance of detection systems in C, B and R differs greatly from that for N incidents. Often, C, B and R incidents are triggered by detection systems, because the latency

effects are generally not immediate, with the exception of some chemicals. Thus, there is a heavy reliance of detection systems in determining the nature of the attack, and also immediate response. However, for nuclear incidents, the effect is accompanied by visible nuclear fallouts and explosions, which trigger immediate death and panic. There is almost no need to detect nuclear incidents technologically; they are detected with our naked eyes. In addition, the detection architecture towards an N incident is categorically different from that of the CBR sensing. In the later, relatively similar emphasis is placed in all aspects of detection from early warning to on-site identification and confirmation. However, due to its severity, the former focuses unbalanced high efforts in post incident monitoring for the aftermath consequence management. The introduction of nuclear element into this dissertation brings the comparison to a different scale point, and unnecessarily complicates the validation of the methodology. Therefore, this dissertation focuses on the comparison of CBR detection capabilities.

2.4 Chemical Threats

2.4.1 Chemical warfare agents

Chemical Warfare Agents (CWAs) are chemicals manufactured with the main purpose of incapacitating, harming or killing in a warfare setting, most of which have modest or no use in industrial applications. The severity of the resulting injuries depends on the type of chemical, the amount and the length of exposure. The most common chemical categories are simplified in Table 2, but they could also be referenced to in several literatures [13, 14].

These agents were typically delivered in vapours and liquid form, but can also be disseminated in sprays of aerosols, resulting in an inhalation hazard. These agents are of great concern not only due to their lethality, but also because of their ease of manufacture with modest laboratory equipment. The level of threat from perpetrator attacks depends on the toxicity of the agent, the technical expertise, the means of delivery, ease of acquisition and the current counter-

measures against them. As detailed in Section 6.3, it is analysed that Sarin, amongst all other potential candidates, has the highest perceived risk of deployment in covert operations.

2.4.2 Toxic industrial chemicals

One huge incentive to use chemicals as the preferred mode of attack is the relative ease of acquisition. There is a wide array of Toxic Industrial Chemicals (TICs) that can easily bring about the same level of harm as their CWA counterparts when used in moderately high concentrations. To qualify as a TIC the chemical must have a lethal dosage concentration of less than 100,000 mg-min/m3 and be produced at more than 30 tons per year at a single production facility [15]. As of 1998, an estimated 25,000 commercial facilities worldwide produce and stockpile chemicals that has potential for dual usages [16], and these figures are increasing to meet the demand of the growing industries over the century.

History has documented the deliberate use of TIC to inflict loss on a massive scale. In 1984, an employee in an Indian pest production facility added excessive water into one of the reactor plants to cause a massive explosion of methyl isocyanate release. According to the density of the population surrounding the vicinity, more than 10,000 fatalities were observed, and 30,000 to 50,000 casualties were reported [17]. Another notable series of TIC attacks was illustrated in Iraq, where chlorine attacks began as early as 2006, with reports of 300 deaths in a series of recent attacks in 2014 [18]. While such common TICs are generally 100 to 1,000 times less toxic than traditional CWAs, they are often stored in quantities 1,000 times larger. The overall package is enticing to perpetrators in their attempt to deliver a cheap and straightforward attack.

Table 3 illustrates the list of TICs employed by NIST[2] in accordance to the hazard level.

[2] National Institute of Standard and Technology.

Table 2: Summarised description of different chemical warfare agents.

Types	Nerve Agents	Blood Agents	Choking Agent	Blister Agents
Mode of attack	Disrupts chemical communication through the nerve systems	Prevents exchange of oxygen and carbon dioxide from the blood to the body cells.	Attacks lung tissue, irritating the bronchi, trachea, larynx and pharynx.	Disrupts nervous systems by blocking acetylcholinesterase.
Dissemination	Aerosol, vapour, liquid	Aerosol, vapour	Vapour	Aerosols, liquid
Effect	Incapacitates at low concentrations. Lethal if inhaled or absorbed through the skin	Incapacitates at low concentration, lethal if inhaled at high concentration	Incapacitates at fairly low concentration, seldom lethal, unless at extremely high concentration.	Temporary blindness, incapacitates at low concentration. Lethal at moderate concentration.
Rate of action	Very rapid by inhalation, slower by skin absorption	Rapid	Rapid	Rapid for sulphur mustard and lewisite
Persistency	Moderate	Low	Low	High
Symptoms	Pupil contraction, involuntary urination, fits, sweating, vomiting, confusion, coma.	Rapid breathing, convulsion, death	Choking	No early symptoms for nitrogen mustard. For Lewisite and sulphur mustard, searing of eyes, stinging of skin, blisters development.
Common Agents	GA, GB, GD, VX	Cyanogen Chloride, HCN, Arsine	Chlorine, Phosgene, Diphosgene	Nitrogen Mustards, Sulphur Mustards, Lewisite

Table 3: List of TICs in accordance to the Hazard Index [19].

High	Medium	Low
Ammonia**	Acetone cyanohydrin	Allyl isothiocyanate
Arsine*	Acrolein	Arsenic trichloride
Boron trichloride	Acrylonitrile	Bromine**
Boron trifluoride	Allyl alcohol	Bromine chloride
Carbon disulfide	Allylamine	Bromine pentafluoride
Chlorine**	Allyl chlorocarbonate	Bromine trifluoride
Diborane	Boron tribromide	Carbonyl fluoride
Ethylene oxide	Carbon monoxide*	Chlorine pentafluoride
Fluorine	Carbonyl sulfide	Chlorine trifluoride
Formaldehyde	Chloroacetone	Chloroacetaldehyde
Hydrogen bromide	Chloroacetonitrile	Chloroacetyl chloride
Hydrogen chloride**	Chlorosulfonic acid	Crotonaldehyde
Hydrogen cyanide*	Diketene	Cyanogen chloride*
Hydrogen fluoride	1,2-Dimethylhydrazine	Dimethyl sulfate
Hydrogen sulfide	Ethylene dibromide	Diphenylmethane-4,4'-diisocyanate
Nitric acid, fuming	Hydrogen selenide	Ethyl chloroformate
Phosgene**	Methanesulfonyl chloride	Ethyl chlorothioformate
Phosphorus trichloride	Methyl bromide**	Ethyl phosphonothioic dichloride
Sulfur dioxide	Methyl chloroformate	Ethyl phosphonic dichloride
Sulfuric acid	Methyl chlorosilane	Ethyleneimine
Tungsten hexafluoride	Methyl hydrazine	Hexachlorocyclopentadiene
	Methyl isocyanate**	Hydrogen iodide
	Methyl mercaptan	Iron pentacarbonyl
	Nitrogen dioxide	Isobutyl chloroformate
	Phosphine**	Isopropyl chloroformate
	Phosphorus oxychloride	Isopropyl isocyanate
	Phosphorus pentafluoride	n-Butyl chloroformate
	Selenium hexafluoride	n-Butyl isocyanate
	Silicon tetrafluoride	Nitric oxide
	Stibine	n-Propyl chloroformate
	Sulfur trioxide	Parathion
	Sulfuryl chloride	Perchloromethyl mercaptan
	Sulfuryl fluoride**	sec-Butyl chloroformate
	Tellurium hexafluoride	tert-Butyl isocyanate
	n-Octyl mercaptan	Tetraethyl lead
	Titanium tetrachloride	Tetraethyl pyrophosphate
	Trichloroacetyl chloride	Tetramethyl lead
	Trifluoroacetyl chloride	Toluene 2,4-diisocyanate
		Toluene 2,6-diisocyanate

* Blood agent
** Choking agent

2.5 Biological Agents

Biological agents are organisms that cause disease in humans, animals or crops, derived from pathogens and toxins found naturally. There are several incidents of biological weapon uses but the most notable in recent history is the post 911

incident, where purified *Bacillus anthracis* powder was mailed through the US Washington post office to government officials, causing disease to 22 individuals and 5 deaths [20]. Although biological agents have far more potential of mass destruction due to their toxicity, there is significantly less cases of such incidents compared to their chemical counterparts. One possible justification is due to the difficulty in dissemination of the agents in their viable state accounted by the small range of temperature that the biological agents can effectively thrive in. Another reason may be due to their difficulty of acquisition/reproduction compared to chemical threat.

Bioagents can cause infection and even death at extremely low doses compared to the chemical domain. Table 4 shows the ID50[3] of typical bioagents.

Table 4: Toxicity of options in terms of ID50 [21, 22, 23, 24]

Biological Agents	**ID50 (Spores/organisms)**
Bacillus anthracis	10,000 Spores
Yersinia pestis	10 organisms
Francisella tularaemia	10 organisms
Smallpox virus	5 organisms
Marburg virus	100 organisms

The Centre of Disease Control and Prevention (CDC) has classified potential bioagents into three priority tiers, as illustrated in Table 5. Category A has the highest priority, and it includes organisms that pose the highest risk to national security in terms of its dissemination ability, transmissibility and lethality. Category B has moderate risks, while category C denotes emerging risks [25]. Similar to the chemical agents, the risk of each biological agent being deployed in an attack is estimated based on various factors such as the availability, lethality, ease of acquisition and many others. As evident in Section 6.4, *Bacillus*

[3] ID50 refers to the infectious dosage that is administrated, causing approximately death in 50% of the exposed population.

anthracis is perceived to be of the highest risk to be deployed in a biological incident.

Table 5: Classification of Bioterrorism Agents / Diseases.

Category A	**Category B**	**Category C**
Bacillus anthracis	*Brucella* species	Nipah virus
Clostridium botulinum toxin	*Clostridium perfringens*	Nipah virus
Yersinia pestis	*Salmonella*	Other emerging diseases
Variola major	*Burkholderia mallei*	
Francisella tularensis	*Burkholderia pseudomallei*	
Filoviruses and arenaviruses	*Chlamydia psittaci*	
	Coxiella burnetii	
	Ricinus communis	

2.6 . Radiological Agents

According to historical records of WMD, radiological threats are seemingly less common compared to biological and chemical counterparts, but since the 1990s, there has been heightened concerns about illicitly obtained nuclear and radiological materials from the dissolved Soviet Unions for use in perpetrators acts [26]. The most recent notable radiological attack is the poisoning and death of Alexander Litvinenko [27], who was poisoned by Polonium-210, a strong emitter of alpha particles.

Although all chemical, biological and radiological threats cause disruption and destruction, the route of effect for radiological threat is dissimilar to its chemical and biological counterparts. The real threat of the radiological material comes not from the radiological particle, but from the radiation that is emitted, damaging the

biological cell in the body. The damage is proportional to the type and intensity of the radiation received, which is influenced by the radiological particle. Radiation emissions are a consequence of an attempt of the radioactive isotope to obtain stability, resulting in the emission of particles or energy such as alpha and beta particles, or gamma energy. The three forms of radiation differ in their ionising and penetrating power, with alpha radiation having the strongest ionising power and weakest penetrating power, and gamma radiation on the opposite end. As such, external exposure to gamma radiation poses the highest threat, while inhalation or ingestion of alpha particles is more lethal.

The biological effects of ionising radiation can be categorised as being either deterministic or stochastic [28]. Stochastic effects are independent of the absorbed dose, and observed to have no threshold, often associated with increased risk of developing cancerous cells. Deterministic effects occur beyond a certain threshold, and occur more quickly and severely with the increase in amount of radiation absorption. Clinical significant effects of acute radiation syndrome occurs at a dose greater than 1 Sv [29], although mild syndromes like nausea and headache may occur at as low as 0.3Sv [30].

Radiological fallouts can also be released during a nuclear attack, such as the massive Hiroshima atomic bomb incident. However, such an incident requires planning and skillsets of a much higher level, of which many may be beyond the means of a non-state sponsored organisation [31].

Of all the possible radiological agents that could be utilised in a dispersed aerosol attack scenario, it is perceived that Cobalt 60 poses the highest threat. The derivation is discussed in detail in Section 6.5.

2.7 Counter CBR Concept of Operation

Figure 1 shows the intimate relationship between the five critical components of a successful CBR defence operation. A successful CBR defence architecture encompasses all the five elements, and because of their strong interdependency, a balanced developmental and deployment effort must be achieved to ensure the

robustness of the architecture. This concept resonates with the US Homeland Security Presidential Directive, which states that the essential pillars of their (bio) defence program are: Threat Awareness; Prevention and Protection; Surveillance and Detection; and Response and Recovery [32]. The detailed studies of each element are required to gain understanding of the entire CBR operational spectrum, but this is beyond the scope of this dissertation.

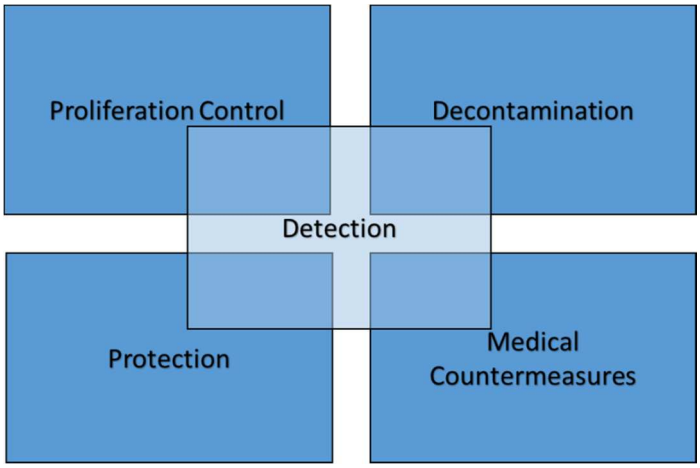

Figure 1: Principle components to a successful CBR defence architecture.

2.7.1 Proliferation control

In FY13, the UK spent two million pounds on supporting projects to reduce the threat of weapons proliferation [33]. This included CBRNE[4] intelligences updates and policing services to understand incidents involving CBRNE materials, emerging threats, trends, trafficking routes and methods [34]. In addition, there are treaties and conventions in place that outlaw production, stockpiling and use of WMD to curb and reduce usage of such CBRN agents [35, 36, 37]. These treaties bind the rallied countries with mutual interests in conforming to the contract, and to exert further confidence, they are often subjected to regular verifications and enforcement inspections. The result is a reduction in weapon proliferations.

[4] Chemical, Biological, Radiological, Nuclear and Explosive

2.7.2 Protection

In a counter response to a CBRN attack, protection for the first responders and equipment are deemed critical for the continuity of the mission. It is also vital that the correct type of Individual Protective Ensemble (IPE) is presented to the individual faced with a different kind of threat. There is currently no one-size-fits-all solution, as different forms of barriers are required to counter each CBRN domain. Even within the chemical domain, there are various protection postures that can be adopted, and the selection to upgrade / downgrade the protection is assessed on the ground, after the chemical agent and its concentration are made known. Usually the responder enters the hot zone in a fully encapsulated suit in response to an unknown threat. Such protection posture exert extremely high heat stress to the wearer, and without proper ventilation, the operator would not be able to endure a 45-minute operation [38]. On the other hand, there are not many choices for IPE in a biological incident, as the operator needs to be constantly in an airtight suit to prevent exposure to airborne particles. IPE is almost[5] non-existent in a radiological scenario. Gas masks are always required as part of the IPE, to prevent inhalation of gases and aerosol particles. They work on HEPA[6] filtration basics, and can stop particles efficiently, only if they are well fitted to the wearer's face.

Collective protection or critical infrastructure protection employ the same concept – to create an area devoid of contaminants for the safe protection of unprotected inhabitants within it. Such protection is necessary in a military context where soldiers operating in IPE are required to recover during shift rotations, and where victims are subjected to decontamination in a hot or warm zone environment. In a civilian context, such protection is necessary for the continued survival in the presence of outdoor contaminants. While the science on protection is profound, the key takeaway is the need for efficient filters or barriers in both personnel and

[5] There have been few companies demonstrating success in IPE that provide full body protection against gamma radiation.
[6] High Efficiency Particulate Arrestance

infrastructure protection, and such filter considerations are varied dependant on the type of threat presented.

2.7.3 Decontamination

This element supports the requirement to neutralise and remove chemical, biological and radiological contaminants from the victims (primarily) and equipment. Personnel and equipment decontamination is usually performed as soon as practically possible after zonal segregation to reduce the risk of contamination, whereas terrain and infrastructure decontamination can take place at a much later phase. The need for speed of decontamination operations is also dependant on the type of CBR agent presented in the intentional release, where chemical agents present a need for more rapid decontamination due to its fast medical effect. While distinct methods are established dependant on the domain and type of agents, the general idea of such an operation is to remove any residual contaminants from the naked body to prevent cross contamination and further intake of the agent. Liquid decontamination in the form of soap and water are the most generic method for personnel, equipment and terrain decontamination. Other decontamination methods such as gas and water spray scrub the air and neutralise aerosols. Decontamination procedures and protocols must be standardised and communicated across the different agencies involved to ensure efficiency under chaotic and stressed conditions set upon by the release of such agents.

2.7.4 Medical countermeasure

As mentioned, the priority of the counter CBRN operation is to save life and reduce injury. One important aspect of life saving is the direct intervention through medical countermeasures, which arrives in the form of antidote treatment and supportive care. It is elementary to note that treatments are often specific to different contaminants, and thus accurate identification of the agents is crucial before administration of the antidotes. In all situations, life support therapy is always required to provide immediate relief to the incapacitated victims.

2.7.5 Detection

As illustrated in Figure 1, the detection and warning element spans across all phases and aspects of an overall CBRN mission, and thus is considered most critical to its overall success. In the early phases, an early warning capability is required to alert any incoming threat to the protected infrastructure in order to adopt a defensive posture. Constant monitoring of the situation also provides updates on the changing ambient environment, providing clues of impeding attacks. Upon the incident, detection systems must be in place to classify the attack and identify the threat. Confirmation of the attack requires high definition and quality of the identification process, and this is crucial to the down streaming evidence collection and potential prosecution. Such identification processes are usually performed in the national established laboratories with appropriately sophisticated equipment to meet the demand of high accuracy and precision.

In all, an effective CBR detection architecture will ensure CBR materials are rapidly detected, identified, monitored and safely managed at all levels of incidents [39, p. 18].

2.8 Chapter Conclusion

The threat from CBR has evolved dramatically since World War II, as more terrorist groups are openly expressing willingness to use weapons of mass destructions, and declaration of CBRN acquisitions [40]. The need to understand and explore all the possible routes of interventions is apparent, and the route to a successful CBRN countermeasure is to couple the knowledge of CBRN agents with a successful framework of defence architecture.

3 DETECTION ARCHITECTURE

3.1 Chapter Summary

This chapter discusses the overall CBR detection architecture by breaking it down into distinct detect-to-warn and detect-to-treat frames of a scenario. It introduces the concept of Key Performance Characteristics (KPC) of a detection system, and its influence towards the success of the depicted scenario. The performance of the current dominant C, B and R detection systems in terms of the KPC will be discussed.

3.2 Chapter Introduction

In response to the demanding needs of a detection system, a careful consideration of the detection architecture is required to ensure a robust implementation of the multistage detection. The detection mechanisms required differs at the three distinct stages of the incident. The initial phase *before* the incident requires both constant monitoring and deliberate screening at key intersection points to act as early warnings. Detection systems are required *during* the actual happening of the incident as a means of attack notification and extent of the release. Lastly, detection systems are required *after* the event to provide confirmatory evidences for treatments and prosecutions. The core functions of detection systems revolves around these stages, and should be examined in detailed. As such, the following sections of the chapter (and subsequently chapters) deconstruct the architecture into four distinct frames as follows, where each frame represent progressive phases through the timeline of a general CBR scenario.

(i) Early Warning Frame (*Before)*

(ii) Security Screening Frame (*Before)*

(iii) Initial Response Frame (*During*)

(iv) Definitive Identification Frame (*After)*

In general, the Key Performance Characteristics (KPC) of the detection system evolves as it progresses into the different frames of the operation. In the early stages, the reactive responses towards a successful detection is more forgiving towards a less sensitive result, but requires a high speed of detection, while the responses in the later stages would choose sensitivity and specificity over speed. The shift of emphasise may be due to the consequences of the actions following the detection results. A multistage detection assessment will mandate the inclusion of several different detection technologies into the overall defence architecture to build in an increasingly accurate understanding of the nature of the attack.

The following sections highlight each of the key frames and the current capabilities within an efficient detection architecture. The KPC selection considerations are elaborated in section 5.4. In general, the main KPCs of a detection system are sensitivity, selectivity, response time and range. In Chapter 7, the efficacy of the KPCS of current detection systems in each C, B and R domain will be analysed.

3.3 Frame 1: Early Warning Capabilities

For all CBR operations, there is a need for early warning, especially so in situations where avoidance and protection of key infrastructure is key in the overall defence strategy. This detect-to-warn system aims to provide ample warning to personnel and potentially infrastructure, preventing exposure and the need for subsequent treatment. The nominal defence concept hinges on the ability to sense a threatening cloud as far upwind as possible in the fastest possible time before they reach the defended perimeter. Early warning of CBR agent infiltration is thus deemed as the most critical key to effective avoidance and protection against any form of contamination. Such capabilities are instrumental in the contamination avoidance scenario. Early warning generally comes in two forms, standoff and remote detection.

There are several definitions [41] of “standoff” detection, but loosely, it refers to the capability to be alerted to a potential attack without physical contact, from a distance away. The general consensus is that deployment of such a C, B or R standoff sensor[7] should result in providing ample time to the commanders to perform certain preventive measures of contamination prevention to the potential targets. These actions are often highly dependent on the type of scenario at hand, and also the confidence level in the sensors used in the detection. Coupled with the accepted inherent limitations of high false alarm for all CBR early warning capabilities, the actions associated with the triggering of the alarm is often limited to low regret and low logistical burden actions, such as:

a. Initiation of further monitoring
b. Initiation of sampling
c. Isolation of HVAC for key infrastructure
d. Deployment of mobile response vehicle to site
e. Increase alert status for first responders

High regret and high logistical burden actions such as full evacuation of building and total turnout of response forces are avoided due to the relatively low confidence of the results provided. Standoff capabilities are often equipped with sensors that sense further from the point of deployment, with a much wider field of view. This implies the deployment of a lesser number of sensors, and thus benefitting from prudence in both a financial and resource sense. In addition, such sensors are usually placed on higher ground, usually right on top of the potential target. Apart from having a line-of-sight, all-round elevated coverage, such deployment is away from public scrutiny and limits access to theft and mischief.

On the other hand, a remote detection system is often associated with having an array of point detectors that are networked within the array. These sensors are deployed upwind with reference to the potential release sites, and they usually

[7] A standoff sensor in this section, refers to a C, B or R equipment that responds in a form of alarm, to the presence of C, B or R threat in the environment. An example of a chemical standoff sensor is Rapid Plus by Bruker.

have a smaller range and field of view. Since the possible release sites are numerous, it implies that a higher number of sensors will then have to be deployed at the different locations. Especially in an urban setting, it may be difficult to decide on where to deploy the fleets of sensors. Deploying arrays of remote sensors also comes with the problem of signature and theft, unless the sensor can be secured to higher grounds. Lastly, wireless sensor networking technology, which serves to interlink the sensors together, may be off-the-shelf but is definitely not a plug and play solution yet. Together with other technological challenges [42], the technology may not be seen fielded in the coming years.

In the derivation of the methodology for CBR detection capability comparison in this dissertation, the study of early warning capability will be limited to standoff solutions.

While this concept of early warning (standoff) is conventional and often applied for C and B defence architecture, such a tactic is not mature for radiological defence, and its success is heavily dependent on the type of dissemination method the perpetrator chooses to adopt. Firstly, nearly all detection technologies for radiation require sufficient energy to reach the sensor before analysis and subsequent alarm is triggered. This means that if an operator holding a handheld radiation detector were to receive warning from his sensor, he himself would already have received the radiation, and this intensity is as high as what the detector had prompted. In a similar sense, if enough intensity were to trigger the sensor placed over the roof of the stadium, it may well indicate that the same intensity of energy would be presented to the spectators in the stadium. Next, early warning would not be so applicable in a point release scenario far away from the intended target, because any perpetrator with the intention to carry out an R attack should minimally understand the basic theory behind radiation exposure. The intensity of the energy radiated by the radioactive source diminishes at magnitudes according to the inverse square law and attenuated in air according to the Beer Lambert law. Even neglecting attenuation, a source with an initial intensity of 1 mSv/hour at 1km away would yield only 1×10^{-6} mSv/hour when it reaches the target, barely sensed by the most sensitive radiation sensor.

To readily affect a target population, the distance between the source and the target must be minimised. To readily find a source that is intense enough to be effective at 1km away would be a challenge in all aspects, and even if the source was obtained, the perpetrator must then derive a plan to shield the source and attenuate the energy during the transportation. Since radiation dissipates in all directions, the perpetrator must also devise a method to release the source when he is further away from the source than the intended target. With all the implausible constraints, it is said with confidence that a point release of radioactive source would not be feasible for a standoff event.

However, it is possible for the perpetrator to aerosolise radioactive material and disperse it from a distance upwind from the target. The smaller radioactive particles would then drift down with the wind, unnoticed by the naked eye. Such dispersion would require a general aerosol particle counter for preliminary detection, but it is also noted that this method is a crude method, and could give rise to multiple false alarms.

3.3.1 Chemical standoff sensing

In this kind of long range scenario, the agents are most likely to be released in the form of aerosol or vapour, whereby it travels downwind towards the intended target. The detection system senses the incoming aerosol / vapour, characterises them, and subsequently alarms the use while tracking the plume direction. Such detection of plumes is dominated by Long Wavelength Infrared (LWIR) Fourier Transform Infrared (FTIR) detection technology [43, p. 18], where the chemical agents absorb characteristic wavelengths of the incident infrared. Detailed explanation of the technology is not within the scope of this dissertation, but they are well documented in literatures [43]. The incident radiation, when in active mode, is emitted by a transmitter such as a hot filament or laser. Passive sensors make use of surrounding blackbody radiation acquired from sources like the sun, landscape or a huge body of water. Most of the LWIR sensors in the market adopt passive sensing, as they are not reliant on artificial line-of-sight sources, and thus have the ability to acquire coverage of a larger area [44, p. 87]. The chemical agent, depending on the electric dipole moment of the molecule, absorbs specific

energy within the infrared radiation. Table 6 lists some of the important chemical agents of concern and their detectable range of wavelengths in the infrared region. It is evident that most of the agents of concern lie within the LWIR (8 to 15 µm), hence alluding to the fact that most detectors employ only LWIR as part of the detection algorithm.

Table 6: CWAs, TICs that can be detected in specific spectral region [45].

Descriptions	Agents
9 – 11.5µm (LWIR)	
CWAs	Lewisite, nitrogen mustard, sulphur mustard, 4-Dithiane, Diisopropyl methylphosphonate, dimethyl methyl phosphonate, isoamyl alcohol, methylphosphonic difluoride, cyclosarin, sarin, soman, tabun, VX, triethyl phosphate,
TICs	Ammonia, arsine, boron trichloride, ethylene oxide, nitric acid
4 – 9 µm (MWIR) – Mid Wavelength	
CWAs	Mustard, sulphur mustard, 4-dithiane
TICs	Boron trifluoride, carbon disulphide, formaldehyde, hydrogen cyanide, hydrogen sulphide, nitric acid, phosgene, sulphur dioxide, tungsten hexafluoride
2.5 – 4 µm (SWIR) – Short Wavelength	
TICs	Hydrogen bromide, hydrogen chloride, hydrogen fluoride

Figure 2 shows a pictorial representation of the theory behind a passive FTIR sensor. The sensor scans the environment for the normal background emittance, and detects for thermal contrast, indicating a potential absorbance. The incoming radiation is then fed through an interferometer, where it is deliberately split and recombined by a fixed and a moving mirror, resulting in an interference pattern, which is then analysed via Fourier transform principle into a spectrum of high signal to noise ratio. The spectrum is then referenced to the inbuilt library of toxic gases to determine the presence (absence) of the agent. The library can

theoretically store a limitless number of experimentally determined spectrums of chemical agents.

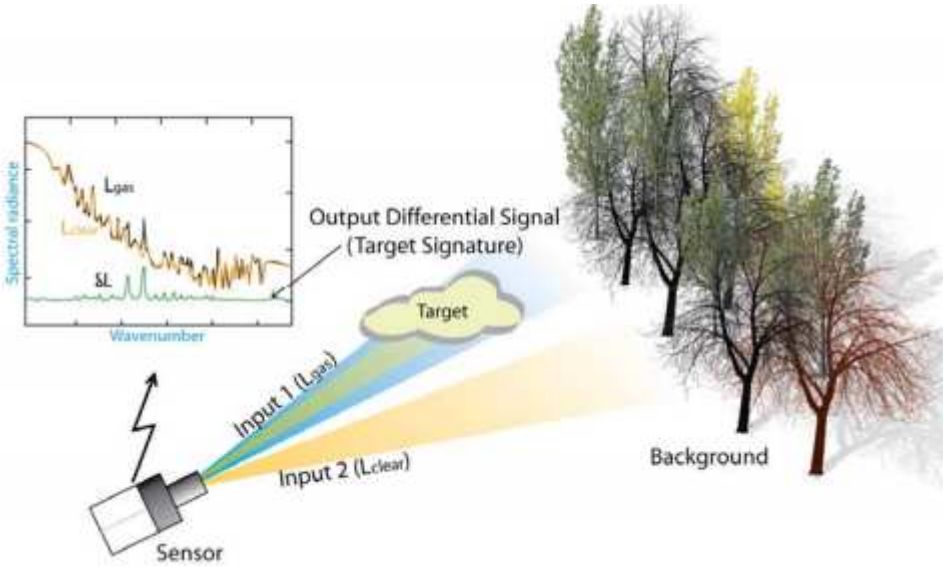

Figure 2: Principle of FTIR [46].

3.3.1.1 Sensitivity

Sensitivity of a LWIR standoff detector is often measured in units of ppm-m[8] or mg/m^2, which is a resultant of the product of the concentration of plume and path length. Thus, this is dependent on the wind direction and the location of the sensor. As the pathlength increases, the concentration required decreases. A typical chemical standoff sensor (Secondsight by Bertin) has a sensitivity of $100mg/m^2$, equivalent to 16ppm-m [47]. This figure is obtained in a laboratory environment, and in reality, it is reasonable to include a 50% factor of uncertainty. This is aligned with the experimental measurements derived by L. Halasz *et al* [48, p. 52].

3.3.1.2 Selectivity

Most chemical standoff sensors work on a specific band of infrared energy for detection of chemical plume. The reliance of only one specific band brings about higher resolution and lesser need for power requirement. The chosen band is

[8] A sensor having a sensitivity of 100 ppm-m means that it can detect concentration as low as 1ppm, provided that the IR light travels a total distance of 100m through the plume.

almost always LWIR, since it covers the widest range of chemical agents that are of threat. However, this alludes to the inability to detect a few selected lists of CWAs and TICs, as shown in Table 6. Evidently, prominent and possible agents such as hydrogen chloride, phosgene, ethylene oxide and sulphur mustard, amongst others, are not detectable in LWIR. Furthermore, chlorine, as a homonuclear molecule, cannot be detected using infrared absorption techniques [49]. In addition, the large poly atomic nature of several CWAs results in several peaks, and thus the use of a wider range of infrared is applicable. This increases the chance of encountering interferent absorption within the same range, resulting in a high false alarm situation. Figure 3 illustrates an example of possible false alarms due to similar spectrum from an interferent.

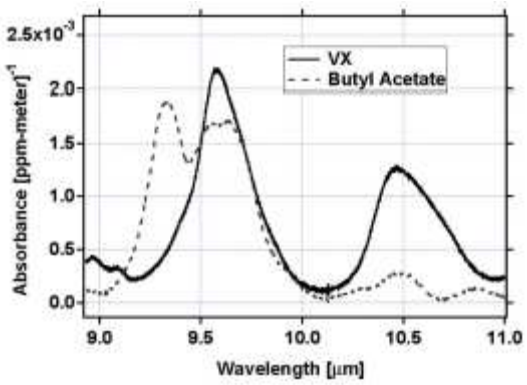

Figure 3: IR-absorption spectra of VX and potentially interfering species, butyl acetate [45, p. 3].

3.3.1.3 Response time

The standoff sensor works by performing a scan in the horizontal and vertical direction to cover the desired area coverage. As such, the sensor may not be able to acquire the agent upon its release. The time taken for the sensor to acquire the plume within its field of view, denoted as the reaction time, plus the processing time of the sensor to alert the operator, is the effective response time of the system. Philipe *et al* suggested a method based on field surface scanning rate of the detector to derive the reaction time of different commercially off the shelf standoff sensors, which ranges from 2 seconds to 145 seconds [50]. Assuming that the plume is only detected at the end of the scan (worst case), and

including a processing time of approximately 60 seconds, the appropriate response time of a current standoff sensor can be estimated at 200 seconds.

3.3.1.4 Range

Conservatively, a typical chemical sensor can detect up to a range of 3km[9], with relatively good resolution and response time.

3.3.2 Biological standoff sensing

Unlike chemical agents, biological agents lack distinctive signature that can be detected from a distance, complicating remote monitoring of the potential biological threats. The current technology for standoff biological detection provides only discrimination of biological and non-biological particles at best.

The dominant technology for standoff biological detection is active UV laser induced fluorescence LIDAR (Light Detection and Ranging). The theory and setup of the equipment are discussed in several literatures [51, 52]. In summary, the transmitter uses a laser source capable of transmitting pulsed ultraviolet lasers of 266nm or 355nm, or a combination of both. Such laser beams are targeted at biological aerosols that absorb the laser, and re-emit them at different (longer) wavelengths. The receiver then collects the re-emitted laser, and filters them in attempt to collect the specific wavelengths in different photomultiplier detectors (PMT) [53, p. 12]. One of the PMT is designed to collect the scattered light at 266nm, which determines the particle's size. With a transmittance of 266nm, the second PMT detects UV light in the 300-400nm range, distinct of emittance from tryptophan[10], a signal of protein presence in bioaerosol. In a system where 355nm is transmitted, the third PMT collects visible light from 400 to 600nm to sense presence of NADPH[11] typically of living bioaerosols. Although such methods are unable to provide the ideal specificity required, it serves

[9] This range was chosen as a conservative figure. Tests from several institutions [50] [228] used 3km as the base requirement for standoff detection experiment or verifications.
[10] Tryptophan is a standard amino acid found in all biological cells. The presence of tryptophan is indicative of only cells of biological origin, but it cannot discriminate between living and dead cells.
[11] NADPH is the reduced form of NADP (Nicotinamide Adenine Dinucleotide Phosphate). When cells die, NADPH is oxidised to NADP. By detecting NADPH, it allows a distinction between viable and non-viable cells.

adequately as an early warning system to indicate an abnormal plume of biological agent organisms approaching the target. Figure 4 illustrates the basic principle of biological agent standoff detection.

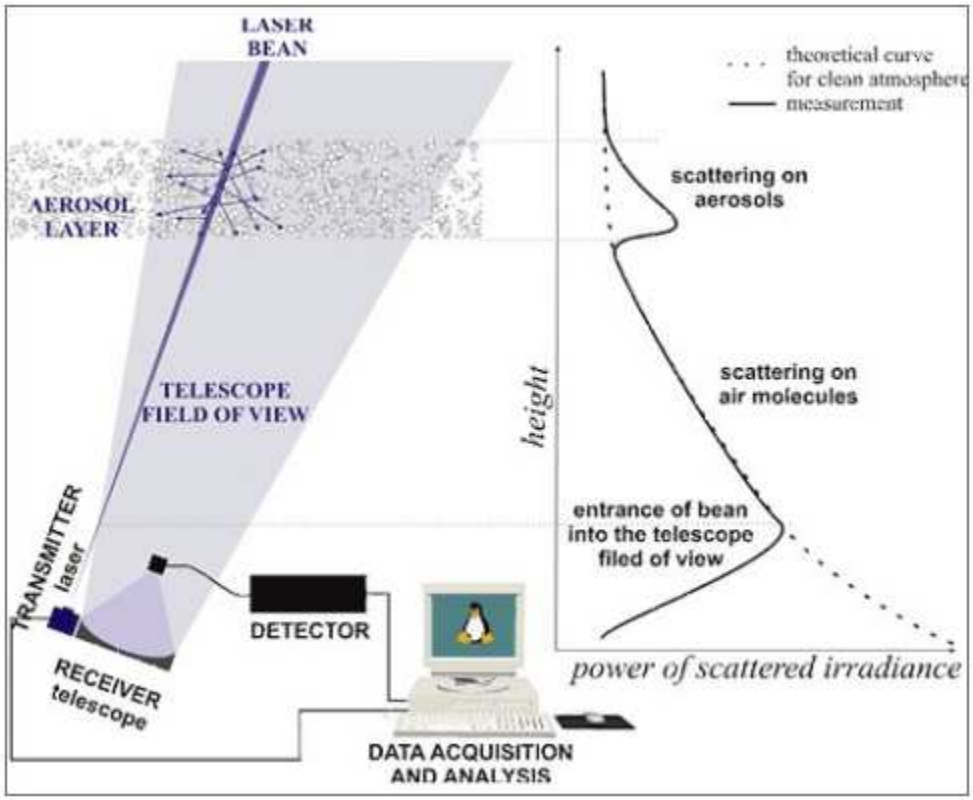

Figure 4: Principle of LIDAR system [54, p. 8].

3.3.2.1 Sensitivity

Similar to the chemical standoff sensor, the sensitivity of a biological standoff system is measured by the product of the concentration and path length. For a biological system, the unit of sensitivity is often recognised to be ppl-m (particles per litre of air) or ACPLA-m (Agent Containing Particles per Litre of Air). A trial conducted by DRDC [55, p. 41] suggested that the sensitivity of SINBAHD ((Stand-off Integrated Bioaerosol Active Hyperspectral Detection) is 144 kppl-m (144 ACPLA[12]) [56] at a range of 1.2km. In another, the US army revealed that the JBSDS (Joint Biological Standoff Detection System) has a sensitivity of 3000 ACPLA-m (assuming pathlength of 1m) at 3km [57]. On the conservative side,

[12] Assuming that the ratio of viable aerosols to total particles in air is 10% [158].

the later shall be assumed as the sensitivity of current biological standoff detection system.

3.3.2.2 Selectivity and false alarm

In the detection of specific emittance by biological particles in the air, the receiver also detects other sources of infrared from the sun, moon reflectance, and scattered lights. A narrow band of filter is thus required to reject these interferents in the night, but an even narrower band is required for the daytime. In addition, unlike chemical detection, the biological standoff detection has no ability to discriminate between harmless biological background aerosols such as fungi spores and polycyclic aromatic hydrocarbons [58, p. 21], and biological agents of concern. Charles [58, p. 19] also suggested that the total number of background aerosols can exceed the target biological agent by orders of many magnitudes. This causes exceptionally high false positive alarms due to the innocent triggers. With the high aerosol background, there may also be potentials of false negatives, where the biological aerosols are masked by the interferents.

3.3.2.3 Response time

The response time of a typical biological standoff sensor can be calculated in a similar fashion as the chemical system. S. Buteau *et al* proved that the field of View (FOV) of SINBAHD is calculated to be 1.34×10^{-3} deg^2 [55, pp. 6,7]. With a pulse repetition rate of 250 Hz, the field scanning rate is calculated to be 0.335 deg^2/sec. With the assumption of 3km range and 1.5km width, the total FOV of 392 deg^2 is required. Thus, the total scanning time calculated is approximately 20 minutes. Assuming that the plume is only detected at the end of the scan (worst case), and including a processing time of 60 seconds, the appropriate response time of a current standoff sensor can be estimated at 21 minutes.

3.3.2.4 Range

Conservatively, a typical biological standoff sensor can detect up to a range of 3km [59].

3.3.3 Radiological standoff sensing

There is currently no radiological standoff capability that can be fielded with much success. The closest to analysing a radiological plume dispersal would be utilising the same LIDAR technology (as the biological standoff sensor) to visualise the increase in concentration of dust particles in the environment. A small pulse of laser light is shone within the field of view towards the environment, typically from NG:YAG laser. In normal ambient conditions, the backscatter from air and insignificant dust particles are measured as background noise. In the event of a release of unexpected plume, the Mie backscatter increases and is reflected via the photomultiplier tube within the LIDAR system; this increases the backscatter coefficient, and the plume is immediately tracked.

This system is flawed with uncertainties leading to high false alarm rates. Communications with other agencies are required at every alarm, and such information sharing systems enhance the understanding of the plume nature, reducing false alarms.

3.3.3.1 Sensitivity

Such an aerosol tracking system has a typical sensitivity of 1000ppl-m at 5km [60, p. 56]

3.3.3.2 Selectivity and false alarms

As expected, this kind of system alerts the operator to any form of aerosol plumes, ranging from haze, soot, industrial releases, and CO (carbon monoxide) emission, to even chemical and biological releases. It does not differentiate the radioactive plume from other non-radioactive plumes, making it non-ideal in terms of selectivity. While the false negative alarms are as frequent as those in the chemical and biological systems, the false positive alarms are much more frequent, even after information sharing from other agencies.

3.3.3.3 Response time

The response time of a typical radiological standoff sensor can be calculated in a similar fashion as the chemical or biological system. Referenced from [61], the FOV of a typical LIDAR system is calculated to be 3.27×10^{-5} deg^2. With a pulse

repetition rate of 5000 Hz, the field scanning rate is calculated to be 0.16 deg^2/sec. With the assumption of 5km range and 1.5km width, the total FOV of 238 deg^2 is required. Thus, the total scanning time calculated is approximately 24 minutes. Assuming that the plume is only detected at the end of the scan (worst case), and including a processing time of 60 seconds, the appropriate response time of a current standoff sensor can be estimated at 25 minutes.

3.3.3.4 Range

While many [60, 61, 62] have claimed that the range of such a LIDAR system can reach between 5 to 55km, it is uncommon for deployment at such distances. Therefore, we can assume the worst case of a maximum range to be typical of 5km.

3.4 Frame 2: CBR Personnel Security Screening Capability

Security screening of personnel and vehicles for illicit CBR agents are highly regarded as an essential means to counter immediate threats. Such detection is aimed at individual or covert attacks, and often performed at cross-boundary areas or prior entrance to a highly secured infrastructure. As will be described in Chapter 7, this dissertation will emphasise on personnel screening to key events.

Security screening for humans is a difficult subject because with the increase in screening, the throughput is generally reduced. This generates another set of security problems because of the increase in human traffic before the security point, providing opportunity for attacks. In addition, while CBR threats are consistently mentioned in many literatures on security screening [63, p. 124, 64, 65], most security screening efforts at such events have not been specially adapted to CBR concern [66]. X-ray machines are deployed mainly for countering conventional weapons such as knives, guns or even grenades, although they can also discover and screen for liquid / powders that potentially can be a chemical

or biological threat. In furtherance, detection of chemical[13] and biological substances is challenged by the difficulty in identifying target substances in the midst of structurally related substances in the environment. The EU Commission has also recognised this as a threat to the public security, and has since performed studies to adopt best practises for background checks and security vetting [67].

At the checkpoint, all bags and personal belongings will be screened through the X-ray machines for metal detection. The analysis of the X-ray technologies are not within the scope of this dissertation, but it is sufficient to know that X-ray technologies such as conventional transmission imaging, dual energy X-ray, scattering imaging and 3D imaging [68], allow for detection of liquids and powders. The person is then required to walk through a metal detector, and is subjected to physical search in case of a positive alarm. The bags are also subjected to random scrutiny and detailed checks. At this stage, it is evident that the speed is equally as important as the actual security check itself, and the concern for a slower throughput is the heightened risk for potential target of a perpetrator attack. A study [68] revealed that rapid screening for faster turnover and inadequate human attention are the top two reasons for screening failure.

3.4.1 Security screening for Chemical and Biological (CB) threats

As mentioned, human security screening lacks proper and efficient procedures for CB checks. The current practise for chemical threat screenings is the usage of conventional X-ray machines with backscatter technology in search of liquid. Occasional bag searches increase the probability of finding hidden CB agents, but this is limited often again by the intention of increasing throughput. In addition, a perpetrator would deliberately disguise threats that can easily fool the eyes of an inadequately trained security officer. For instance, liquid agents can be disguised in milk for babies, while powdered agents can be placed in cosmetic pouches. CB point sensors are always only on standby, and only utilised on rare

[13] Although there are easily measurable indicators for chemical agents like pH changes, they are highly unstable and prone to false alarms, thus seldom deployed.

occasions because such procedures will reduce the throughput time, and signatures of such spraying devices would be easily picked up by the X-ray machines.

3.4.1.1 Sensitivity

The sensitivity of the current CB security screening is limited to the ability of the X-ray system to pick up liquid and solids in powder form. Even with the successful detection of the suspect, the overall success of the detection of CB threat is dependent on human intervention. This dependency on humans to resolve the alarm is definitely not the most desired and sensitive method.

3.4.1.2 Selectivity and false alarm rates

The current X-ray systems visualise the objects within the bags according to the density, atomic mass on the screen, and leaves the human operator to interpret the results.

Any liquid or powder of adequate quantity and size is alerted to the operator, prompting him to conduct the secondary human intervention at his own discretion. This non-ideal selectivity also results in high false alarms, as most of the liquid and powders are brought in for legitimate reasons. This is also a classic example of the catastrophic effects of false alarms; the operators get complacent or lose confidence in the detection, and often perform low standards of post inspection.

3.4.2 Security screening for radiological threats

It is common for radiological portals [69] to be deployed at ports to screen for increase in radiation beyond background. Such technologies are often found at human screening points. These are passive devices that capture any radioactive emission. In addition, radiation sensors are also placed near the bag checking areas, where any increase in radiation will trigger alarms for further inspections. At certain events, personnel may also walk through a metal detector, coupled with beta and gamma radiation detectors. Common detection technologies employed includes scintillation counters and the Geiger Muller (GM) detector. It is not practical for one to smuggle in alpha particle emitted radioisotopes. Such isotope poses no risk to external exposure due to its weak penetrating power,

and although it is an exceptional inhalation hazard, to deploy such an attack would require an accompanying spraying device, which is detectable by X-ray machines.

3.4.2.1 Sensitivity

The measurable range of typical radiation portal monitors starts from 0.1mSv/hr.

3.4.2.2 Selectivity and false alarm

The radiation portal is only selective to pick up gamma (and neutron) emission, because of its relatively high penetrating power. However, this does not have significant influence on the false negative alarm rates, due to the low possibility that the perpetrator will attempt to bring across the checkpoint alpha and beta emitters as a form of attack. More often, the alarms are due to legitimate and innocent sources of radiation from medical isotopes.

3.4.2.3 Response time

As with all radiation detectors, the reaction to an increase in radioactive dosage is instantaneous.

3.5 Frame 3: Initial Response to CBR Incident Capability

When detect-to-warn fails, the CBR defence architecture is exposed to attacks. Responders face a lot of challenges when they arrive at the scene of a deliberate terrorist release. The primary challenge is the ascertaining and distinguishing between the CBRN releases. The presumptive identification of the agents in this scenario takes a two-phased approach. The first phase is aimed at narrowing the scope of detection to the specific regime. Situation awareness and on the spot elimination is of high importance here, where the responder on site surveys around for immediate casualty, and distinct smell and colour. A chemical attack has the greatest potential of displaying observable clues, due to their inherent physical properties. For instance, common chemical warfare agents such as Tabun has a distinct fruity smell, while toxic industrial chemicals like chlorine, ammonia and sulphur each have their distinguishable odour. Most chemicals

achieve at least the incapacitating effect at fairly low concentrations, and the latency period is often faster compared to biological and radiological attacks. On the other spectrum, biological and radiological aerosols or particles are often colourless, odourless and cannot be seen by naked eyes. For biological agents, the latency period varies, but rarely felt immediately. Effects of radioactive isotopes are only felt immediately (deterministic effect) with high dose in excess of 1 Sv, and it should be noted that in most perpetrator radiological incidents, the radiation exposure levels will be far lower than those shown to have an immediate latency effect [70]. That being said, the visual observation of the situation would allow the commander to preliminarily rule out the potential of a biological and radiological event should one of the following observations be made.

1. Distinct or unexplained odour
2. Distinct colour of vapour, liquid
3. Perception of ‘oily’ atmosphere
4. Immediate casualty

This is however, just a preliminary result that temporarily discards the possibility of biological and radiological incident due to time constraint, and efforts to revisit these areas must not be undermined, shall detection of chemicals fail.

3.5.1 Chemical detection capability in an initial response scenario

There are many technologies in the market that can be adopted in such a detect-to-treat scenario, and they rely on specific physiochemical properties of the target analyte for a qualitative or at best semi-quantitative analysis.

One of the most common technologies used is that of the IMS (Ion-Mobility Spectroscopy) technology. To date, several established equipment such as RAID-M-100, CAM and GID-3 are based on IMS technology to respond selectively and accurately to the toxic chemical vapours. It is not the scope of this dissertation to detail all the various technologies deployed in the sensors, but their implementation, advantages and disadvantages can be easily referenced to several open sources [71, 72, 73]. The various sensors in the market that incorporate such technologies can be sourced online [19].

IMS technology classifies the chemical agents according to their ion mobility within the drift tubes. The air samples are absorbed into the sample chamber, where the radiation source (commonly used is Nickel-63 [74]) bombards the sample with beta emissions, thus ionising it, and breaking them into their individual components. The components drift down the drift tube at various times depending on their weight and such drifting induces electrical activities, which are characteristic of the chemical.

Another technology that is commonly used is that of Flame Photometry techniques. In such a technique, the air samples (or solid samples in other cases) are fed into the inlet of the detector, where a hydrogen flame of 2000 to 5000 Deg C decomposes all organic compounds into ions, emitting photons of different wavelengths. In such a detector, the optical filter is selected to only filter photons emitted from excited phosphorous and sulphur containing compounds, and the signals are relayed through the photomultiplier tube to generate an alert in the presence of such elements.

The cheapest and most widely used detection system in a detect-to-treat scenario is the colorimetric detection method. The detectors are filled with substrates that are impregnated with certain colorimetric reagent specific to the target of interest. When the target is present in the sample, chemical reaction occurs, causing a change in colour of the sorbent. This change is detected visually. Such detectors range from simple strips of paper for conventional warfare agents like Sarin and Sulphur mustards, to tubes impregnated with adsorbing reagents for more diverse ranges of chemicals.

There are many other technologies that can be easily adopted to answer to the needs for immediate response, but each has their own limitations. The concept of use for these detectors must be outlined clearly, so that the advantages of the different technologies can be leveraged accordingly.

3.5.1.1 Sensitivity

Different technologies yield different sensitivities, depending on the intrinsic physiochemical properties of the target and the performance of the detector itself.

Independent tests conducted by the US Department of Defence (DOD) on various detectors suitable for such scenarios showed that most of these detectors could at most detect at IDHL[14] level when exposed to Sarin gas. Table 7 showed a compilation [75, 76, 77, 78, 79, 80, 81] of these tests in terms of the detector sensitivities. Since IMS is one of the most common instruments used, the common sensitivity of detectors found in these scenarios can be assumed to be approximately 0.03 mg/m^3.

Table 7: Sensitivity of various point detectors.

Detector Model	**Technology Used**	**Sensitivity to Sarin (mg/m^3)**	**Response Time (Sec)**
RAID-M	IMS	0.037	8 - 41
APD2000	IMS	0.021	16 - 20
IMS2000	IMS	0.03	8 - 41
AP2C	Flame Photometry	0.02	6 - 72
SAW MiniCAD	SAW	0.4	158 - 301
HazmatCAD	SAW	0.3	186 – 209
DCT[15]	Colorimetric Technology	0.02	400
Nextteq Civil Defence Kit	Colorimetric Technology	0.1	450

3.5.1.2 Selectivity and false alarm

Most technologies for chemical detection are selective towards specific agents. For instance, flame spectrometry is only able to detect chemicals with sulphur and phosphorous elements, which excludes common TICs like chlorine, ethylene oxide, ammonia and many others. IMS has a potential of detecting a wide spectrum of chemicals, but due to the limitation of its resolving power, most of the commonly available MS detectors can only classify between nerve, blister, blood,

[14] Immediately dangerous to health level. The IDHL for Sarin is 0.1mg/m^3.
[15] Draeger Colorimetric Tube

and choking agents, with very limited selection of TICs. The colorimetric technology is even more limited by the availability of the various reagent tubes on the scene, and definitely cannot cover all the possible chemical agents that a perpetrator will use. This is not ideal for a detect-to-treat scenario, where the agents used are unknown and limitless. In addition, IMS detectors are relatively low resolution and prone to false positive alarms when innocuous chemicals in the ambient air has similar ion mobility and may be misidentified as an agent of concern. Commonly found urban chemicals also include insecticides, which are an interferent for flame photometry. Orthogonal detectors in the market utilise different technologies to target different physio-chemical properties of the spectrum, and thus reduce false alarms. However, not all countries or first responders use this equipment because they are often bulkier and more expensive. Instead, most response forces resort to using the technology in combinations to eliminate false positive alarms and increase selectivity. For instance, the SAW technology provides more accuracy but lacks sensitivity. On the other hand, IMS and Flame Photometry provide the ability to detect at low concentration, but are prone to false alarm. When used in combination, the technologies complement each other and achieve better results.

3.5.1.3 Response time

Table 7 also shows the response time for each detector to detect their respective minimum detectable concentration. Although it is seen that IMS can typically detect the agents at less than 30 seconds, such technology requires a warm-up and setup time of approximately 3 to 4 minutes. Thus, the effective response time of a typical chemical detector can be estimated as 5 minutes.

3.5.2 Point detection for biological threats

Technologies for biological point detection are the least matured of the three. The technologies of biosensing in such detect-to-treat mechanisms can be found in several open sources [82, 83], but in general the range of devices for field detection is narrower, and most of them do not work in real time. In this scenario, where time is of the essence, the first responders do not have the luxury of deploying equipment that require 30 minutes or 1 hour to give a reading, and thus

have to rely on a simple test that yields fast results. Where the output may not be as fruitful as the chemical sensing, it provides a means to affirm a biological attack, where a complete series of tests could be performed at the laboratory before a confirmative identification can be made [84].

Point detection of bioaerosol often begins with sampling, and most point sensors couple their mechanism with simple sampling devices. Sophisticated samplers such as gravity devices, impactors and suction samplers are normally reserved for dedicated samplers, which feed directly to confirmative identifiers [84]. Simple aerosol collectors found in point detectors include swabs, wipes and sponges moisture with buffer solutions [85].

The actual biological detection for an initial response scenario consists of point and handheld sensors that target the different biological aspect of a bacterial or virus cell. Simple, one-time use of handheld immunoassay technology relies on the different molecular responses towards specific antigens. Most fielded immunoassays come in strips of a pass-fail test (Figure 5). The air samples are collected and concentrated in small amounts of liquid buffer, and lined against the dye labelled antibodies that targets specific biological threats. If the sample antigen is positive of the suspected biological agent, the affinity of the antigen and antibody induces the appearance of control lines, confirming the presence of the agent.

Bioluminescence based detection targets the presence of Adenosine Triphosphate (ATP), a test of living cells, but they are unable to confirm the identification of the agent. With the presence of luciferin and luciferase [86], the increase in bioluminescence is captured and the intensity reflects on the concentration of the target agent. Such a test has low limit of detection as compared to other assay methods, but it lacks selectivity.

Figure 5: An Illustration of a suite of immunoassay detection kit. (Source: http://www.environics.fi/product/envi-assay-system/)

3.5.2.1 Sensitivity

Table 8 extracted from a market survey [3] performed by Pacific Northwest National Laboratory shows the sensitivity of various detectors towards detection of *Bacillus anthracis.*

Table 8: Sensitivity of common biological detectors.

Model	**Technology**	**Limit of Detection (spores/ml)**	**Response Time (minutes)**
Haztech WMD Kit	Immunoassay	100,000	10
Biothreat 1 Agent	Immunoassay	15,000 to 83,000	15
RAID 5 / RAID 8	Immunoassay	100,000	15
BBI Detection	Immunoassay	10,000	15
New Horizon Diagnostic	Immunoassay	100,000	15
Prime Alert	Bioluminescence	100,000 to 1million	15
Profile 1	ATP Test	2,000 to 10,000	15

The average sensitivity of a typical biological detector for initial response is assumed from Table 8 to be 100,000 spores/ml. Assuming that 1ml out of 5ml of buffered sample solution is used in the analysis, in order for a successful analysis, the buffered solution must contain 500,000 spores. Assuming that the sample collector has an efficiency of 50%, 2 minutes of sampling will sample 400L (assuming an effective sampling collection of 200 L/min) of contaminated air,

which should contain 1,000,000 spores. Therefore the sensitivity of the biological detector in terms of the contamination air is extrapolated to be 2.5 million spores/m^3.

3.5.2.2 Selectivity and false alarm rate

Such a generic biological test is non-selective, as it is not targeted at specific biological agents, but detects the presence of all biological molecules in the air. This also leads to high false alarm rates due to the potential interferents in the ambient air. The antigen-antibody based detection is more specific, but currently there are only solutions for common biological agents. Furthermore, it is uncommon and impractical for responders to perform sampling to cater to individual tests for the wide range of biological agents.

3.5.2.3 Response time

From Table 8, the response time for a typical biological detector for the initial response capability is estimated to be 15 minutes.

3.5.3 Point detection for radiological threats

While the perpetrator can easily disperse chemical agents that yield immediate visible injuries, such an outcome is not easily achievable for radiological incident. In addition, in most cases the populace exposed would most likely be able to walk away from the source before being administered with lethal doses, since the primary damages are likely to be only stochastic effects.

In such event of a radiological incident, identification of the source could be performed at a later stage to initiate the specific treatment. At this frame, it is crucial to confirm the radiological nature of the attack to ensure subsequent identification can be performed at the laboratory with much higher precision. This is made more tedious than the chemical scenario because unlike chemicals, radiological particles are odourless and colourless, and the only way to initiate a radiological detection response is the suspicions aroused by unusual parcel or powders floating in the air.

Exact identification of the isotope does not provide additional value to the decision at this stage. This hypothesis is supported by the fact that any form of radiation is deemed unnecessary and hazardous to exposed victims, and exposure and subsequent contamination to the public must be avoided at all cost.

Radiation detectors generally fall into two categories, gross counters and energy sensitive. The former type of systems detect each emission as a count regardless of the energy emitted, and thus the output will be proportional to the number of emission events, without identification of the radioactive isotope. The latter system is normally more sophisticated and analyses the radioactive isotope's distinct energy emission and, based on the resolution of the technology, the source can be identified with varying confidence. This technology, as will be elaborated in the next section, is generally more costly and requires additional training to optimise the performance. The immediate first responders thus may not always have the luxury of being equipped with such field equipment. More viable solutions come in the form of gas filled detectors. These technologies provide readings in counts per minute, which reflects generally the amount of activity, and in some cases, the types of activity.

The principle behind gas filled detectors lies in the ionization of the gas within the detector, inducing current that is analysed to provide the output reading. The fast moving radiation in the form of alpha, beta and gamma passes through the gas, and depending on the ionisation energy of the radionuclide, the gas molecules are ionised, forming an electron and a positively charged molecular ion. The ions move toward the electrodes at extreme ends of the detector, producing an electrical signal. The numbers of ion pairs are dependent on the (i) type of radiation presented, and (ii) the potential applied across electrodes. The different potential applied reflects on the different types of gas filled detectors, which are well documented in different literatures and texts [87, pp. 171-182, 88, 89, 90], and summarised in Figure 6

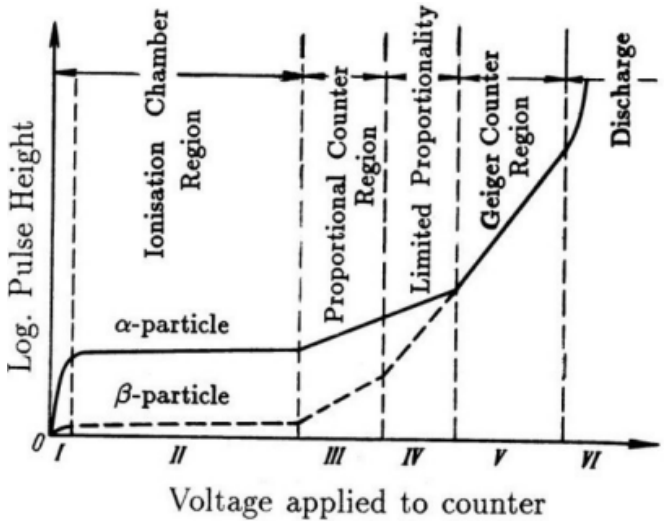

Figure 6: Different potential applied results in different applications for radiation detector.

Of these, the most common and applicable detection system in such a scenario is the Geiger Muller (GM) counter. Unlike the ionization chamber and proportional counters, the GM counter requires very high potential across the electrodes. As the potential increases, the acceleration of the ion towards the anode increases, and this increased energy results in multiple collision with the neutral gas (normally argon), resulting in further ionisation. Due to the secondary ionisation, the electrical signals are often amplified by factors of 10^8. Distinctively, each type of emission produces different magnitudes of primary ionisation, but with the high gas amplification, they cannot be easily distinguished from the output electrical signal, as depicted in Figure 6.

3.5.3.1 Sensitivity

In general, a GM detector displays radiation detection in terms of counts/second (cps) or counts/minute (cpm), but based on the detector probe area and the specific nuclide of interest, this reading can be internally calibrated to reflect radiation in mSv/hr or mGy/hr. Table 9 shows the specification of a typical Geiger Muller probe [91] that is capable of measuring all alpha, beta and gamma radiation.

Table 9: Typical sensitivity for a radiation detector for initial response.

	Sensitivity of Probe (cps/Bq)	**Sensitivity of Probe (cps per µSv/hr)**	**Measurement Range**	**Minimum[16] Detectable Dose / Exposure**
Co-60 (Gamma)	-	6.4	1 – 9999cps	0.1 µSv/hr
Sr-90 (Beta)	0.65	-		1.53 Bq/m^3
Am-241 (Alpha)	0.12	-		8.33 Bq/m^3

3.5.3.2 Selectivity and false alarms

A typical GM counter, intrinsically, is unable to differentiate between alpha, beta and gamma emission. Due to the different penetrating power of the different emissions, different probes are required to target the different emissions. An alpha or low energy beta probe usually has a wide sampling area with a thin mica window to permit the entry of particles with such low penetrating power. For the detection of gamma radiation, no windows are required due to the higher penetrating power. Although there are also probes that can accommodate the detection of all alpha, beta and gamma radiation, it comes at the expense of sensitivity. In addition, even with a ‘all-in-one” R detection system, it is physically challenging to detect alpha particulate in an aerosol dispersion scenario, since alpha particles have low penetration power, and may not be easily detectable in the open environment.

A different approach to false alarm is adopted in a radiological environment, as opposed to a chemical or biological scenario. Before the event, the background radiation around the area is measured and tabulated to understand the required

[16] Assuming minimum range is 1 cps. Area of probe is approximately 15cm^2. Therefore, minimum detectable exposure is calculated to be 1 / (sensitivity*0.000015m^2)

threshold, eradicating the notion of background radiation as a form of interference. The next level of innocent alarms comes from medicinal isotopes, which are irrelevant in this scenario, where victims and un-related personnel are ushered away from the inspection area. Therefore, this infers that there are negligible sources that will cause false positive alarms to the radiation detector.

3.5.3.3 Response time

The GM counter offers real time reading without appreciable start-up time.

3.6 Frame 4: Definitive / Confirmative Identification

While rapid and prompt qualification of either C, B or R agents are life-saving and essential, accuracy and sensitivity are often compromised. Where more detailed analysis of the agents is required, definitive identification of the agents are performed. None of the field analytical instruments described in Section 3.5 could be substitutes for a full scale laboratory analysis. Definitive identification pure from any doubts is performed in the laboratories or mobile facilities, where more sophisticated equipment will yield results with magnitudes of improvement in accuracy. Samples are collected from various sources, be it washdown from the decontamination process, the personal belongings, or ambient air samples taken from various locations downwind. The results of the identification will be coupled with a full incident report submitted to the higher authority for decision of subsequent actions regarding the sports event. These actions may include decision support, evidence collection for legal prosecution[17], investigation of agent sources, contamination monitoring, and other actions leading to normalcy restoration. For radionuclide identification, the identification of the isotope also aids in the aftermath decontamination protocols.

[17] The gold standard for any courtroom evidence is laboratory analysis [243].

3.6.1 Chemical definitive identification

The detection methods and protocols used in the previous frames for chemical detections are at most presumptive identification, where the information serves extreme importance for immediate decisions in casualty management, especially since chemical threats, when administrated in appropriate doses, would yield immediate observable results. However, even with the high resolution mass spectrometry sensors, mistakes can still occur in the identification of unknown analyte with complex molecular structures. Considering the latency of chemical agents, it is vital that a confirmative identification of the agent be performed to dismiss any ambiguity in the presumptive identification stage. This is especially so, since certain antidotes[18] are in itself toxic, and may cause deadly side effects to the normal population [92]. Confirmative identification will give the green light to administrating such antidotes to incapacitated, but not life-threatened casualties.

The current gold standard for definitive identification of chemical warfare agents is the Gas Chromatography Mass Spectrometry (GCMS) method. Such method is also particularly important to detection and identification of nerve agents, which readily hydrolyse into products such as alkyphosphoric acids. Several references for GCMS exists [93, 94], but in summary, it is an instrumental technique, comprising a gas chromatograph coupled to a mass spectrometer, and in the process vapour samples are separated and identified in a quantitative manner. The sample is sent to the laboratory, where it is pre-processed into a vapour before feeding into the GC inlet. The vapour is carried through the GC column by an inert gas such as helium, where it interacts with the stationary phase in the GC column. The rate of interaction influences the elution rate out of the column. As such, the samples are separated by the different retention time, characterised by a chromatogram, with peaks of different compounds in the sample reflecting the intensity. Such separation technique provides insight to the compounds within the sample, but it is unable to determine the confirmation of the presence of target

[18] For instance, atropine to nerve agents.

agents. The separated compounds are then fed into the inlet of a mass spectrometer, where they are ionised into fragments of characteristic mass/charge ratio, commonly by means of interactions with beams of highly accelerated electrons. These fragments are captured by the analyser at different times and intensities, forming another spectrum. The two spectra are analysed on a single 3-D graph, providing a high-resolution chromatogram that is matched to the library spectra to reveal the identity of the agent.

GCMS equipment typically comprises several bulky components that at best could be easily transported in mobile laboratories. While there are miniaturised and field portable GCMS systems[19], these systems generally lack the resolution required for real confirmative identification.

3.6.1.1 Sensitivity

It has been claimed [95, 96, pp. 61,64] that such a sophisticated laboratory instrument is capable of measuring Sarin in parts per trillion (ppt) in air. Taking a conservative estimation of 100 ppt, the minimum detectable concentration of Sarin for a GCMS is 5.7×10^{-4} mg/m3.

3.6.1.2 Response time

It is claimed [97, pp. 173, 160, 283] that typical GCMS laboratory equipment has a start-up time of 1 hour, and a reaction time of 30 minutes. Therefore, the effective response time is thus estimated to be 1 hour 30 minutes.

3.6.2 Biological identification

With the relatively longer incubation and thus latency periods, first responders have more time to confirm the identity of the biological agents. However, field identification of biological agents is mostly serving the purpose of a yes/no response, and thus heavier reliance is placed on the laboratory identification of the agents.

[19] Hapsite ER by Inficon [247]

A common method of confirmation for *Bacillus anthracis* is that of Polymerase Chain Reaction (PCR) using real-time Taqman assays [98]. The sample is first subject to a thermal cycling under 95^{o}c for 2 minutes for denaturation of the sample's double-stranded DNA. A Taqman probe is then made to attach to the DNA and as the single stranded DNA grows, the receptor of the Taqman is cleaved, giving a fluorescence signal as a result. As the PCR progresses, the number of DNA amplifies, and thus the fluorescence intensity increases. This fluorescence is captured and monitored, and it reflects the presence of the target species.

3.6.2.1 Sensitivity

This method of definitive identification is reported [98, p. 288] to have a sensitivity of 49 spores/m^3.

3.6.2.2 Response time

The Taqman PCR process takes approximately 1 hour [99] to complete.

3.6.3 Radiological identification

Radiological detection and confirmation is the most advanced amongst the three classes. By using different techniques of spectrometry, confirmative identification of all alpha, beta and gamma radioisotope can almost be done on the field, in order to develop the spectra analysis for the radioactive sources. These field analytic equipment are, however, expensive and thus not always available in incidents as "first tier" asset [66, p. 245].

Of these, the most established is that of gamma spectrometry using a High Purity Geranium (HPGe) semiconductor detector. The principle behind this technology is similar to that of the gas-filled detectors, but instead of gas as the medium, a high purity geranium semiconductor fills the void of the HPGe detector. Gamma radiation passes through the semiconductor, and deposits its energy to create electron-hole pair. HPGe is chosen as the gold standard of gamma spectrometry as it requires extremely low energy to create an electron pair, and with this, it has a better resolution compared to other semiconductors. Depending on the energy of the gamma radiation emitted on the spectrometer, each pulse of radiation

creates different numbers of electron-hole pairs, thus generating different intensities of electrical signal. This signal is displayed on a spectrogram, and the intensity reflects the type of gamma radiation.

The gold standard for alpha and beta spectrometry is the solid scintillator technology. In such a system, a fraction of the alpha and beta particles interacts with the medium, usually plastic polystyrene or polyvinyl toluene [100], causing a molecular fluorescence (scintillation). The photons emitted then pass through a thin window towards the photomultiplier tube, where they are amplified before being captured as an electrical signal. The size of the output signal is proportional to the energy dissipated by the incident radiation, which is characteristic of the alpha or beta particles.

3.6.3.1.1 Sensitivity

For gamma spectrometry, a typical HPGe spectrometer is reported to have a sensitivity of 0.10 µSv/hr [101, p. 276], while that for a typical alpha-beta spectrometer is 5.6 Bq/m^3.

3.6.3.1.2 Response time

In order to perform a definitive identification of the isotope of concern, on-site sampling must be conducted. This process, depending on the flowrate of the sampler, usually takes approximately 10 minutes. An additional 10 minutes of waiting time is required for the short-lived radon product from the background to decay. The spectrometry process takes around 10 minutes to complete. Therefore, the total response time is estimated to be 30 minutes.

3.7 Chapter Conclusion

This chapter discusses the four frames within a specific scenario in a detection architecture. In each frame, the current performance of the detector is defined within the selected characteristic of the detection system. A full study of all the scenarios cannot be achieved within the timeframe stipulated for this dissertation, but it is expected that each unique scenario requires the same amount of analysis

to derive the frames and the detector characteristics that are paramount to the success of the scenario. The KPCs of the C, B and R detection systems contribute to the success of each frame within the scenario, and must be thoroughly analysed to understand the limit of the current capability.

4 MULTI CRITERIA DECISION ANALYSIS

4.1 Chapter Summary

This chapter reviews the Multi Criteria Decision Analysis (MCDA) and its applications. The two most common methods of MCDA will be compared and its application to this dissertation will be discussed.

4.2 Chapter Introduction

Decisions for a complex problem are often related to plurality of points of views from different stakeholders [102, p. xxi] arising from the multiple competing criteria imposed by the problem. Without a properly structured analysis, the decision makers are often misguided into decisions that are debatable in their logic. It is vital that the problem be structured into logical components, often decomposed into their fundamental criteria before a thorough analysis is performed. Such method resides within Operational Research (sometimes known as Operational Analysis), where military commanders have been using operational decision tools to aid staff planning, war gaming and logistic relief since World War II [103]. Since then it has been widely acknowledged that sciences are often inadequate in providing quantifiable relationships between many causes and effects, and expert judgement is required to objectify a subjective problem [104].

Multi Criteria Decision Analysis (MCDA) is one of the most established modelling tools for studying such multifaceted problems [105]. Belton and Stewart described MCDA as “a collection of various approaches that seek to take explicit account of multiple criteria in helping individual or groups explore decisions that matter” [106, p. 343]. However, it is noted that these methods and tools are often not available in a readily off the shelf form that can be easily adopted for supporting decision making, especially for complex and multi-dimensional

problems. Therefore, components of such techniques are adopted and modified by analysts to derive a decision support system for the specific problem [107].

There are four basic steps in most MCDA models. First, a hierarchy system or value tree is constructed. The tree systemically breaks down the goal into the various criteria and sub criteria, down to the elemental criteria, showing the inter relationship and dependency to the goal. Next, the relative importance of each criterion is determined via prescribed methods. The accuracy of the decision model is heavily reliant on the different methods used in constructing these criteria's scales and weightages. Concurrently, the options are scored against the criterion via a subjective or objective scoring model. Lastly, the net score is derived via integration of the scores and weightages, summing up to the overall goal.

In regard to this dissertation, the understanding of the current C, B and R detection capability performance gap can be modelled as a MCDA problem. The goal is defined as identification of the CBR detection capability ranking. The comparison of C, B and R sensing capabilities involves multiple conflicting criteria that require an extensive array of studies to derive a quantitative decision. As mentioned, there are several techniques to derive the decision, and each technique yields different complications that will be discussed in the preceding sections.

Two of the better-recognised methods residing within MCDA are the Analytic Hierarchy Process (AHP) and Simple Multi-Criterion Rating Technique (SMART). The following sections describe the two methods in detail and recommend the appropriate method to be used in this dissertation.

4.2.1 Analytic Hierarchy Process

The AHP is a MCDA method developed by Thomas Saaty [108]. Since then, AHP has been widely used in almost every industry to solve problems in an objective manner, such as management decisions [109], supplier selection [110] and strategy selections [111], amongst many others. The most visible advantage of

AHP is its ability to model a problem with multiple conflicting and subjective criteria in a simplistic manner to facilitate decision-making.

AHP allows judgements on intangible qualitative criteria alongside tangible quantitative criteria [112]. The options are placed at the lowest hierarchy for comparison with respect to each of the common elemental criterion. The criteria are then compared to their importance with respect to their higher criteria (if applicable) until they converge at the single goal set. AHP acts on the cognitive behaviour of human, and utilises their subjective experience to derive the relative ratio of performance or importance of the options or criteria respectively.

The steps of the AHP are generally consistent with many other methods within the MCDA. First, the hierarchy tree is generated, with the overall goal at the top of the hierarchy. This goal is then decomposed into several criteria that directly determine the success of the goal. These criteria, depending on the complexity, are then further decomposed until each criterion can be judged independently with respect to other criteria. These elemental criteria form the last layer of the hierarchy [113].

The key to AHP is the usage of pairwise comparison matrix to derive relative weights (importance) for different criteria. Compared to methods that are based on absolute scales, the pairwise comparison method ensures that the decision maker is deliberately placed in a situation whereby he must compare every single criterion to one another, instead of generalising the comparison across the criteria. This way, he is exposed to a comprehensive breakdown of the comparisons between each criterion, reducing judgemental error and providing complete justification for the ranking results based on the comparison [114]. However, pairwise comparison stresses the cognitive nature of a human and as the number of criteria increases, the judgement of the pairwise comparison generally deteriorates. As such, the number of pairwise comparisons in each hierarchy is recommended to nine [115], but there are instances where researchers limit the criterion to six or less [116].

The mathematical formulae to derive the weightages for each matrix are deliberately left out in this paper, but they can be referred to in several textbooks and references [115] [117] [118].

As a summary, each matrix is an *m* x *m* matrix, where *m* is the number of evaluation criteria matrix. Each entry a_{jk} of the matrix **A** represents the importance of the *j*th criterion to the *k*th criterion. Saaty [119] [120] has suggested that the following ratio scale in Table 10 be used, where the relative importance is measured accordingly from 1 to 9, with 2, 4, 6 and 8 representing the intermediate of the intensities.

Table 10: Fundamental scale of importance [121].

Intensity	**Definition**	**Explanation**
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation

Reciprocals of above	If activity *j* has one of the above non-zero numbers assigned to it when compared with activity *k* , then *j* has the reciprocal value when compared with *k*	A logical assumption
Measurements from ratio scales		When it is desired to use such numbers in physical application. Optionally, often one estimates the ratios of such magnitudes by using judgement

The following rules apply:

1. $a_{jj} = 1$
2. $a_{jk}. a_{kj} = 1$

Various methods for calculating the criterion weights from the pairwise matrix were proposed. Saaty recommended the eigenvector method [108], while others estimated the principal Eigen vector of the positive reciprocal matrix or computationally simpler methods using geometric mean of the rows of the priority matrix [122] and column normalisation method [123][20].

The method to be chosen in this dissertation is that of the column normalisation method, whereby weightages are obtained by normalising each column in the matrix and computing the average across each row of the matrix.

Because of the cognitive nature of such comparisons, there is a need to quantity the inconsistency of the comparison results. Saaty **[115]** defined a measure of inconsistency as shown in the equation below:

[20] Taught as part of Operations Research Module in National University of Singapore (NUS) by Prof. Poh

Equation 1: Measure of Inconsistency

$$\mathrm{C.I.} = \frac{\mathrm{I_{max}} - N}{\mathrm{N} - 1}$$

Where

- C.I. = Consistency index
- I_{max}= Eigen value
- N = Dimension of the matrix

A consistency ratio (C.R.) is calculated as the ratio of the C.I. to a Random Indices (R.I.). As shown in Table 11, the RI is related to the dimension of the matrix. A consistency ratio is less than 0.1 (10%) is acceptable as a consistent judgement. If the C.R. value is above 0.1, the decision maker is then required to relook into the judgments to ensure a consistent result.

Table 11: Values of the Random Indices [115, p. 171].

N	1	2	3	4	5	6	7	8	9
R.I.	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

4.2.2 SMARTS

As mentioned, the principles of MCDA can be implemented in several ways. SMART (Simple Multi-Criterion Rating Technique) is arguably the simplest form of them [124] [125]. SMART was introduced by W. Edwards [126] as a method to assess weights for each of the criteria in reflection of the relative importance to the decision. The weight assessment is often performed on a linear scale, with the criteria perceived as least important assigned with a crucial importance of 10. The next least perceived importance criterion is then assigned a number reflecting the ratio of relative importance to the least important criteria. This

process is then iterated until all criteria are assessed. The last step involves normalising to sum the weights to 1.

Edwards and Barron [127] modified SMART to include the swing weight methods (SMARTS) in an attempt to fine-tune the criteria weightage assessment.

The SMARTS method [126] implements steps that are similar to AHP. Firstly, the goals and stakeholders are defined. Next, the criteria and sub criteria are evaluated and placed in a hierarchy. While AHP utilises pairwise comparison matrix to derive the relative weightages of each elemental criterion to their parent criteria, the weights are derived via swing method [128], which garners responses from the decision makers from a different facet. Firstly, two benchmarks are set for each criterion; one representing a “best” or target value that the criterion should attain, and the other represents the “worst” or current value of the criterion. The decision maker is then tasked with ranking the criteria in terms of the desire to swing them from the worst to the best value. The criterion with the highest desire to swing would be given the highest score of 1(or any arbitrary number). The desire to swing for the rest of the criteria is then assessed, and rated relative to the first criterion. There may be instances where the score of a criterion is 0, indicating that there is no desire to swing as the criterion is currently performing at the target value.

The output of this sub exercise is a weightage of the perceived importance for each criterion with respect to their parent criteria.

4.2.3 Differences in the AHP and SMARTS

Based on the descriptions above, it is apparent that the major differences between the two methods are the weight allocation in the criteria and the performance ranking in the options against the criteria.

It is extensively cited that both methods yield their advantages and disadvantages [129, 130, 131], and the method chosen is heavily dependent on the circumstances. The pairwise comparison method is a heavily structured method that follows strong mathematical rationale to derive the weightages. It is useful in hierarchies where there are several layers of criteria before the elemental criteria

are reached. AHP thus provides the formal structure to ensure that every decision node is documented towards the selection of a particular option. Although this inevitably creates more mathematical steps than required to establish the weightages, by defining the compulsory steps it forces the decision maker to infer and analyse each decision node, including redundancy to ensure consistency. This leaves less room for subjectivity compared to the SMARTS method.

However, AHP poses a risk of rank reversal, as described in numerous literatures [114, p. 396, 132]. With the addition of a new option or criterion, the ranking may be reversed for the options, impacting decisions especially when the options are similar. The need for consistency also poses a cognitive problem. While the inconsistency ratio highlights the logical rationale behind the subjective judgement, it introduces the potential for a circulative problem [133]. This problem relates to the famous rock-paper-scissor game, whereby there is no one absolute dominator in the game. Likewise, there may be a situation whereby option A favours over B, B favours over C, and yet C does not favour over A in a consistent fashion. If not within the tolerable range of the inconsistency ratio, this matrix will be flagged up for re-discussion. AHP has not catered sufficiently to such circulative scenarios. Lastly, there is a possibility that decision makers align their pairwise comparison toward the consistency ratio, at times by reverse-engineering the problem to fit the answers within the tolerable range. Such practises allude to a consistent result within the AHP, yet an unrealistic fit to the selection of the options.

While SMARTS do not face these problems, the simplicity of the framework often results in overlooking details amidst the complexity of the problem. By not introducing ‘redundant’ steps as in AHP, SMARTS leaves the logical judgement to the decision maker, and does not possess the means to prompt the user on any possible inconsistency. This problem, however, can potentially be resolved by active brainstorming, or by getting different stakeholders to challenge the collective answer in a holistic manner. In general, SMARTS has been found to be extremely robust for various applications [134].

While AHP and SMARTS both pose different sets of pros and cons, the selection of the MCDA methodology is highly dependent on the relevancy of the method to this dissertation requirement. As iterated throughout this dissertation, the main objective is to compare the C, B and R detection capabilities in their respective environment. The success of such a comparison requires inputs from several facets, and thus with its successful implementation, it will require the involvement of several parties such as first responders, maintainers, purchasers, product analysts and technical researchers. The output of this comparison is the relative ranking of the C, B and R detection capabilities, and they are achieved by dissecting the goal into four different frames, each decomposed to two to four measurable criteria. This process is elaborated in the next section, but following the argument, a total of 12 elemental criteria are derived, and each elemental criterion is made as a subject of performance comparison for the three options (C, B and R detection capabilities). With the deployment of AHP, there will be 36 (12 criteria x 3 options) similarly structured questions. The intent of such questionnaires is to bring clarity and consistency, but as the number of such questions increases beyond a cognitively acceptable limit [115], it brings about more confusion. Although the questions within the questionnaires are straightforward and simple, they pose undesirable cognitive challenges in providing the answers in a clear and concise manner. Comparatively, Brugha [135] analysed that questions set for swing methods in SMARTS are generally more welcoming in comparison to that for pairwise comparisons. He had staged several interviews, and suggested that AHP's 1 to 9 scale caused difficulties leading respondents to constantly reconsider some of their answers. Brugha's findings resonates with the informal interview and pilot run performed with two experts[21] in the CBR field, where the experts were presented with a draft questions to solicit opinions via pairwise comparison methods. Both experts faced cognitive challenges in answering the AHP questions objectively. This affirms that the true usefulness of the MCDA method resides in the procedural

[21] Both reside in Cranfield as permanent staff. Pilot discussion held anonymous.

aspect, where ease of understanding is the key to a successful decision analysis involving discussion from different facets [136].

With the apparent advantages of the SMARTS method, it is proposed that this method be employed for the C, B and R detection comparison. However, as will be discussed in Chapter 6, AHP will be employed in the selection of the C, B and R representative.

5 METHODOLOGY DISCUSSION

5.1 Chapter Summary and Introduction

This chapter details the prescribed methodology in a chronological manner. It forms the skeleton of this dissertation, and the subsequent comparisons are built around the foundation. The subsections detail the procedures of the proposed methodology in a chronological fashion, providing an important outline to the entire methodology.

5.2 Step 1: Defining the Scenario

As articulated in Chapter 3, the detection architecture consists of detection mechanisms in various frames. In order to perform a holistic examination of the C, B and R detection capability, it is pivotal that essential frames of detection be analysed appropriately. While it is not feasible to perform an analysis to encompass every detection scenario and stage, the deliberate creation of a realistic scenario encapsulates the necessary detection phases and ensures that comparisons are performed on a similar platform to instil objectivity. The scenario creation is detailed in Chapter 7, but in summary, the scenario is set on the context of a covert urban dispersion of CBR agents during a high profile event. Such a scenario will encompass both detect-to-warn and detect-to-treat mechanisms. The first frame of the scenario discusses the CBR early warning capabilities and the second frame denotes the personnel security screening capabilities. This scenario assumes that the former two frames of the detection architecture fail to deny the perpetuator's attempt. The third frame sets a platform to compare the CBR detection capabilities during an initial response, while the last frame discusses the CBR definitive identification capabilities.

5.3 Step 2: Defining the Selection of Agent

The selection of a representative agent for each class (C, B and R) is detailed in Chapter 6. In summary, different agents within the same class respond differently to the detection system in place. It is impossible to compare the C, B and R detection capability taking into account the wide array of responses and effects expected from the different agents within the class. To set a constraint for meaningful comparison, a representative of chemical, biological and radiological agent is selected to participate in the comparison. This selection is done via AHP, and is based on several criteria that a perpetrator would consider before selecting an agent for attack. In summary, Table 12 shows the results of the AHP analysis performed in Chapter 6.

Table 12: Summary of representative agents to be used in the comparison.

Class	**Representative Agent**
Chemical	Sarin vapour / liquid aerosol
Biological	*Bacillus anthracis* aerosol
Radiological	Cobalt-60 particulate aerosol

5.4 Step 3: Define the Key Performance Characteristics to be Examined

The performance characteristics of each C, B and R detection system contributes to the success of the respective frame of detection. This performance can be measured in terms of various KPCs of the detection system. For instance, in frame 1, the response time of the detection system plays a crucial role in determining the success of the early warning capability as it directly impacts the time catered for contamination avoidance. On the other spectrum, sensitivity of the detection system in initial response capability determines the ability to detect the desired agents in minute concentrations, and thus is pivotal to the success of frame 3.

Some attributes of a detection system are more important than others in determining the success of the frame, and these KPCs must be explicitly captured in the hierarchy as decomposed elements of the individual frame. The KPCs that are not as influential are deliberately left out to simplify the comparison.

On the other hand, all three C, B and R detection systems in a specific frame may have KPCs that have already met the ideal requirement. For instance, all three detection capabilities in the initial response frame are portable enough to be handheld (although there are some detectors that are slightly heavier). As such, all three C, B and R detection systems in the initial response frame will yield the same result when compared in terms of size and portability. In another instance, at the definitive identification stage it is also assumed that all the C, B and R identification systems possess the minimal requirement to distinctly differentiate the target agent from other interferences. As such, a comparison of this nature adds non-meaningful and unnecessary depth to the hierarchy.

The selection of the KPC must also be stringent enough to sieve out complementary criteria with the aim of avoiding redundancy. For instance, a selective detector senses specific agents, but due to the selectivity, the detector may also face higher false alarms. As such, since false alarm is a consequence of selectivity, the two KPCs are complementary, and by including both of them in the comparison, problems of double counting may arise. Table 13 shows the lists of KPCs to be considered in the comparison.

Table 13: KPCs selected for comparison.

Frame	**KPCs to be considered for comparison**
Early Warning Capability	Sensitivity, Selectivity, Response Time, Range
Security Screening Capability	Sensitivity, Selectivity, Response Time

Initial Response Capability	Sensitivity, Selectivity, Response Time
Definitive Identification Capability	Sensitivity, Response Time

5.5 Step 4: Defining the Hierarchy

The value tree (Figure 7) allows for a visual decomposition of the problem. In this case, the goal of the analysis is the ranking of the current C, B and R detection capability. This goal is decomposed into the four distinct frames, all of which contribute to the successful detection in the overall C, B and R detection architecture. Each frame is then further decomposed into several critical KPCs that directly contribute to the success of the detection in the particular frame. Lastly, the performances of the current C, B and R detection capabilities are measured with respect to each of the KPC.

5.6 Step 5: Defining the Target Value for each KPC

As mentioned in Section 4.2.2, the SMARTS method requires the benchmarking of each CBR option against a predetermined threshold relevant to the KPC that it is measured against. The thresholds for each individual KPC are set to mimic the ideal target state of the KPC for the successful detection. The derivations of these targets are detailed in Chapter 7, but are summarised in Table 14.

5.7 Step 6: Defining the Current Performance for each Detection System in each Frame

The current performances of the C, B and R detection capabilities are sourced through several technical brochures and market surveys. These are detailed in Chapter 3, and summarised in Table 15.

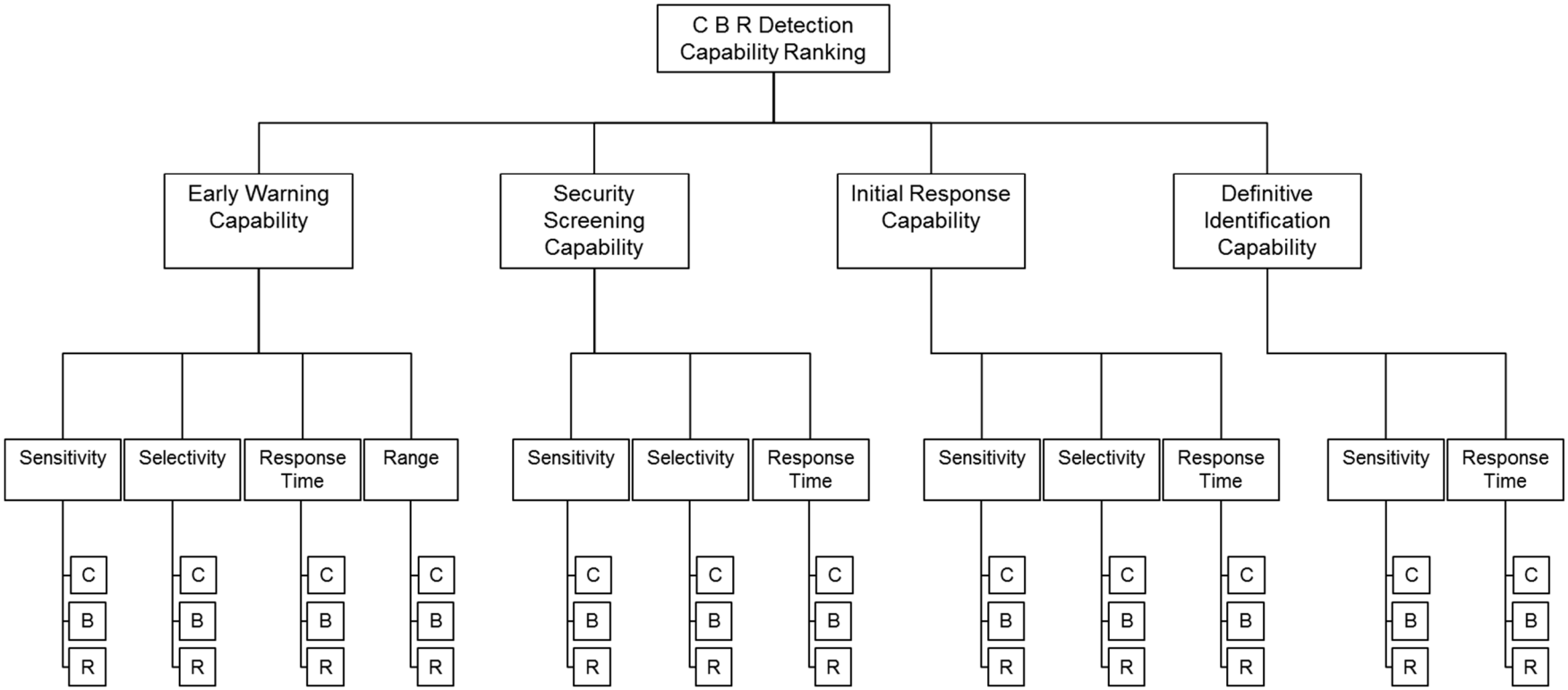

Figure 7: Hierarchy tree for the CBR detection capability ranking.

Table 14: Target values of KPCs for different C, B and R environment in different frames, extracted from Chapter 7.

KPC	Target Performance Value of KPC		
	Chemical	Biological	Radiological
Scenario 1: Early warning capability			
Sensitivity	15 mg/m^2	5.7 x 10^6 ACPLA-m	9.23 x 10^8 ppl-m
Selectivity	To be able to detect all forms of chemical plume. Acceptable to some false alarm.	To be able to detect all forms of biological plume. Acceptable to some false alarm.	To be able to discriminate between radiological plume from other plumes. Acceptable to some false alarm.
Response Time	1 minute	1 minute	2 minute
Range	4 km	4 km	5 km
Scenario 2: Security screening			
Sensitivity	10 mg/m^3	10,000 spores	0.2 mSv/hr (γ)
Selectivity	To be able to detect all forms of chemical threat, and discriminate from interferents. Acceptable to very low false alarm.	To be able to detect all forms of biological threat, and discriminate from interferents. Acceptable to very low false alarm.	To be able to pick up sources that emits gamma radiation. Acceptance to very low false alarm.

Response Time	1 minute	1 minute	1 minute
Scenario 3: Initial Response			
Sensitivity	0.0001 mg/ m^3	400 spores/ m^3	13 Bq/ m^3 (α) 13 Bq/ m^3 (β) 0.11 µSv/hr (γ)
Selectivity	To be able to detect all forms of chemical threat, and discriminate from interferents. Not acceptable to any false alarm.	To be able to detect all forms of biological threat, and discriminate from interferents. Not acceptable to any false alarm.	To be able to pick up sources that emits all alpha, beta and gamma radiation. Not acceptable to any false alarm.
Response Time	1 minute	1 minute	1 minute
Scenario 4: Definitive Identification			
Sensitivity	0.00003 mg/m^3	40 spores/m^3	13 Bq/ m^3 (α) 13 Bq/ m^3 (β) 0.11 µSv/hr (γ)
Response Time	1 hour	1 hour	1 hour

Table 15: Current C, B and R detection system performance in the four frames, extracted from Chapter 3.

KPC	**Current Performance Value**		
	Chemical	Biological	Radiological
Scenario 1: Early warning capability			
Sensitivity	150mg/m^2	3,000 ACPLA-m	1,000 ppl-m
Selectivity	Able to detect most chemical warfare agent and select TICs. Frequent false alarm due to interferent absorption.	Unable to distinct between biological threat and harmless biological pathogens, leading to high false alarm.	Unable to distinct between radiological plume and non-radiological plume, leading to undesirably high false alarms.
Response Time	3 minute 20 seconds	21 minutes	25 minutes
Range	3 km	3 km	5 km
Scenario 2: Security screening			
Sensitivity	No capability	No capability	0.1mSv/hr (γ)
Selectivity	No capability	No capability	Able to pick up sources that emit gamma radiation. Very low false alarm
Response Time	No capability	No capability	Immediate

Scenario 3: Initial Response			
Sensitivity	0.03 mg/ m^3	2.5 million spores/ m^3	8.33 Bq/ m^3 (α) 1.53 Bq/ m^3 (β) 0.10 µSv/hr (γ)
Selectivity	Unable to identify all agents with one system. Unable to discriminate from interferents. High false alarm rates.	Most systems unable to discriminate between biological threat and harmless biological agents, leading to high false alarms.	To be able to pick up sources that emits all alpha, beta and gamma radiation. Not acceptable to any false alarm.
Response Time	5 minute	15 minute	Immediate
Scenario 4: Definitive Identification			
Sensitivity	0.00057 mg/m^3	49 spores/m^3	5.6 Bq/ m^3 (α) 5.6 Bq/ m^3 (β) 0.1 µSv/hr (γ)
Response Time	1.5 hour	1 hour	0.5 hour

5.8 Step 7: Performance Measurement

For each individual KPC, the performance of the options are measured based on the swing weight method (Section 4.2.2). The decision maker is asked to consider the current case where all the options are performing at their current capability in a specific frame. The option with the highest perceived desire to ‘swing’ from the current capability to the target capability is identified with a rating of 1. The next option with the higher perceived desire to swing to the target capability is identified, and the rating is referenced to the first option. The last option is rated with reference to the first option. During this process, the option that has met the target capability performance has a rating of 0, indicating that there is no added desire to improve the specific detector for that KPC. The entire process of performance measuring is iterated across the hierarchy for all the elemental criteria (KPCs).

As mentioned, KPCs such as sensitivity, response time and range are often specific to agents, and to attain such values, it is sensible to select agents that are representative of the class.

The performance measurement is detailed in Section 8.2 to 8.5.

5.9 Step 8: Deriving Weights of KPCs in each Frame

Weights are allocated to each of the KPC within each frame to reflect the importance of the KPC to the frame. To determine the weight, the option with the highest perceived desire to swing from current to target capability for each KPC within a scenario is placed in comparison. Similar to the procedure described in the previous section, the options with the highest perceived desire to ‘swing’ from the current capability to the target capability is identified with a rating of ‘1’. The other representative options are then rated with referenced to the first option. The details are reported in Section 8.6.

After this exercise, the remaining options are normalised with their representative option in their frame in this exercise. The comparison takes into consideration the

importance of each KPC in contribution to the success of the specific scenario. The output of this exercise is a single performance score for the options, with the incorporation of the weight importance of the respective KPCs.

5.10 Step 9: Deriving Weights of Frame towards the Success of Overall Detection Architecture

The four frames stipulated are the first criteria that directly contribute to the success of the ranking. At this phase, the relative importance depicts the different reliance of the success of the ranking exercise on each of the scenarios. This weightage is determined by comparing the KPC that resides within the highest rated KPC of each scenario. Subsequently, the other criteria are normalised and referenced to the selected option within the scenario. This is detailed in Section 8.7.

5.11 Step 10: Summation of Weights

This bottom-up approach adopts intensive use of the swing method to incorporate perceptions from different facets. The first set of comparisons explores the individual performances of the option in terms of their current capability, and the availability and consequences of their target agents. The next tier of comparison incorporates the need to consider the impact of each KPC to the scenario in the respective environments. The last set of comparison sums up by encapsulating the relative importance of the scenarios in the overall defence strategy.

The resultant output of this suite of comparison is the direct summation of the scores for each option under the elemental KPC. The highest scored alterative reflects on the highest perceived need to improve to the ideal situation, and thus regarded as the worst capability of the three.

6 SELECTION OF A CHEMICAL, BIOLOGICAL AND RADIOLOGICAL AGENT

6.1 Chapter Summary

This chapter summarises the selection of a specific chemical, biological and radiological agent via AHP. A total of three AHP models were presented to select the agents based on the relevant criteria. The output denotes the respective agents that are likely to be used in a chemical, biological or radiological attack. It must be noted that full validation from all facets require analysis of a much more massive scale, such as incorporation of a detail risk analysis from political intelligence, and breakdown of individual bio-chem-physical traits of each agent. Such a study is beyond the scope of this dissertation. The selected agents are used as representations for comparisons in subsequent chapters.

For this comparison, the pairwise comparison is performed with the author's inherent knowledge on the CBR agents and their properties. The author has been working in the CBR community for seven years under a government organisation, in charge of the engineering procurement and subsequent operation support of selected CBR equipment in his country. During his course of work, he has performed studies on CBR agent characteristics and technology outlook in anticipation for adversary attacks. He attended several courses, including the basic CBR commander training in his country, and the CBRN Defence Course conducted in Cranfield University. His knowledge about CBR agents has granted him adequate credibility to perform the pairwise analysis in the AHPs, and the views are purely the Author's perception based on his knowledge and other literatures. While AHP provides the objective platform required, it accommodates subjective and judgemental evaluation based on the relative importance perceived by the decision maker. In order to instil more objectivity, the Author incorporates statistics into the pairwise comparison whenever possible.

It is relevant to note that the author acknowledges the presence of several sources providing differing quantitative measurement values of the same criteria

(e.g, lethalithy of C, B and R agents). Different sources may or may not result in different perception towards the weightages, however, this is beyond the scope of the dissertation.

6.2 Chapter Introduction

Different agents have specific properties or functional groups that respond to the detectors. The response of each chemical, biological and radiological agent to the C, B and R detector respectively varies. With so many complexities and variables, it is impossible to compare chemical detection, biological detection and radiological detection in a generic manner. For instance, when comparing C vs B sensing capability in terms of sensitivity, it would be a challenge to put down a numeric figure for the detection capability as it ranges from 0.01mg/m3 (Nerve Agents) to 50 mg/m3 (Blood agents), or for biological agents, $3x10^5$ spores of *Bacillus anthracis* to $6x10^6$ colonies of *Yersinia pestis*. To avoid generalisation, the next best alternative is to select a chemical, biological and radiological agent that is representative of their class. This selection sets the constraints for the comparison, and limits comparisons to derive quantifiable comparison.

The selection is based on AHP, where the outcome depicts a typical agent that has a good possibility of deployment by the perpetrators. Three AHPs are derived for the selection of agents from the three different classes, each selection having different criteria as considerations. Five agents from each class are selected based on the threat level perceived in several literatures. The five options are then placed in pairwise comparison with respect to each criterion, whose weightages are predetermined, also via pairwise comparison. The selected agents are used as representations for comparisons of the different detection capabilities in subsequent chapters.

6.3 Selection of the Chemical Agent

6.3.1 The hierarchy

The hierarchy consisting of the goal and elemental criteria is depicted in Figure 8.

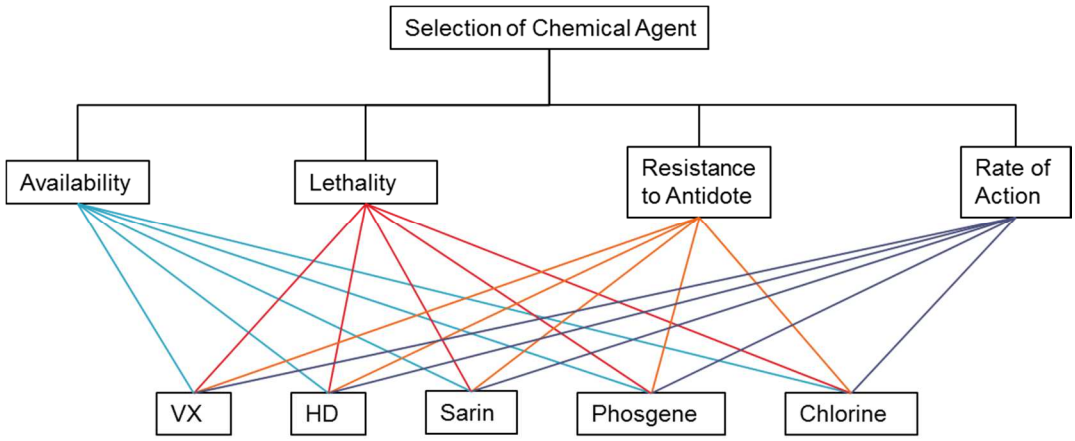

Figure 8: Hierarchy for the selection of chemical agents.

6.3.2 The criteria

As seen from Figure 8, the criteria chosen are availability of the agents to the perpetrators, toxicity of the agents selected, resistance to antidote for the agents, and the rate of effects of the agents. The author perceived that availability is the most important criteria in the selection of the agent as the perpetrator would likely choose the agents that are easily available in large quantities. The toxicity of the agent selected also plays an important role if the main intent of the perpetrator is to deliver lasting emotional blow to the target, as the toxicity of CBR weapons are pivotal to ensure that the unrest in citizens are multiplied. The rest of the criteria are ranked in order perceived by the author, as seen in Table 16. As shown in Table 16, the upper diagonal shows judgement comparison of the row criterion with respect to the column criterion, i.e. Availability (row) is as important (rated as ‘1’) as toxicity (column); availability is 3 times as important as resistance to antidote (column); availability is 5 times as important as rate of action (column). The lower triangle matrix (shaded is grey) is the reciprocal of the upper triangle matrix. **This method of organising the judgemental comparison is consistent throughout the AHP analysis in this dissertation.**

Table 16: Pairwise comparison of elemental criteria in the selection of chemical agent.

	Availabilty	Lethality	Resistance to Antidote	Rate of Action	Weights
Availability	1	1	3	5	0.4225
Lethality	1	1	2	2	0.3089
Resistance to Antidote	1/3	1/2	1	2	0.1630
Rate of Action	1/5	1/2	1/2	1	0.1056

The weightages of the elemental criteria are estimated using the column normalisation method. The calculation for the derivation of weights in this matrix is detailed as an example. **The subsequent calculations of the same nature are omitted in this dissertation.**

First, each column of the matrix is normalized as shown in Table 17. The weightage of each criterion is computed by averaging across each row of the matrix.

Table 17: Normalised matrix for the elemental criteria in the selection of chemical agent.

	Availabilty	Lethality	Resistance to Antidote	Rate of Action	Weights
Availability	0.395	0.333	0.462	0.500	0.4225
Lethality	0.395	0.333	0.308	0.200	0.3089
Resistance to Antidote	0.132	0.167	0.154	0.200	0.1630
Rate of Action	0.079	0.167	0.077	0.100	0.1056

6.3.3 The options

Three of the five options are listed in Schedule 1 of the Chemical Weapon Convention (CWC) [137]. One of the agent Sarin has been extensively published online since the Tokyo Subway Attack [138], and thus making it accessible to re-invent the wheels. VX was chosen mainly due to its extreme toxicity amongst all the chemical agents. The third agent chosen is Sulphur Mustard (HD), a blister agent that has received similar attention in literatures due to its high toxicity, rapid rate of actions, stability in environment and wide publications on its usages in history [139].

Phosgene is listed in Schedule 3 of the CWC, and considered to be less toxic compared to chemicals and precursors listed in Schedule 1 and 2. However, they

are produced in large quantities and easily sourced in industries. Phosgene has an estimated annual production of 5 to 6 million tons [140], and it is produced in various industries, some with low security. A chemical of similar concern is Chlorine, whose annual production in 2006 is estimated to be 65 million tons [141]. Chlorine is easily manufactured on a laboratory scale by mixing concentrated hydrochloric acid with an oxidising agent such as potassium permanganate solution, leaving perpetrators with an option to reduce signatures of obtaining toxic industrial chemicals.

6.3.4 Comparison of options with respect to availability

Table 18 shows the pairwise comparison for the options with respect to the availability of the agents. VX and HD are perceived as equally (un)available as they and their precursors are listed in Schedule 1 of the CWC, and none of them are featured in any industrial application[22]. It is difficult to acquire them, and the only way is to steal them from highly secured national laboratories, or to synthesise them in their own laboratories, both of which are posed with abnormally high difficulties. Although Sarin is listed under Schedule 1 of the CWC, due to extensive effort poured into research during the Aum Shinrikyo attack on the Tokyo Subways, it may still be possible to retrieve information from online sources or through their own organisational networks. As a reference, it has been made possible[23] by Aum Shrinrikyo cult to produce at least 70 tons of Sarin within 40 days in a fully setup plant with proper distillation columns and established laboratories [142]. Toxic industrial chemicals, on the other hand, are easily available and do not require great expertise to be adapted into chemical weapons. It is obvious that phosgene and chlorine is widely available due to their vast industrial applications, with chlorine's availability edging over that of phosgene due to its higher annual production.

[22] Although the said agents have no industrial application, the precursors (for example, thiodiglycol (for HD) and dimethyl methylphosphonate (for Sarin) have heavy industrial usages. However, as technical knowledge is required for the actual synthesis of the agent, and the availability of the precursors are one of many factors that determine the overall availability of the agent, and is thus not considered in the comparison.
[23] Projected figure.

Table 18: Pairwise comparison for options with respect to availability.

	VX	HD	Sarin	Phosgene	Chlorine	Weights
VX	1	1	1/4	1/5	1/8	0.0488
HD	1	1	1/4	1/4	1/9	0.0493
Sarin	4	4	1	1/3	1/5	0.1418
Phosgene	5	4	3	1	1/3	0.2374
Chlorine	8	9	5	3	1	0.5227

6.3.5 Comparison of options with respect to toxicity

Table 19 shows the pairwise comparison for the options with respect to the toxicity of the agents. The comparison is made directly with their statistical value as derived from literatures, as shown in Table 20.

Table 19: Pairwise comparison for options with respect to toxicity.

	VX	HD	Sarin	Phosgene	Chlorine	Weights
VX	1.00	15.00	1.00	32.00	60.00	0.4729
HD	0.07	1.00	0.07	2.13	4.00	0.0315
Sarin	1.00	15.00	1.00	32.00	60.00	0.4729
Phosgene	0.03	0.47	0.03	1.00	1.88	0.0148
Chlorine	0.02	0.25	0.02	0.53	1.00	0.0079

Table 20: Toxicity of options in terms of LCT50 (mg-min/m3) [143, 144, 145].

Chemicals	**LCT50 (mg-min/m3)**
VX	100
HD	1500
Sarin	100
Phosgene	3200
Chlorine	6000

The toxicology data shown in Table 20 depicts the typical LCT50 value of the options, and in general, the lesser the LCT50 value, the more toxic the chemical, and lesser amount is required to kill 50% of the population exposed. As seen from the table, VX and Sarin have the highest LCT50, and as expected, the toxic industrial chemicals in comparison to the chemical warfare agents, require a larger amount to intoxicate the exposed population. For instance, in comparing

the toxicity of VX (LCT50 = 100 mg-min.m3) vs HD (LCT50 = 1500 mg=min/m3), VX is 15 times (1500/100) as toxic as HD, while VX is “as toxic” as Sarin (it takes the same amount of VX and HD to kill 50% of the exposed population).

6.3.6 Comparison of options with respect to resistance to antidote

While the chemicals listed in this section all proved to be harmful, antidotes have been developed to counter the effects that these agents created in our biological systems. For instance, nerve agents inhibit the active site of acetylcholinesterase (AChE), a key enzyme breaks down acetylcholine, responsible for controlling several functions within the nerve systems. Without the control, acetylcholine floods and overstimulates the nerve systems. Atropine and pralidoxime focuses on blocking the acetylcholine receptors to alleviate further damages [146].

However, not all agents have specific treatment measures, and many rely on symptomatic treatment that eases the symptoms without addressing the basic cause of the disease. Sulphur mustard poisoning consists of decontamination and symptomatic treatment that includes life support and blood transfusion. Such treatment emphasises on superficial relief of the victim’s pain and most often do not assist in countering the true effect caused by the agent.

Treatment of victims and saving lives remain the most critical aspect of CBR countermeasures. [147] On the other extreme, the ability and resource required for treatment is an aspect that perpetrators will consider whilst selecting a suitable agent for dissemination. An agent poisoning with high treatability utilising low resources are deemed to exert less damage compared to another on the other end of the scale. Table 21 shows the pairwise comparison for the options in terms of antidote availability. As articulated, VX and Sarin have specific treatment and thus ranked lower over HD, phosgene and chlorine. HD on the other hand faces higher fatality rates when exposed to the LCT50 concentration, compared to phosgene and chlorine.

Table 21: Pairwise comparison for options with respect to antidote availability.

	VX	HD	Sarin	Phosgene	Chlorine	Weights
VX	1	1/7	1	1/2	1/2	0.0753
HD	7	1	7	4	4	0.5560
Sarin	1	1/7	1	1/2	1/2	0.0753
Phosgene	2	1/4	2	1	1	0.1467
Chlorine	2	1/4	2	1	1	0.1467

6.3.7 Comparison of options with respect to rate of action

Table 22 shows the pairwise comparison of the options with respect to the rate of actions of the agents. This comparison is reference directly to Table 23, which depicts the time to onset of symptoms of the agents.

Table 22: Pairwise comparison for options with respect to rate of action.

	VX	HD	Sarin	Phosgene	Chlorine	Weights
VX	1	3	1/3	7	3	0.2590
HD	1/3	1	1/5	1	1/3	0.0680
Sarin	3	5	1	7	5	0.4854
Phosgene	1/7	1	1/7	1	1/3	0.0540
Chlorine	1/3	3	1/5	3	1	0.1336

Table 23: Rate of actions for selected agents [148, 149, 150, 151].

Chemical	Rate of Action
VX	Very rapid, ~15 minutes
HD	Delayed, dependant on concentration[24]
Sarin	Very rapid, ~ 15minutes
Phosgene	Delayed, dependant on concentration[25]
Chlorine	Rapid for high concentration

[24] Under field conditions (without protection), symptoms only developed gradually after a few hours, and it also depends on the mode of exposure [151].
[25] Low dosages can damage the lungs in 24 – 48 hours.

6.3.8 Selection of the chemical agent – Results

The output of the pairwise comparisons denotes the weightages of the options when weighed against the criterion. The weightages are then compiled in a matrix as shown in Table 24. The agent with the highest score after the matrix multiplication between Table 24 and Table 16 is the agent that is perceived to be representative of the chemical domain, and will be used in subsequent chemical sensing capability comparisons.

Table 24: Matrix of options vs elemental criteria to derive quantitative score.

Matrix of Options

	Availabilty	Lethality	Resistance to Antidote	Rate of Action	Total
VX	0.0488	0.4729	0.0753	0.2590	0.2064
HD	0.0493	0.0315	0.5560	0.0680	0.1284
Sarin	0.1418	0.4729	0.0753	0.4854	**0.2696**
Phosgene	0.2374	0.0148	0.1467	0.0540	0.1345
Chlorine	0.5227	0.0079	0.1467	0.1336	0.2613

x

Matrix of Elemental Criteria

	Weight
Availability	0.4225
Lethality	0.3089
Resistance to Antidote	0.1630
Rate of Action	0.1056

=

	Score
VX	0.2064
HD	0.1284
Sarin	**0.2696**
Phosgene	0.1345
Chlorine	0.2613

Sarin is the most likely chemical threat perceived as a result of the comparison exercise. Sarin, although not as easily available as the usual toxic industrial chemicals, has detailed recipes that could be referenced from several online publications [152] and even from perpetrators organisations that have perform detailed studies on its production. Although Chlorine is ranked closely to Sarin in terms of the threat possibility, there are payload issues when mounted on lightweight drones (Section 7.5) that complicate the logistical burden of the attack. The properties of Sarin are tabulated in Table 25.

Table 25: Properties of Sarin [143, 144, 145] [148, 149, 150].

Properties	**Description**
Common Name	Sarin
Chemical Formula	(CH3)2CHO]CH3P(O)F
Military Classification	Nerve Agents
Form in which the agent is likely to be disseminated	Vapour, Aerosol or spray

Boiling Point	158 Deg C
Melting Point	-56 Deg C
Physical State at room temperature and pressure	Liquid
Vapour Pressure	2.10 mm Hg at 20 Deg C
Solubility	Soluble in all organic solvents, but immiscible in water. Rapid uptake through skin.
LCT50	100 mg-min/m3
ICT50[26]	75 mg-min/m3
Rate of effect	Usually very rapid, within 15 minutes

6.4 Selection of the Biological Agent

6.4.1 The Hierarchy

The hierarchy consisting of the goal and elemental criteria is depicted in Figure 9.

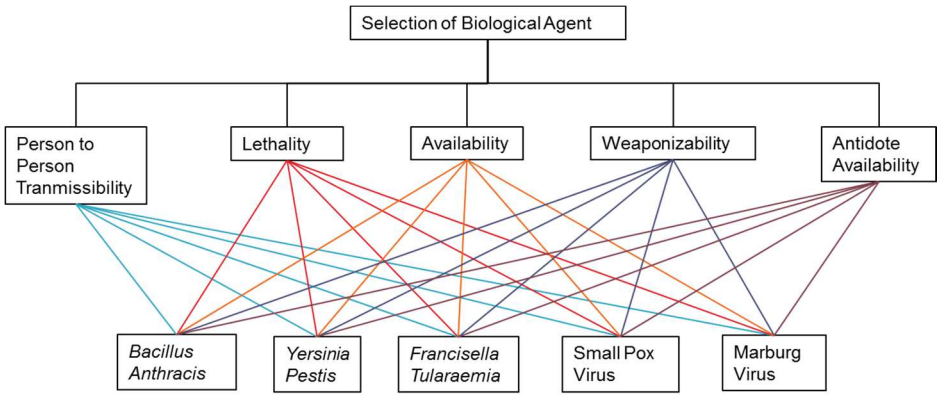

Figure 9: Hierarchy for the selection of biological agents.

[26] Dosage required to incapacitate 50% of the exposed population.

6.4.2 The criteria

The criteria chosen are the potential for P2P (person to person) transmissibility, toxicity of the agents selected, availability of the agents to the perpetrators, difficulty of weaponisation of the agent, and the antidote availability. Similar to chemical agent selection, the availability of the biological agent is perceived to be of upmost importance. This is followed by P2P transmissibility over toxicity of the biological agent, as a transmissible disease will strain more technical, financial and human resources in the clean-up of the situation[27], and warrant more attention compared to a non-transmissible one. Weaponisation in this case refers to the ease of disseminating the biological aerosols as weapons, and is perceived to be as important as toxicity. Without a workable plan or device to execute the attack, an agent of highest toxicity would not have a chance to be released in the most efficient manner. On the other hand, an executable plan to release an agent with low toxicity would not cause considerable damage to achieve the intended outcome. While antidote availability is important as a consideration, it is placed as the least importance relatively as the fear and message that perpetrators wanted to convey could have been carried across with a harmful, transmissible and weaponisable biological weapon, even if antidotes are available to facilitate the recovery of the patients. Table 26 shows the pairwise comparison of the importance for the elemental criteria.

Table 26: Pairwise comparison of elemental criteria.

	P2P Transmittability	Lethalithy	Availability	Weaponizability	Antidote availability	Weights
P2P Transmittability	1	2	1/3	2	5	0.2302
Lethalithy	1/2	1	1/5	1	3	0.1250
Availability	3	5	1	3	5	0.4610
Weaponizability	1/2	1	1/3	1	1	0.1113
Antidote availability	1/5	1/3	1/5	1	1	0.0725

[27] If a disease is contagious, additional human and financial resources must be deployed for patient isolation and quarantine. In addition, more emphasis must be placed in both social and medical health consequence management.

6.4.3 The options

The five options (*Bacillus anthracis, Yersinia pestis, Francisella tularensis,* Variola major and Marburg Virus) chosen for the selection are all Category A pathogens that poses the highest risk to US national security and public health (cited by the U.S. Centers for Disease Control and Prevention [153]).

6.4.4 Comparison of options with respect to P2P transmissibility

Table 27 shows the pairwise comparison for the options with respect to P2P transmissibility. *Bacillus anthracis* and *Francisella tularaemia* are not known to be transmissible from human to human, while *Yersinia Pestis*, smallpox and Marburg virus are most frequently transmitted from an infected person via direct deposition of large, infective airborne droplets of saliva onto the nasal or oral mucosal membrane during face to face contact. As such, transmissible diseases are given a score of 5, while the non-transmissible are given a score of 1.

Table 27: Pairwise comparison for options with respect to P2P transmissibility.

	Bacillius anthracis	*Yersinia pestis*	*Francisella tularaemia*	Smallpox	Marburg Virus	Weights
Bacillius anthracis	1	1/5	1	1/5	1/5	0.0588
Yersinia pestis	5	1	5	1	1	0.2941
Francisella tularaemia	1	1/5	1	1/5	1/5	0.0588
Smallpox	5	1	5	1	1	0.2941
Marburg Virus	5	1	5	1	1	0.2941

6.4.5 Comparison of options with respect to toxicity

Table 29 shows the pairwise comparison for the options with respect to toxicity of the biological agents. The comparison is made with their statistical value as derived from literatures, as shown in Table 28.

Table 28: Toxicity of options in terms of ID50[28] [21, 22, 154, 155].

Biological Agents	ID50 (Spores/organisms)
Bacillus anthracis	10,000 Spores
Yersinia pestis	10 organisms
Francisella tularaemia	10 organisms
Smallpox virus	5 organisms
Marburg virus	100 organisms

While it distinctly shows that the number of spores required to achieve ID50 for Anthrax infection outweighs that for the rest, this value must only be taken at a superficial value. It is difficult to determine the exact number of spores required to cause an infection, let alone decipher the number required to cause 50% of the population to get infected. (ID50). The values depicted in Table 28 are estimations, and these estimations vary amongst the different literature. For example, it was mentioned by Simpson LL that the ID50 for *Bacillus anthracis* ranges from 8,000 to 25,000 [156], while another research claimed to measure it at over 60,000 [157]. In addition, the possibility of inhaling 10,000 spores, logically, would not be much lower compared to inhaling 10 organisms within 10 minutes of exposure given the sheer physical size; inhaling 10,000 spores of *Bacillus* anthracis may be as possible as breathing in 10 organisms of other bacteria and virus.

Table 29: Pairwise comparison for options with respect to toxicity.

	Bacillius anthracis	*Yersinia pestis*	*Francisella tularaemia*	Smallpox	Marburg Virus	Weights
Bacillius anthracis	1	1/3	1/3	1/5	1/3	0.0690
Yersinia pestis	3	1	1	1	1	0.2261
Francisella tularaemia	3	1	1	1	1	0.2261
Smallpox	5	1	1	1	1	0.2527
Marburg Virus	3	1	1	1	1	0.2261

[28] Infectious dose.

6.4.6 Comparison of options with respect to availability

Certain biological agents are more available to the perpetrators compared to others. For instance, *Bacillus anthracis* strains are found in abundance in soil and all sorts of domestic animals. They could also be cultured from a single spore, retrieved from infected patients or animals, or even contaminated soil. In addition, there are over 1,200 strains of *Bacillus anthracis* collected in the world [158]. Comparing to the other bacteria, *Bacillus anthracis* can be considered available to the perpetrators, and this is even more apparent when compared to Smallpox and Marburg virus. There is only one strain of Marburg virus occurring naturally [159], while smallpox was considered eradicated in 1980 [160]. Table 30 shows the pairwise comparison for the options with respect to the availability.

Table 30: Pairwise comparison for options with respect to availability.

	Bacillius anthracis	*Yersinia pestis*	*Francisella tularaemia*	Smallpox	Marburg Virus	Weights
Bacillius anthracis	1	3	3	5	5	0.4603
Yersinia pestis	1/3	1	1	1	5	0.1778
Francisella tularaemia	1/3	1	1	1	5	0.1778
Smallpox	1/5	1	1	1	1	0.1179
Marburg Virus	1/5	1/5	1/5	1	1	0.0662

6.4.7 Comparison of options with respect to weaponisability

Table 31 shows the pairwise comparison of the options with respect to their weaponisability. Apart from the ability to retrieve and grow the cultures of biological agents, the ease of weaponisability is paramount to the success of the attack. The effective delivery of a biological agent poses more problem than its production by a perpetrators group, as it requires detailed formulation of the delivery systems and the optimal amount of agent to casualty ratio over the target area, all of which needs killed personnel and sophisticated equipment. The mechanical stress in optimising the aerosol sizes must be carefully managed to maintain the required efficiency of the agents. This knowledge required in effective delivery can be acquired by experience, or lessons learnt from the past. For instance, *Bacillus anthracis* and smallpox have been documented as weapons used in the past, and relevant information may be available as a guide for the perpetrators. In this aspect, *Bacillus anthracis* scores the highest due to

its recent (2001) anthrax letter attack. While *Francisella tularaemia* and Marburg virus has been studied [161], there were only claims of stockpiling, but it was never used in any form of attacks, limiting the perpetrators from gaining any additional information.

Table 31: Pairwise comparison for options with respect to weaponisability.

	Bacillius anthracis	*Yersinia pestis*	*Francisella tularaemia*	Smallpox	Marburg Virus	Weights
Bacillius anthracis	1	3	5	5	5	0.4837
Yersinia pestis	1/3	1	3	3	3	0.2305
Francisella tularaemia	1/5	1/3	1	1/2	1	0.0780
Smallpox	1/5	1/3	2	1	1/3	0.0898
Marburg Virus	1/5	1/3	1	3	1	0.1180

6.4.8 Comparison of options with respect to antidote availability

Similar to chemical agents, not all biological agents have antidotes. Agents that offer no forms of recovery therapies are preferred by the perpetrators in the overall scheme of the attack. Although *Bacillus anthracis* and *Yersinia pestis* infections have specific antidotes, they are required to be administered early before the symptoms manifest. Till date, there is no specific antidote for Small pox and Marburg virus, and all treatments are symptomatic therapies, where the best that can be offered to the patient infected is supportive therapy plus antibiotics as indicated for treatment of occasional secondary bacterial infections [162]. Table 32 shows the pairwise comparison for options with respect to antidote availability.

Table 32: Pairwise comparison for options with respect to antidote availability.

	Bacillius anthracis	*Yersinia pestis*	*Francisella tularaemia*	Smallpox	Marburg Virus	Weights
Bacillius anthracis	1	3	5	1/3	1/3	0.1618
Yersinia pestis	1/3	1	3	1/5	1/5	0.0788
Francisella tularaemia	1/5	1/3	1	1/7	1/7	0.0400
Smallpox	3	5	7	1	1	0.3597
Marburg Virus	3	5	7	1	1	0.3597

6.4.9 Selection of the biological agent – Results

The output of the pairwise comparisons denotes the weightages of the options when weighed against the criterion. The weightages are then compiled in a matrix as shown in Table 33. The agent with the highest score after the matrix

multiplication between Table 26 and Table 33 is the agent that is perceived to be representative of the biological class, and will be used in subsequent chemical sensing capability comparisons.

Table 33: Matrix of options vs elemental criteria to derive quantitative score.

Matrix of Options

	P2P Transmittability	Lethalithy	Availability	Weaponizability	Antidote availability
Bacillius anthracis	0.0588	0.0690	0.4603	0.4837	0.1618
Yersinia pestis	0.2941	0.2261	0.1778	0.2305	0.0788
Francisella tularaemia	0.0588	0.2261	0.1778	0.0780	0.0400
Smallpox	0.2941	0.2527	0.1179	0.0898	0.3597
Marburg Virus	0.2941	0.2261	0.0662	0.1180	0.3597
Sum	1.000	1.000	1.000	1.000	1.000

X

Matrix of Elemental Criteria

	Weights
P2P Transmittability	0.2302
Lethalithy	0.1250
Availability	0.4610
Weaponizability	0.1113
Antidote availability	0.0725

=

	Score
Bacillius anthracis	0.2999
Yersinia pestis	0.2093
Francisella tularaemia	0.1354
Smallpox	0.1897
Marburg Virus	0.1657

Bacillus anthracis is the most likely biological threat, considering all the different performances with respect to each criterion, perceived as a result of the pairwise comparisons. Unlike smallpox or Tularaemia, anthrax is not contagious. However, it is easy to cultivate and easily available for production. As the bacterium exists as hardy spores during the production phases, it can withstand the mechanical stresses of the aerosolisation process, and such spores can remain viable for decades [163]. Table 34 shows a summary of the properties of *Bacillus anthracis*.

Table 34: Properties of *Bacillus anthracis* [164, 165, 158, 161].

Properties	**Description**
Bacteria	*Bacillus anthracis*
Disease	Anthrax
Medium	Domestic and wild animals, soil and human transmission.
Form in which the agent is likely to be disseminated	Aerosol

ID50	8,000 – 20,000 spores
Incubation period	1 – 6 days
Symptoms	Fever, chest discomfort, shortness of breath, dizziness, cough, nausea, headache and fatigue.
Diagnosis	X-rays or CT scans to confirm mediastinal widening or pleural effusion. Blood sampling for bacteria.
Treatment	Anthrax can be treated with antibiotics such as ciprofloxacin and doxycycline. However, they are only effective before the onset of the symptoms.

6.5 Selection of the Radiological Agent

6.5.1 The hierarchy

The hierarchy consisting of the goal and elemental criteria is depicted in Figure 10.

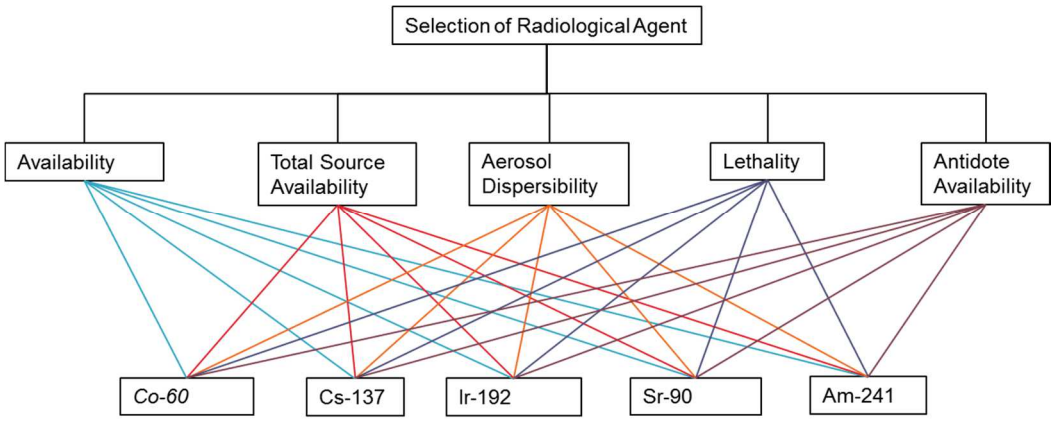

Figure 10: Hierarchy for the selection of radiological agents.

6.5.2 The criteria

The criteria chosen are availability of the agents to the perpetrators, the total source activity, aerosol dispersibility of the agents, toxicity of the agents, and treatment availability to remove the agents from the body. The success of a

radiological event to perpetrators is heavily dependent on the amount and type of radiation dosage received by the victim, which is in turn reflective of the type of radioactive isotope selected for the attack.

It is important to relate the risk of each isotope to the total number of sources manufactured worldwide and their typical activity. This may be the first consideration that the perpetrators may undertake to eliminate the acquisition of certain isotopes. It is also crucial to couple these findings with the ease of obtaining the isotope from their manufacture or typical industries, as some facilities have inherently lower security measures compared to others, based on their applications. The author perceived these two factors as equally important criteria that would be examined at the initial planning stages, especially since stealing and buying off the black market are the only two plausible methods of obtaining the raw material for a radiological attack. These considerations take precedence over the consideration of converting the raw material into dispensable aerosols[29] in the production process. Consistent with biological events, the author perceived that the importance of toxicity is not as apparent as the production considerations, and perpetrators would most likely lay their hands on easily available sources, as long as it emits enough radiation to initiate a pandemic response by the authority. The availability of antidotes to excrete the isotopes from the body is perceived as the least important in the selection of a suitable radioactive agent. Table 35 shows the pairwise comparison of the importance for the elemental criteria.

Table 35: Pairwise comparison of elemental criteria.

	Availability	Total Sources	Aerosol Dispersability	Lethalithy	Antidote Availability	Weights
Availability	1	1	3	4	5	0.3639
Total sources	1	1	1	4	5	0.2933
Aersol Dispersability	1/3	1	1	3	3	0.2034
Lethality	1/4	1/4	1/3	1	1	0.0729
Antidote availability	1/5	1/5	1/3	1	1	0.0665

[29] To be consistent with the scenario, it is assumed that the intent of the attack will be via inhalation of aerosolised radioisotope. Although the radioisotope can also be released as a single point source, the external irradiation is never as deadly and effective as the internal contamination of tissues and organs in the body via inhalation.

6.5.3 The options

The five options chosen for the selection are Co-60, Cs-137, Ir-192, Sr-90 and Am-241. These five isotopes are listed in a paper published by Monterey Institute of International Studies [166] as five of the seven top radioactive isotopes that poses the greatest security threat in US, and they have been further validated by IAEA [167], where these radioactive sources are listed in category 1[30] from a radiation safety perspective, posing the greatest risk and typically containing activities in excess of thousand curies worth of radioactivity. Table 36 shows the summary of the radioisotopes and their properties.

Table 36: Summary of selected radiological agents [166] [168].

Radioisotope	**Decay Mode**	**Half-life**	**Typical Specific Activity [Ci/g]**	**Physical form**	**Major application**
Co-60	Gamma	5.27 years	150	Metal slugs	Irradiators, Teletherapy
Cs-137	Gamma	30.17 years	20	Pressed power	Self-contained irradiators, Brachytherapy, Calibrators
Ir-192	Beta	74 days	500	Metal	Industrial radiography
Sr-90	Beta	28.9 years	140	Metal oxide	Radioisotope thermoelectric generator
Am-241	Alpha	432.2 years	3.5	Metal oxide	Well Logging

[30] Am-241 is listed under category 2, but as an alpha emitter, it causes more damage per activity due to its high penetrating ability.

6.5.4 Comparison of options with respect to availability

Table 37 shows the pairwise comparison for the options with respect to agent availability. The availability of the radioactive sources can be traced to the type their industrial, scientific and public uses, and the security measures in place in each of the facilities that houses the radioisotopes. Co-60 is the most widely used as a teletherapy source, and while the security in hospitals housing such radioactive sources are relatively less stringent than other government facilities, planning is still required to gain access through various security doors to the theatre. Removing the radioactive source from the machine (Figure 11) may also not be an easy task, as it involves certain technical expertise to reach out to the required source. It is equally tedious to remove a Cs-137 source from a brachytherapy machine since such machines are normally not portable. Other sources of Cs-137 are found in industrial irradiators, which also houses layers of security before access to the main irradiator room.

Table 37: Pairwise comparison for options with respect to agent availability.

	Co-60	CS-137	Ir-192	Sr-90	Am-241	Weights
Co-60	1	1	1/3	7	5	0.2167
Cs-137	1	1	1/3	7	5	0.2167
Ir-192	3	3	1	9	7	0.4723
Sr-90	1/7	1/7	1/9	1	2	0.0504
Am-241	1/5	1/5	1/7	1/2	1	0.0439

Figure 11: Illustration of a modern Co-60 telepathy machine [168].

Ir-192, on the other hand, stands out in terms of availability and ease of obtaining due to its usage in portable industrial radiography. Ir-192 has been employed in several portable gamma radiographic examinations for inspection of castings, welded assemblies and other structures for internal defects [169]. It is extremely portable as this machine is used in replacement of bulky x-ray apparatus for the non-destructive testing. Figure 12 provides an idea of the size of a typical radiographic inspector that perpetrators could easily obtain.

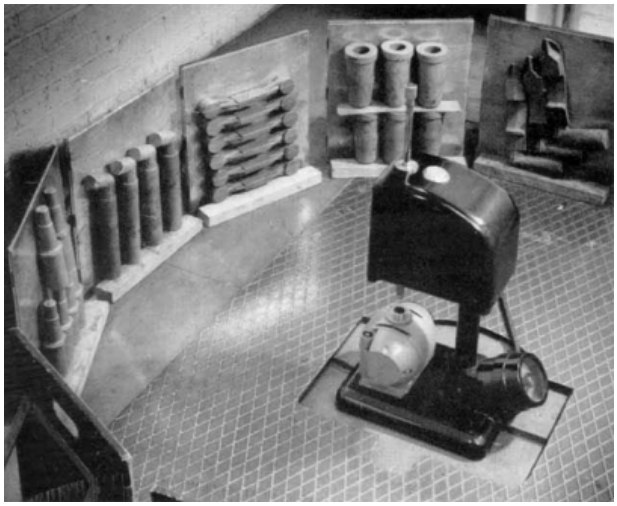

Figure 12: Illustration of a portable Ir-192 carrier used in gamma radiography of copper alloy castings [170].

One of the most abundant uses of Sr-90 is in Radioisotope Thermoelectric generator (RTG) as a power generator for lighthouses along the coast of Russia [171]. Such RTG were often not guarded and there were several incidents of break-ins to steal the value metal shielding. Similarly, a perpetrators group could gain access to the RTG core, exposing the radioactive isotopes. However, the location is isolated, and it may be logistically taxing to retrieve the RTGs from the location, and furthermore, time and effort have to be spent to decipher the exact location of the source within the bulky RTG. Am-241 has been extensively employed in well-logging practises for elemental and neutron porosity analysis [172]. This is especially applicable for oil and gas industry in search of potential area with access to hydrocarbon. There is no reason to exert high levels of security for such industries because of its secluded location and often at times, offshore, limiting access to perpetrators to steal the loggers.

6.5.5 Comparison of options with respect to total source availability

Table 38 shows the pairwise comparison for the options with respect to the total number of source available. The derivation of the estimated total number of sources is detailed in Table 39, and the pairwise judgement is performed by direct comparison of the derived total number of sources. For an example, Co-60 is $\frac{8250}{1400}$ as available as Cs-137.

Table 38: Pairwise comparison for options with respect to total source availability.

	Co-60	CS-137	Ir-192	Sr-90	Am-241	Weights
Co-60	1	5.89	5.62	95.93	25.46	0.7156
Cs-137	0.17	1	0.95	16.28	4.32	0.1214
Ir-192	0.18	1.05	1	17.08	4.53	0.1274
Sr-90	0.01	0.06	0.06	1	0.27	0.0075
Am-241	0.04	0.23	0.22	3.77	1	0.0281

Table 39: Derivation for the estimated number of sources.

Radioactive Sources	Total Activity in U.S. Inventory (Ci)[31]	Typical Activity (Ci)[32]	Estimated number of sources[33]
Co-60	198 x 10^6	24,000	8,250
Cs-137	2.8 x 10^6	2,000	1,400
Ir-192	146,922	100	1,469
Sr-90	1.73 x 10^6	20,000	86
Am-241	6482	20	324

[31] Information retrieved from [211]
[32] Information retrieved from [211]
[33] Estimated number of sources = Total activity / Typical activity

6.5.6 Comparison of options with respect to aerosol dispersibility

To be an effective inhalation threat, the raw material (radioisotope) must be grinded into minute metal particles of size 1 to 5 microns in order to be an effective inhalation threat. Cs-137 inherently exists as caesium chloride powder in its industrial application, and thus reducing the need for further complicated processing. The others either exists as metal oxide or solid metal and alloy forms, and sophisticated precision machines must be employed to process the minute amount of radioactive material obtained, to even smaller micron sized particles. In addition, the danger and thus additional protection resources required for processing gamma emitting radioisotope (Co-60, Cs-137 and Ir-90) is much higher compared to beta emitting isotope (Sr-90) and alpha emitting Am-241.

Table 40 shows the pairwise comparison for the options with respect to aerosol dispersibility, taking into account the effort and protection requirement for the aerosolisation process.

Table 40: Pairwise comparison for options with respect to aerosol dispersibility.

	Co-60	CS-137	Ir-192	Sr-90	Am-241	Weights
Co-60	1	1/3	1	1/3	1/4	0.0834
Cs-137	3	1	3	1	3/4	0.2500
Ir-192	1	1/3	1	1/3	1/4	0.0833
Sr-90	3	1	3	1	3/4	0.2500
Am-241	4	1 1/3	4	1 1/3	1	0.3333

6.5.7 Comparison of options with respect to toxicity

Unlike chemical and biological agent, radioisotopes do not possess any unique ability to affect the human anatomy in different manners. Instead, all radioisotopes inflict injury by emitting radiation, and the hazard associated with each isotope is closely related to the amount and type of radiation that it emits. When inhaled or ingested, different type of radiation affects the biological tissues in different manners, with alpha radiation producing more severe effect than gamma or beta radiation, and this is represented by a quality factor to derive the equivalent dose. Ultimately, the equivalent dose that a victim receives will determine the health impact on the receiver.

In this comparison, the author examines the mass of each radioisotope required to achieve 4Sv, a dose that would cause 50% of the exposed population to die in 60 days [173]. The concentration of isotope required is calculated from the following equation:

Equation 2: Effective dosage of radiation received in the body

$$E = C_{air}\ I\ e_i\ T$$

Where

- E is the effective dosage received in the body [Sv]
- $C_{air,i}$ is the average air concentration of isotope I [Bq/m3]
- I is the inhalation speed
- e_i is the committed effective dose coefficient[34] of isotope I [Sv/Bq]
- T is the time for plume passage

The inhalation rate of an average adult with mild activity is assumed to be 0.000033 m^3/s, while the time for plume passage is assumed to be 10 minutes in an outdoor release scenario. The concentration in Bq/m3 can be easily converted to mass concentration (g/m3) by relating to the specific activity of the isotope (Table 41). This mass concentration corresponds to the mass of the specific isotope required to cause 50% of the population to die in 60 days, after exposure for 10 minutes.

Table 41: Details of mass concentration of isotope in air to achieve LD50.

Radioisotope	**Committed Effective Dose Coefficient (Sv/Bq)**	**Air Concentration of isotope (Bq/m^3)**	**Typical Specific Activity (Ci/g)**	**Mass concentration of isotope in air (mg/m^3)**
Co-60	7.1×10^{-9}	2.85×10^{10}	150	5.126
Cs-137	6.7×10^{-9}	3.02×10^{10}	20	40.746

[34] Committed effective dose coefficients for inhalation intakes of radionuclides by workers are compiled in Annex A of ICRP Publication 119 [224]

Ir-192	2.2×10^{-9}	9.183×10^{13}	500	4.963
Sr-90	3×10^{-8}	0.673×10^{10}	140	1.300
Am-241	2.7×10^{-5}	0.748×10^{7}	3.5	0.0578

Table 42 shows the pairwise comparison of the options with respect to the isotope's toxicity, based on the calculations above.

Table 42: Pairwise comparison for options with respect to toxicity.

	Co-60	CS-137	Ir-192	Sr-90	Am-241	Weights
Co-60	1	7.95	0.97	0.25	0.01	0.0106
Cs-137	0.13	1	0.12	0.03	0.00	0.0013
Ir-192	1.03	8.21	1	0.26	0.01	0.0109
Sr-90	3.94	31.34	3.82	1	0.04	0.0415
Am-241	88.84	706.17	86.02	22.53	1	0.9357

6.5.8 Comparison of options with respect to antidote availability

The treatment to radiation poisoning lies in excreting the radioisotope from the body with chelating agents. Different chelating agents aim to bind to ingested radioactive material, thus effectively removing them from the body. While some of them are FDA approved, not all are FDA approved for the public. For instance, DTPA[35] is FDA approved for the treatment of internal contamination of Co-60 and Am-241 for adults' usage, and it is not yet approved for children [174, p. 1249]. Oral calcium and Prussian Blue tablets are FDA approved for all ages, in treatment against internal contamination of Sr-90 [175] and Cs-137 [176, p. 14] respectively. Table 43 shows the pairwise comparison for options with respect to antidote availability.

[35] Diethylenetriaminepentaacetate

Table 43: Pairwise comparison for options with respect to antidote availability.

	Co-60	CS-137	Ir-192	Sr-90	Am-241	Weights
Co-60	1	1/3	1	1/5	1	0.0988
Cs-137	3	1	3	1	3	0.3243
Ir-192	1	1/3	1	1/3	1	0.1081
Sr-90	5	1	3	1	3	0.3607
Am-241	1	1/3	1	1/3	1	0.1081

6.5.9 Selection of the radiological agent – Results

As seen in Table 44, the weights of the options are consolidated to derive the summated score of each biological agent. Co-60 receives the highest score for the matrix multiplication between Table 35 and Table 44 and thus will be selected as the representative of the radiological domain.

Table 44: Matrix of options vs elemental criteria to derive quantitative score.

Matrix of Options

	Availability	Total Sources	Aerosol Dispersability	Lethalithy	Antidote Availability
Co-60	0.2167	0.7156	0.0834	0.0106	0.0988
Cs-137	0.2167	0.1214	0.2500	0.0013	0.3243
Ir-192	0.4723	0.1274	0.0833	0.0109	0.1081
Sr-90	0.0504	0.0075	0.2500	0.0415	0.3607
Am-241	0.0439	0.0281	0.3333	0.9357	0.1081

X

Matrix of Elemental Criteria

	Weights
Availability	0.3639
Total sources	0.2933
Aersol Dispersability	0.2034
Lethality	0.0729
Antidote availability	0.0665

=

	Score
Co-60	0.3131
Cs-137	0.1870
Ir-192	0.2342
Sr-90	0.0984
Am-241	0.1675

6.6 Chapter Conclusion

This chapter defines the need to select a chemical, biological and radiological agent from the respective classes as a representation for the class's sensing capability demonstration, in terms of the elemental criteria for the sensing comparison. This step is crucial as it bounds an initially unconstrained problem of comparison with different performances within an option to the elemental criteria. AHP is selected over SMARTS for the comparison due to the availability of the literatures of agent properties, providing the decision maker with prerequisites on the comparisons. The agents selected as a representation are Sarin, *Bacillus anthracis*, and Co-60 for chemical, biological and radiological respectively. A meaningful evaluation can thus be analysed against the criteria identified to determine the current capability rankings of C, B and R detection.

7 SCENARIO PLANNING AND ANALYSIS OF SCENARIO

7.1 Chapter Summary

This chapter details the analysis and derivation of the target performance value for each KPC in the four frames of the stipulated scenario. In each frame, the KPCs of a detection system are analysed and rationalised to create an upper boundary for the scale of comparison, allowing the decision maker to effectively perform his interval rating. It is emphasised (refer to Section 5.4) that only the KPCs of the detection system that will bring about meaningful comparison will be discussed.

The scenario stipulated sits within a tropical country (80% humidity) with relatively low wind (5m/s) wind conditions. It depicts a major sports event happening during sun set period (6pm) but sensors (early warning) and security screening checkpoints were fully deployed before the event. The actual release takes place at around sun-set, where the agent is delivered via drone-spraying. Additional pertinent information would be discussed at length in each section.

7.2 Chapter Introduction

Detection architecture spans across various stages of the overall counter-CBRN strategies. It is not feasible to perform an analysis to encompass every detection scenario and stage within the research period. The deliberate scoping of a realistic scenario encapsulates the necessary detection phases and ensures that comparisons are performed on a similar platform to instil objectivity. This scenario accommodates the four frames described in Chapter 3. The hypothetical scenario created in this dissertation facilitates comparison of the different KPCs of the detection systems. Although in most cases, scenarios planned may not mimic the future events in an exact manner, they are required to envisage plausible consequences as a result of numerous complex interactions among the unknowns [177, p. 4]. To ensure an effective and meaningful comparison, the

scenario must accommodate equal possibility of C, B and R incident occurrences without prejudices to any single domain.

This scenario is set on the context that a high profile sports event will be staged in a tropical country. This is the first time the country is holding such an event, and several dignitaries will be attending, including visiting presidents and prime ministers. With the global media coverage, a group of perpetrators have noted this event as a potential medium to spread their propaganda, and they have decided to leverage on their expertise to convey the message.

In lieu of the potential threat the country is facing, the government has tasked a team to provide a full spectrum of counter CBR terrorism plans to deny any threat that will jeopardise the event. Based on the Intel provided, there are equal chances of the perpetrators utilising C, B or R agents as the means of attack.

The planned detection architecture consists of both detect-to-warn and detect-to-treat mechanisms. The detect-to-warn systems include early warning and security screening capabilities, while the detect-to-treat system includes initial response capabilities and definitive identification capabilities as mentioned in Section 3.2.

7.3 Analysis of Frame 1: Early Warning Capability

As mentioned in Section 3.3, early warning exists as standoff and remote detection, and the standoff capability is often used in military or urban settings. In this scenario, CBR release intents must be discovered early through means of standoff warning capabilities for contamination avoidance. C, B and R standoff sensors are deployed on top of the stadium pointing at strategic directions where threats are most likely to be deployed. Figure 13 shows a schematic of the CBR early warning system deployed.

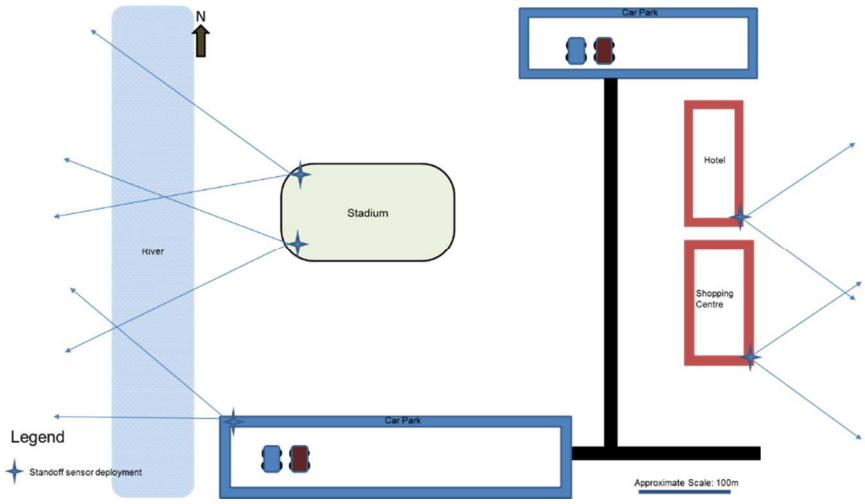

Figure 13: Schematic of possible deployment of early warning capability.

The C, B and R standoff sensors are deployed in anticipation of C, B and R aerosols or vapours respectively. This mode of sensing tracks plumes of aerosols or vapours proceeding towards the target, within the line of sight of the sensor. This is to counter any possibility of remote detonation or covert actions that releases huge amount of contaminants brought with the wind towards the target. This scenario assumes equal chances of C, B or R releases.

7.3.1 Sensitivity

7.3.1.1 Sensitivity for chemical standoff sensor

The sensitivity of a chemical sensor is defined by the product of the average concentration and the pathlength of the plume (unit mg/m^2). The larger the total length of the plume within the line of sight, the smaller the average concentration required to be detected.

To derive the required sensitivity of the chemical standoff sensor, there is a need to model the dispersion of the plume from the source. In this dissertation, the desired dose administered at the target is assumed to be at least LCT50, which causes 50% of the population to die upon receiving the dose. The LCT50 of Sarin is estimated to be 75mg-min/m3 **[178, 179, 180]**, and with 10 minutes of estimated exposure time, the concentration to be delivered to the target is estimated to be 7.5mg/m3. An equation suggested by Hanna *et al* **[181]**

suggested that the worst case concentration downwind of a point source can be estimated by the following equation:

Equation 3: Worst Case Downwind Concentration

$$C_{wc} = \frac{10^9 Q}{UH_{wc}W_{wc}}$$

Where

- C_{wc}= Worst case concentration, taken to be 7.5mg/m^3, based on LCT50 of Sarin for 10 minutes exposure.
- Q = Source strength in kg/s
- U = Wind speed, taken to be 5m/s
- W_{wc}= Worst case cloud width, assumed to be 10% of the distance from the source, taken to be 2km
- H_{wc}= Worst case cloud depth, taken to be 50m.

Therefore, the calculated source strength is 0.375 kg of Sarin in 1 second. This is a feasible release, where perpetrators can easily acquire or produce a total mass of 5kg to be disseminated.

With the source strength and the assumed minimum distance from the target being 2km, the estimated concentration (worst case) at 100m[36] from the source is estimated at 150mg/m^3 using Equation 3 (W_{wc} = 0.1 x 100m). In order to detect the cloud immediately upon release, the pathlength of the cloud within the line of sight is assumed to be 10m, and thus the sensitivity required is 15mg/m^2.

7.3.1.2 Sensitivity for biological standoff sensor

As with the chemical agent release, the expected concentration of *Bacillus anthracis* is much less than the source release because of the dispersion of plume downwind towards the target. Taking this into account, a realistic target exposure dosage (a distance away from the source) should be 10,000 spores so

[36] 100 meters is chosen as a guide to understand the concentration of sarin near the source.

as to kill 50% of the exposed population (ID50) [182]. Alexandra et *al* [183] suggested that the concentration of the aerosol spores in the air can be derived from the following equation:

Equation 4: Concentration of Aerosol Spores

$$\mathrm{C} = \frac{-\ln(1-P)\,ID50}{\mathrm{D_v} t \mathrm{W_h} ln2}$$

Where

- C= Concentration in spores/m^3
- P = Probability of infection, taken to be 0.5 in this case (50% chance of infection)
- ID50 = 10,000 spores of *Bacillus anthracis*
- D_v= Fraction of viable organism, taken to be 0.25[37]
- T = time of exposure, taken to be 10minutes
- W_h= Respiration rate, assumed to be 0.014m^3/min

As such, the concentration of the spores in the air exposed to the target is estimated to be 286,000 spores/m^3. Since each spore is estimated to be 10^{-12}g [184], the concentration is 0.286 µg/m^3. This is then modelled as a Gaussian distribution and by Equation 3, the source strength, and thus the ideal sensitivity of a biological standoff detector is 0.005714mg/m^3. This is equivalent to 5.7 x 10^6 ppl (particles per litre of air), and assuming 10% [185] ratio between ACPLA (Agents Containing Particles per Litre of Air) and ppl, the required sensitivity is 5.7 x 10^5 ACPLA. Assuming an average concentration pathlength of 10m, the sensitivity required is 5.7 x 10^6 ACPLA-m.

7.3.1.3 Sensitivity for radiological standoff sensor

To date, there is no dedicated standoff sensor for radiological detection. As mentioned in Section 3.3.3, the early warning capability is taken to be in the form of a generic aerosol tracker using LIDAR. The derivation of the required sensitivity of the LIDAR is similar to that of the UV-LIF used in biological standoff detection.

[37] Assuming that 25% of *Bacillus anthracis* spores released are less than 5µm is diameter [233, p. 84].

To achieve a “LD50” effect, a total radiation dosage of 4Sv is required **[173]**. The inhalation concentration required to derive the required dosage is derived by the following equation:

Equation 5: Inhalation Concentration of Aerosol

$$\mathrm{C} = \frac{D_i}{t\mathrm{W_h}D_e}$$

Where

- C = Concentration of radioactive isotope
- D_i= Inhaled dose, 4Sv in this case
- T = Time of plume, taken as 10 minutes
- W_h= Respiration rate, taken as 0.014m^3/min
- D_e= Committed Dose Equivalent, for Co-60, 7.1 x 10^{-9} Sv/Bq [186]

The concentration of Co-60 aerosol required is derived in units of Bq/m^3 from Equation 5, and with a specific activity of approximately 120 Ci/g [187, p. 7], the concentration of Co-60 aerosol required to be inhaled is calculated as 0.91mg/m^3. From Equation 3, the required source strength is 0.046 kg/s. This is achieved by releasing 15g worth of radioactive Co-60 aerosols in 5 minutes. It can also be estimated from Equation 3, the approximate concentration of aerosol near (100m) the source (18.39 mg/m^3). Assuming an average density of 2.2g/cm^3 of Co-60 [188], and a 10% purity [189] of Co-60 in a spherical aerosol particle, the concentration is derived to be 9.237 x 10^7 ppl. Assuming an average concentration pathlength of 10m, the sensitivity required is 9.3 x 10^8 ppl-m.

7.3.2 Selectivity

7.3.2.1 Chemical Selectivity

As a detect-to-warn capability, an ideal chemical standoff detector must be able to detect plume from all chemical warfare agents and TICs, amongst the hundreds of gases present in the outdoor environment. Although a precise quantitative analysis of the agents is not required at this point, a semi-qualitative

display of the plume will guide the responder in making a crucial decision for contamination avoidance. Such decisions are often low regret decisions with less undesired consequences in the event of a false alarm. These false alarms are due to the problem of interference rejection from the overlap of target absorption spectrum with the interferent features. As these problems are already accommodated into the decision making process, it is thus not critical for the standoff sensor to achieve an extremely low false alarm rate. However, false negative alarms are severely detrimental to the mission success of the early warning capability, and will not be tolerated.

7.3.2.2 Biological Selectivity

An ideal biological early warning capability, similar to the chemical counterpart, is required to detect all possible biological agents in the presence of biological interferences in the air. In addition, it must be able to discriminate harmful and harmless particles of biological origins, while maintaining a decent level of false alarm rate.

7.3.2.3 Radiological Selectivity

A radiological early warning capability, on the other hand, is required to exhibit discrimination ability from radiological and non-radiological plume. There is no requirement to distinguish between alpha, beta or gamma emitting particles, as this piece of information does not aid in the decision making process at this point in time. In addition, the ideal sensor must have an acceptably low false alarm rate to instil confidence in the detection.

7.3.3 Response time

Response time is the essence of early warning capability. The aim of the early warning capability is to provide ample time for the decision makers in executing plans and orders to avoid the contamination to as much extent as possible. While all aspects of an ideal detector play an important role in this, deploying a detector with fast response time has a direct influence on the amount of time the decision maker has to impact the avoidance effort.

In general, the response time required from a standoff detector is dependent on the type of action required, and the time for the plume travel, as shown in the equation below.

Equation 6: Relationship between Response Time, Plume Travel Time and Reaction Time.

$$\text{Response time} > \text{Plume travel time} + \text{Reaction time}$$

The plume travel time can be determined by the range of the sensors and the speed of the agent travel. The maximum distance that a C and B standoff detector can sense is assumed to be 3km, while that of a radiological standoff detector is assumed to be 5km due to the inherent properties of the detector. The wind speed on a typical evening is assumed to be 5m/s. The reaction time depends on the type of action that is required for successful contamination avoidance. As the actions are all of low regret and low burden actions, the required time for such actions is generally shorter, as shown in Table 45. These responses assume that the contamination to the spectators in the stadium can be avoided by shutting the retractable roof of the stadium. Aligning with the context of the specific scenario, detection of all C, B and R releases from afar results in the closure of the retractable roof, which is considered as a low regret and low logistical burden action in countering a system with high inherent false alarm. While the false alarm rate for C and B can be considered on the same magnitude, R standoff detector, due to its inability to discriminate the nature of the plume, requires an additional step to increase the confidence of the detection. Once the responders are alerted to a potential plume towards the target, the environmental agencies and fire departments are contacted for updates to the environmental condition to sieve off potential plumes due to fire or haze.

Table 45: Responses required following an alert from the standoff sensor.

Actions Required	C	B	R
Alerting HQ	1 minute	1 minute	1minute
Communication with other Agencies	--	--	5 minutes
Decision Making	1 minute	1 minute	1 minute
Retraction of Roof	7 minutes	7 minutes	7 minutes
Standby of CBRN Responder	3 minutes*	3 minutes*	3 minutes*
Total Time Required	9 minutes	9 minutes	14 minutes

**Could potentially be conducted in parallel to the retraction of roof, thus not included in the calculation of the total reaction time required.*

The ideal response time can be calculated from Equation 6 and defined as follows:

Target response time for chemical early warning capability: 1 minute

Target response time for biological early warning capability: 1 minute

Target response time for radiological early warning capability: 2 minute

7.3.4 Range

The earlier the operators are alarmed, the more time can be set aside for remedial actions. The detectable range should ideally be as far as possible, so that it can detect the source at any distance from the target[38]. In order to establish such a baseline, the C, B and R response time is assumed to be 5 minutes, which includes the scanning and target acquisition time. The required reaction time is referenced from Table 45. As referenced from Equation 6, the plume travel time and consequently the ideal range is defined as:

[38] It must be noted that as the distance goes beyond a threshold, the marginal benefit of having such a range decreases because the possibility of attacks from extreme distances is low in an urban setting.

Target detectable range for chemical early warning capability: 4km

Target detectable range for biological early warning capability: 4km

Target detectable range for radiological early warning capability: 5km

7.4 Analysis of Frame 2: CBR Personnel Security Screening

The need for CBR detection capability has been under-emphasised in personnel security screening points. This is also evident in the aviation security. The UK aviation security screening approved equipment list provides evidence that screening methods are mostly geared towards trace explosive detection, and not focused on CBRN [190]. The process of human security screening for illicit CBR material is elaborated in Section 3.4.

This section highlights the ideal requirements of a C, B and R human screening detector capability to be installed at such sites where a huge crowd is expected.

7.4.1 Sensitivity

In order to fully appreciate the required sensitivity of an ideal C, B or R human screening capability, there is a need to perform a risk analysis to understand and predict the intention of the perpetrators, which is beyond the scope of this dissertation. However, in general, in order to produce widespread fear and attract the attention of mass media publicities, the act of violence must impact a substantially wide group of people, and even better if the harm continues to propagate and transmit when the spectators return back to their country of origin. As such, the expected amount of CBR agents to be brought across the security screen should be sufficient to kill at the minimum, a small group of people, or at least incapacitate them. There is no added incentive to carry any agents that do not deliver sufficient dosage to cause harm of significant concern. As such, detection devices at the security screening point are not required to detecting minute traces of agents, but should rather aim to provide detection against a substantial amount of deadly agents.

7.4.1.1 Chemical Sensitivity

For a chemical screening device, the minimum anticipated amount of Sarin detected is assumed to be at least 10mg/m^3, which is equivalent to a 50% chance of death in an exposure of 10 minutes. This is likely to come in a form of bottled liquid, likely to be disguised as drinking water.

7.4.1.2 Biological Sensitivity

The minimum amount of *Bacillus anthracis* required for a meaningful attack is 10,000 spores (LD50), which merely amounts to micrograms of powder, easily disguisable as cosmetic powders or simply placed in areas out of sight for the X-ray devices.

7.4.1.3 Radiological Sensitivity

Assuming an exposure time of 1 hour, radiological releases are expected to be a point source with an activity that could create an exposure of approximately 1Sv (onset of acute radiation symptoms). However, this radiation must be carefully shielded by inches of lead or other densely packed metal, so that the radiation is attenuated and minimised to prevent injuries to the attacker. Firstly, the radioisotope must be shielded to prevent injury to the attacker prior to the release. Logically, the shield must be thick enough to attenuate substantial amount of radiation from the source, yet realistic enough to pass the screening test. The half value thickness (HVL)[39] of lead for Co-60 is 12mm [191]. To ensure a smooth and undisruptive passage across the checkpoint, a shield of 48mm on each side can be assumed to be the maximum thickness, beyond which would arouse suspicions. Working backwards, the emitted radiation would equate to 62.5mSv/hr from the source. Assuming that the sensing unit of the detector is 20cm away from the source, the attenuation due to air severely reduces the signal to approximately 0.2mSv/hr[40]. Therefore, this equates to the minimum sensitivity required of a radiological detector in this frame.

[39] HVL refers to the thickness of shielding material required to reduce the radiation emission to half its original value.
[40] Inverse square law.

7.4.2 Selectivity and false alarm rate

With a detect-to-warn capability, an ideal screening capability must be able to pick up all possible kinds of C, B and R threats. This is difficult because of the exposure to a large number of possible interferents found in the bags of the spectators that may mask the identity of the agent. The screening capability must thus be able to sieve out all possible agents amongst the interferents, and provide accurate readouts. There may be legitimate reasons that a spectator may carry with them chemicals, biological and even radiological material[41], and thus adding on to the difficulty of sieving out the illicit ones. While false negative reading is absolutely unforgivable, there is very little room for accommodation of false positive detection. The main aim of the human security screening capability is to deny possible threats from crossing the boundary, whilst not compromising on the throughput of the screening point. This is exceptionally paramount because a choke will unnecessarily cause the build-up of human traffic, which indirectly provides an additional platform for perpetrators to act.

For ideal chemical screening capabilities, there is a need to encompass the entire suite of toxic industrial chemicals and chemical warfare agents at low false positive alarm rates, and zero false negative alarm rates. For biological capabilities, while the false alarm rates required are similar to that of the chemical capabilities, the spectrum of detection is narrower as the scope is limited by the availability of the biological agents to be misused. In a radiological scenario, being of the nature of the penetrating power and the subsequent harm to the public, a release that would cause substantial harm to the public would be that coming from a gamma source[42]. Thus, the radiological screening only needs to be selective towards particles emitting gamma radiation at low false alarms.

[41] For instance, a person may have medical conditions that require radioactive tracer implants. Medicine containing methyl salicylate can also cause false alarms to the chemical detectors.
[42] Alpha and Beta particles have low penetrating power, and could be stopped or attenuated easily through few centimetres of air.

7.4.3 Response time

In order not to amplify the already existing problem of bottlenecking at security checkpoints, the response time of the CBR screening capabilities must be kept to a minimum. Realistically, based on currently technology, there is no means to achieve an instantaneous response (except for R). However, if such detection can function in parallel to the existing inspection of X-ray machines, it would not exert additional stress to the security threat. Such parallel inspections would increase the quality of the security check without increasing the time spent on the checks. A typical X-ray inspection can be assumed to be 1 minute, including a thorough full body inspection, X-ray scrutiny, and additional secondary human intervention at occasional incidents. As such, the target response time of the C, B or R screening capability is capped at 1 minute, provided it is incorporated into the existing inspection procedures.

7.5 Analysis of Frame 3: Initial Response to CBR Incident Capability

This scenario assumes that the first two frames are unable to detect any CBR agents, and the perpetrators attempt to disperse the C, B or R agent outside the stadium via drone technology (just one of many methods that can escape from the detect-to-warn architecture). This method of aerosol dispersion has been widely used in agriculture to survey crops, disease monitoring and irrigation. It has also been used extensively in both perpetrators and counter terrorist operations in Pakistan [192]. Although usage of drone technology has never surfaced in CBRN attacks, this is a robust method of dispersing the agents into security-tightened areas. The flight path could be pre-programmed via waypoint settings to avoid frequency jamming and the aerosols could be timed to be released at precise location. In furtherance, in 2014, the Pentagon responded to the threats by issuing a Request for Information (RFI) [193] to solicit countermeasures for drones armed with chemical or biological agents.

The latency effects to the victims are dependent on the class of agent used. Upon a chemical attack, the effect is observed almost immediately, where the victims

experience pain and discomfort to their eyes and throat area, and in severe cases, the victims may collapse in signs of breathlessness or seizures[43]. In such an attack, anxiety affects the crowd, and soon turns the scene into chaos with abled victims running away in all directions. Upon a biological or radiological aerosol dispersion, generally the symptoms are delayed and the dispersion may go unnoticed for a brief moment. Suspicion will arise with the hovering of the drone around the release point. In both paths, the turmoil within the crowd starts to rise and police and first responders can be seen arriving at the scene to investigate.

The detection response to such a scenario can be more challenging than one of a larger scale, as the relatively small and camouflaged attack brings about less signs and symptoms for initial confirmation of an attack. While the casualty rate may be lower, the response protocols are almost similar (but on a smaller scale), Alarms and alerts to the incident may arrive much slower, and by the time the responder reaches the scene, the agents may have already dispersed to a substantially low concentration for effective sampling and subsequent identification. While this brings good news, it also complicates the initial detection process, and the race against time to confirm the agent's identity becomes an increasingly uphill task.

At this initial stage of an incident, it must be noted that the main purpose of the detector is to provide confirmation of the nature of the attack. No quantitative data is required of the detector to make a decision on performing subsequent responses. The task force commander decides on the need for cordoning and medical triage based on whether the attack is of a chemical, biological, radiological or hoax nature. The classification of the agents can aid the commander in assessing the need for immediate hospitalisation and subsequent decontamination procedures. The magnitude of the release (if available) would allow the commander to assess the need for full evacuation. Without exact identification and quantification, the initial response force can still be fully

[43] This is a generalisation of a typical chemical attack. However, dependant on the agent used, the latency and symptoms may vary.

deployed to introduce risk reduction strategies soon after the initial detection of the agents.

7.5.1 Sensitivity

An ideal C, B or R detector responding to such a situation should have extremely low sensitivity, so that it can pick up any residual traces of agents. This is crucial in many situations like the specific scenario depicted, where the concentration of non-persistent agents can get diluted severely in neutral or stable atmospheric stability conditions [194].

7.5.1.1 Chemical Sensitivity

As inferred in the report published by DSTO [194], the initial estimation of the diluted concentration can be much less than 0.1 mg/m3. Therefore, to err on the side of caution, an ideal chemical detector should target to detect a minimum concentration equivalent to the short-term exposure limit (STEL)[44] of 0.0001 mg/m^3 [195].

7.5.1.2 Biological Sensitivity

Such derivation of airborne exposure limits is rare for biological warfare agents, due to the apparent lack of scientific data on infectious doses [196]. However, Alexandra *et al* [183] has suggested that the STEL value of *Bacillus anthracis* can be derived from Equation 4, where the risk of infection (P) is assumed to be 0.001 (0.1% risk of getting infected), viability of aerosol (D_v) to be 0.25, exposure time (t) 10 minutes and respiration rate (W_h) 0.014m^3/min. As such, the derived STEL for *Bacillus anthracis* is estimated to be 400 spores/m^3.

7.5.1.3 Radiological Sensitivity

In the case of radiological dispersion, it is most empirically challenging. Many subscribe to the Linear no Threshold (LNT) theory, whereby there are no safe limits of radiation, and any increase in radiation doses accumulated over long exposure to increase the stochastic risk of cancers. Others [197] dispute that

[44] An airborne exposure limit designed to address short-term upward deviation in exposure. Typically, such exposure should not last longer than 15 minute, and not more than 4 times a day.

such a threshold exists based on experimental data. However, due to lack of validation, clinical practitioners and responders tend to rely on the former theory in minimising exposure.

With LNT, any amount of radiation above background level is considered harmful. It is thus relevant to relate the sensitivity of the detector to the background radiation level for alpha, beta and gamma exposure. Figure 14 shows the annual radiation dose to the UK population. The main source of alpha and beta radiation in the atmosphere comes from the progenies of Radon, and can be averaged at an annual background intake of 1.3mSv, approximately 26 Bq/m^3 [198, p. 18]. There are equal numbers of alpha and beta progenies, thus for both alpha and beta detectors, the ideal target sensitivity should be 13 Bq/m^3.

In 2014, the average background gamma radiation in UK is tabulated to be 0.11 µSv/hr [199].

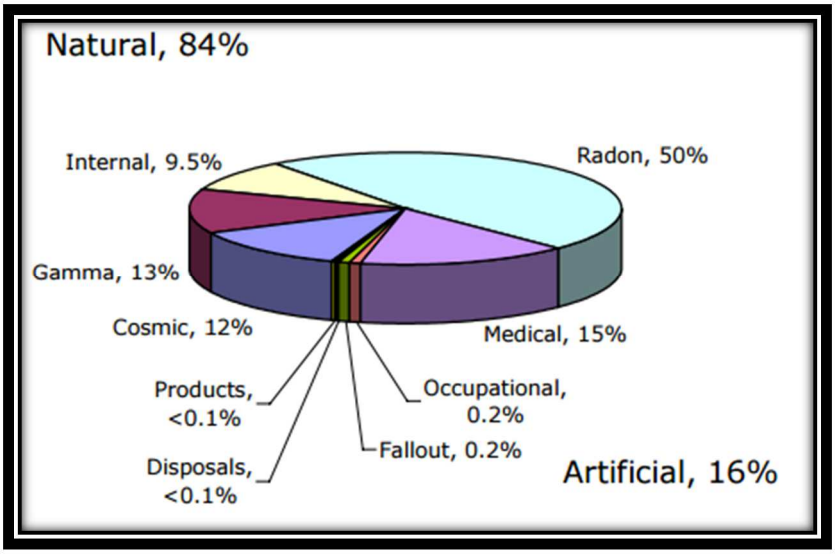

Figure 14: Average annual dose to the UK population [198, p. 71].

7.5.2 Selectivity and False Alarm

The motivation of the initial response is twofold: the confirmation of an attack and identifying the nature of the attack. In order to achieve these outcomes, the system must be able to accommodate the detection of all possible chemical agents, including warfare and industrial related agents. At this stage, it is not useful that the detector only targets specific agents, because of the vast

possibility of a wide range of chemicals being deployed. While the same concept applies to biological and radiological terrorism acts, it is more apparent for the chemical sector because of the wider spectrum of available dangerous chemical agents. However, ideally the false alarm rate for a chemical system is more tolerable than the biological one because of the rate of manifestation of symptoms. For instance, the symptoms of inhaled Sarin is felt within 15 minutes or less, and with the manifestation of the symptoms, the responders are able to predict the nature of the attack, which initiates first aid treatment, and buys time for more sophisticated detection. The false alarm rate of biological detection is intolerable because of the prolonged latency period of *Bacillus anthracis*, inferring a huge reliance on the detector for accurate results.

In an airborne radiological contamination situation, there are possibilities of finding all alpha, beta and gamma emitting particles, unlike that of a security screening frame (Section 7.4.2). Although alpha particles possess low penetrating power and are assessed to be useless in a point source release, these particles are highly favourable for aerosol attacks due to their high ionization power, where they transfer a large amount of ionising energy to the surrounding tissues, damaging the DNA and other cellular material. As a result, there is thus a need for the ideal radiological detector to pick up all three forms of emitters. As with other radiological scenarios, there is not a big concern for false positive alarms due to the absence of interference after background calibration.

7.5.3 Response time

In order to provide the promptest response to the required victims, the response time of the C, B or R detection system must be close to immediate. This is especially true to chemical scenario, where the agents are relatively fast acting, and require immediate medical attention. For the case of biological and radiological dispersion, the confirmation of such an attack gives enough justification for the first responder to initiate cordoning and evacuation. Many literatures [200, 201] have suggested that the ideal response time of such a detect-to-treat C, B and R system is 1 minute, starting from the initial exposure of the system to the contamination of air.

7.6 Analysis of Frame 4: CBR Laboratory Confirmation Capabilities

In order to provide a definitive confirmation of the agent released, samples are sent to the national laboratories for confirmative identification. In pursuit of a prompt and decisive answer, samples are usually collected onsite to be delivered directly to the accredited laboratory. Further tests are supplemented by body fluid samples from the suspected victims. It must be noted that samples collection, however, are not the main priority of the incident management, and performed only after primary life-saving missions are under control. High resolution of agent identification is required for the initiation of higher order treatment of victims, declaration of state of emergency and subsequent prosecution and recovery missions.

7.6.1 Sensitivity

In the scenario where covert attacks are performed, they are normally scaled down to affect a smaller population when compared to state-sponsored attacks. The sample collection task is made difficult with the unpredictable wind conditions and the chaos expected on the scene. Many literatures have suggested different priorities in a mass-casualty event [202, 203, 204], but none have mentioned sampling as one of them. It is thus inferred that collection of air samples or sample swipes only occur after the main task of crowd control and medical triage is performed. With time and unforgiving weather conditions, the concentration of the agents in the sample reduces drastically.

Having a good sampling kit aids in preserving and concentrating the agents but such equipment may not be on site or in some cases, the samples collected cannot be concentrated. In order to maintain the competency of definitive identification with minimal concentration, the detector (identifier) will thus have to process at extremely low sensitivity.

7.6.1.1 Chemical Sensitivity

For chemical confirmative identification, the system must have a sensitivity lower than that provided in the initial response capability. A representative sensitivity can be taken as the worker population limit (WPL)[45] of 0.00003 mg/m^3 for Sarin.

7.6.1.2 Biological Sensitivity

For biological confirmative identification system, the minimum sensitivity of 40 spores/m^3 is derived from Equation 4, where the risk of infection (P) is assumed to be 0.0001 (0.01% risk of getting infected), viability of aerosol (D_v) to be 0.25, exposure time (t) 10 minutes and respiration rate ($W_{h)}$) 0.014m^3/min to be 40 spores/m3, assuming a 0.01% risk of infection.

7.6.1.3 Radiological Sensitivity

As already mentioned, the background radiation should be taken as the benchmark for all alpha, beta and gamma radioactivity detection, and this applies to confirmative identification systems as well. The same set of ideal targets (as the initial response scenario for radiological attack) is applied.

Sensitivity of Alpha particle identification system: 13 Bq/m^3

Sensitivity of Beta particle identification system: 13 Bq/m^3

Sensitivity of Gamma radiation identification system: 0.11 µSv/hr

7.6.2 Response Time

Although it is crucial for the results of the definitive identification is be delivered to the authority as quickly as possible, there is no widely discussed acceptable analysis time. The target for the response time of all C, B and R definitive identification system is set to be 1 hour, to allow post incident management to be carried out as smoothly as possible in a time-efficient manner.

[45] It is defined by CDC as the airborne exposure limit designed to protect workers, expressed as a time-weighted average (TWA) for exposure over an 8 hour shift. The long hours reflect on the estimated time of exposure a general public may face outdoor.

7.7 Chapter Conclusion

The chapter deliberates target setting of the KPCs in the frames within the scenario. The targets are chosen with a suite of rationale thinking and logics that frames the entire performance ratings to ensure effective comparisons. These target values of the KPCs are used as the upper boundary for the SMARTS comparison analysis in Chapter 8.

8 RESULT GENERATION

8.1 Chapter Introduction

This chapter analyses the performances of the options (C, B and R detection capabilities) with respect to each KPC (Tier 1 comparison), consequently deriving the weight importance of each KPC within a scenario (Tier 2 comparison), and ultimately, the importance of each scenario in the overall defence strategy (Tier 3 comparison). This bottom up approach develops the analysis in a holistic manner. The operational analysis tool used in this analysis is the SMARTS method (Section 4.2.2) and is an intermediate between the demanding AHP process and the generic active brainstorming method.

In this study, ‘1’ denotes the highest desire of a detection system to swing from the current performance (with respect to the specific KPC) to the target performance level, while ‘0’ denotes no desire to swing to the target level. It is important to emphasise that this section generates results based on the Author’s perception of the deviation of current performances (Chapter 3) from the target performances (Chapter 7) of the C, B and R detection capabilities.

This analysis is performed with the author’s inherent knowledge on the CBR agents and their properties. The author has been working in the CBR community for seven years under a government organisation, in charge of the engineering procurement and subsequent operation support of selected CBR equipment in his country. During his course of work, he has performed studies on CBR agent characteristics and technology outlook in anticipation for adversary attacks. He attended several courses, including the basic CBR commander training in his country, and the CBRN Defence Course conducted in Cranfield University. His knowledge about CBR agents has granted him adequate credibility to perform the analysis, and the views are purely the Author’s perception based on his knowledge in the field, and other supporting literatures.

8.2 Tier 1: Comparison of Early Warning Capability

8.2.1 Sensitivity

Table 46 summarises the performance comparison of the options with respect to sensitivity requirement of the systems in the early warning capability. As seen, it is perceived that the current B and R performance surpass the performances of the target B and R detection capability in terms of sensitivity requirement. Both B and R standoff detectors currently have the capacity to detect lower concentration of aerosols than what is required, and as such, there is no immediate need to improve the biological and radiological system from a sensitivity aspect.

For chemical early warning capability, it is evident that the sensitivity is at best approaching the target requirement. The minimum detectable concentration of an early warning capability system depends highly on wind speed, source concentration, source location, release rate, and weather conditions, many of which are not within the operator's control. The lack of control implies a need to improve the sensitivity for a C detection system, in comparison with B and R detection systems.

Table 46: Summary of performance comparison of options with respect to sensitivity of the systems in the early warning capability.

Option	Target Performance	Current Performance	Ranking
C	15 mg/m^2	150mg/m^2	1
B	5.7 x 10^6 ACPLA-m	3 x 10^3 ACPLA-m	0
R	9.3 x 10^8 ACPLA-m	1 x 10^3 ppl-m	0

8.2.2 Selectivity

Table 47 summarises the performance comparison of the options with respect to selectivity requirement of the systems in the early warning capability. The highest level of desire for improvement is given to R early warning capability in this aspect. Firstly, the stipulated technology for R early warning capability is a

generic aerosol counter as elaborated in Section 3.3.3. With such a rudimentary system, R early warning system is perceived to have the highest deviation away from ideal because of its inability to even provide the basic level of discrimination between a radiological plume and non-radiological plume. Without this ability, the system alarms to any form of plume, increasing the false alarm possibility. This is highly unacceptable and thus has the highest desire to swing from current to target performance level.

Comparing chemical and biological, the perceived desire to improve the B systems in terms of selectivity (and false alarm) requirements is higher compared to C systems due to several reasons. Firstly, the physical amount of *Bacillus anthracis* required is less[46] compared to that of *Sarin*, implying that if an attack were to take place, the release of *Bacillus anthracis* would most likely be less compared to Sarin in terms of mass and physical size in order to achieve the same effect. This alludes to the postulation that the biological aerosol may have higher potential to be masked within the abundance of particulates in the atmosphere, leading to false negative readings in the detection system. In addition, there are more background biological[47] interferences than chemical[48] ones, leading to a higher potential for false positive alarms. The improvement for B systems is thus interpreted to be more critical to improve the selectivity requirements in an attempt to reduce or overcome the false alarm potential. In addition, improving the selectivity of B systems compared to C is of the higher calling because the implication and consequences of a non-ideal selectivity often leads to high false alarm, and false alarm towards a biological incident commands a much higher cost of recovery compared to chemical incident. It is valid to relate this argument to a higher need to reduce the false alarm rate of the B system, which in turns exemplifies the need to improve the selectivity of the system.

[46] In terms of mass, not ACPLA.
[47] In a report, Cheryl *Et Al* claimed the presence of close relative of *B. anthracis* in soil samples and urban aerosols in 14 of the US cities surveyed [287].
[48] H. Lavoie *Et Al* performed experiments to conclude that obscurants in the background do not significantly affect the detection capability of a passive standoff detector because they lack the spectral signature typical of the specific gaseous target in the LWIR range [288].

Table 47: Summary of performance comparison of options with respect to selectivity range of the systems in the early warning capability.

Option	Target Performance	Current Performance	Ranking
C	To be able to detect all forms of chemical plume. Acceptable to some false alarm.	Unable to detect certain chemical agents. False alarm rates present.	0.3
B	To be able to detect all forms of biological plume. Acceptable to some false alarm.	Unable to discriminate between living biological and non-living biological plumes. High false alarm rates.	0.7
R	To be able to discriminate between radiological plume from other plumes. Acceptable to some false alarm.	Unable to discriminate between alpha, beta and gamma radiation plumes from other aerial particulates. Extremely high false alarm rates.	1

8.2.3 Range

Table 48 summarises the performance comparison of the options with respect to range requirements of the systems in the early warning capability. As seen, currently C and B standoff detection has a typical standoff distance of maximum 3km, and this is 25% away from the target of 4km. There is thus an equal desire to swing from current to target performance level to ensure sufficient time catered for contamination avoidance actions. On the other end, the R standoff capability is able to meet the target performance requirement and thus no incentive to improve the capability in this aspect.

Table 48: Summary of performance comparison of options with respect to range requirements of the systems in the early warning capability.

Option	Target Performance	Current Performance	Ranking
C	4 km	3 km	1
B	4 km	3 km	1
R	5 km	5 km	0

8.2.4 Response Time

Table 49 summarises the performance comparison of the options with respect to response time requirement of the systems in the early warning capability. As seen, all three capabilities currently have not met the target requirement, with B and R having the largest deviation from target performance. Response time is one of the most important aspects of early warning capability because it directly influences the critical action after a successful alert. With ample response time, the users would have more than sufficient time to perform actions of contamination avoidance. It is highly likely that without any improvement, the B and R system may have very little use in the early warning capability with such long response time, and thus it is perceived that there is equal motivation in improving both systems at least close to the target performance. This is not for the case of C systems, where the response time of the current C systems takes an additional 2.5 minutes to the time for contamination avoidance. This means that drills and responses can still be carried out, and that there is still a possibility of partial if not complete avoidance. As such, there is less desire to swing the C detection system capability from current to target performance level in terms of response time requirement.

Table 49: Summary of performance comparison of options with respect to response time requirement of the systems in the early warning capability.

Option	Target Performance	Current Performance	Ranking
C	1 minute	3 minute 20 sec	0.3
B	1 minute	21 minutes	1
R	2 minute	25 minutes	1

8.3 Tier 1: Comparison of Security Screening Capability

8.3.1 Sensitivity

Table 50 summarises the performance comparison of the options with respect to sensitivity requirement of the systems in the security screening capability. As seen, C and B systems require drastic improvement from current performance. X-ray and secondary visual inspection do not have the means to detect the presence of any illicit chemical or biological agent with quantifiable sensitivity. Manual intervention applies for both primary and secondary methods of detection in such chemical and biological security screening, where the security officer calls for secondary manual checks on the suspected baggage. The lack of surety in sensitivity generates very little confidence. Under scrutiny, the desire to swing the B capability is ranked higher compared to C because of the smaller physical size of the biological agent to create the impact similar to the chemical agent (based on the mass of agents required for incapacitating 50% of the population exposed), which heightens the possibility of perpetrators attempting to smuggle biological agents across the checkpoint. On the other end of the spectrum, the R detector serves the security screening well by being able to detect low levels of gamma radiation (recall in Section 3.4.2, alpha and beta emitters are unlikely to be a concern in this frame), beyond the target requirements.

Table 50: Summary of performance comparison of options with respect to sensitivity of the systems in the security screening capability.

Option	Target Performance	Current Performance	Ranking
C	10 mg/m^3	No capability	0.8
B	10,000 spores	No capability	1
R	0.2 mSv/hr (γ)	0.1 mSv/hr	0

8.3.2 Selectivity

Table 51 summarises the performance comparison of the options with respect to selectivity requirement of the systems in the security screening capability. With the same rationale as Section 8.3.1, B and C capabilities is perceived to require drastic improvement towards the target value, with B having a higher perceived desire to swing from current to target performance. On the other hand, currently, there are dedicated gamma sensors that detect the presence of gamma radiation. In addition, there are very few interferents around the security screening area, and few legitimate reasons for having radiation source on the body and bags (except for medicinal purpose), reducing the false alarm possibility. With the low possibility of interference and false alarms, it seemed apparent that the current performance for R capability is close to the target performance level, and thus no added desire for swing. There is no apparent need to detect alpha and beta sources at the security screening area, with justifications elaborated in Section 3.4.2.

Table 51: Summary of performance comparison of options with respect to selectivity range of the systems in the security screening capability.

Option	Target Performance	Current Performance	Ranking
C	To be able to detect all forms of chemical threat, and discriminate from interferents. Acceptable to very low false alarm.	No capability	0.8
B	To be able to detect all forms of biological threat, and discriminate from interferents. Acceptable to very low false alarm.	No capability	1
R	To be able to pick up sources that emits gamma radiation. Acceptance to very low false alarm.	Selective towards gamma radiation. Few interferents to initiate false alarms.	0

8.3.3 Response Time

Table 52 summarises the performance comparison of the options with respect to response time requirement of the systems in the security screening capability. With the same rationale as Section 8.3.1, B and C capability is perceived to require drastic and immediate improvement towards the ideal target, with B having a higher perceived rating. On the other hand, the immediate response of the R detection system exceeds the target requirement, and thus no added incentive to swing.

Table 52: Summary of performance comparison of options with respect to response time requirement of the systems in the security screening capability.

Option	Target Performance	Current Performance	Ranking
C	1 minute	No capability	1
B	1 minute	No capability	1
R	1 minute	Instantaneous	0

8.4 Tier 1: Comparison of Initial Response Capability

8.4.1 Sensitivity

Table 53 summarises the performance comparison of the options with respect to sensitivity requirement of the systems in the initial response capability. B detection system is perceived to require immediate improvement towards ideal based on the following rationale:

(i) B system has the largest deviation (a factor of 6,250 times) away from ideal in terms of sensitivity.
(ii) B is more lethal in terms of damage per mass
(iii) It is likely that perpetrators employ biological agents in such a scenario.

On the other hand, relative to B, C has a perceived rating of 0.5, based on the following rationale

(i) C system has smaller deviation (a factor of 370 times) from ideal, compared to B.
(ii) C is less lethal in terms of damage per mass.
(iii) It is likely that perpetrators employ chemical agents in such a scenario.

Lastly, R systems currently surpass the target performance of the ideal detector in terms of sensitivity. In addition, such a radiological dispersal is less likely compared to chemical and biological because additional steps are involved to aerosolise the metal isotope, making it less attractive for perpetrators

deployment. Instead, it may be more straightforward for the perpetrator to hide the source among the crowd for radiation exposure.

Table 53: Summary of performance comparison of options with respect to sensitivity of the systems in the initial response capability.

Option	Target Performance	Current Performance	Ranking
C	0.0001 mg/m^3	0.03 mg/m^3	0.5
B	400 spores/m^3	2.5 million spores/m^3	1
R	13 Bq/ m^3 (α) 13 Bq/ m^3 (β) 0.11 µSv/hr (γ)	8.33 Bq/ m^3 (α) 1.53 Bq/ m^3 (β) 0.1 µSv/hr (γ)	0

8.4.2 Selectivity

Table 54 summarises the performance comparison of the options with respect to selectivity requirement of the systems in the initial response capability. B detection system is the most desired to be improved from its current performance as it is unable to detect all the possible biological agents within one detector system, and there is a wide spectrum of biological substances that will introduce false alarms. While the situation is very similar to C, the latency onset period for biological agents are much longer compared to chemical agents, and thus in a chemical attack, victims often show symptoms within minutes, implying that preliminary deduction of the chemical nature can be done possibly without the use of a detection system For biological and radiological incidents, there are no visible signs of attack, thus the added reliance on the detector to provide an accurate (low false alarm) result amongst the interference in the surrounding air. When comparing C and R detector systems, R requires more attention to improve from the current to the target performance due to challenge of detecting airborne alpha and beta particles. (Refer to Section 3.5.3.). As such, current R capability in an initial response capability can be described as selective only towards

gamma. In such a scenario, alpha and beta particles are likely to be used (compared to gamma) due to their higher inhalation risk, and thus command the need for enhanced selectivity of the current R system to improve the selectivity for alpha and beta detection.

Table 54: Summary of performance comparison of options with respect to selectivity range of the systems in the initial response capability.

Option	Target Performance	Current Performance	Ranking
C	To be able to detect all forms of chemical threat, and discriminate from interferents. Not acceptable to any false alarm.	Unable to detect all possible chemical threats with one single detector. Problems cannot be fully solved with complementary detectors. Experiences high false alarm rates.	0.5
B	To be able to detect all forms of biological threat, and discriminate from interferents. Not acceptable to any false alarm.	Able to detect most possible biological agents. Experiences high false alarm rate.	1
R	To be able to pick up sources that emits all alpha, beta and gamma radiation. Not acceptable to any false alarm.	All in one detector not sensitive to alpha and beta radiation. Switching to different probes is required. Low false alarm rates due to low presence of interferents.	0.7

8.4.3 Response Time

Table 55 summarises the performance comparison of the options with respect to response time requirements of the systems in the initial response capability. There is a perceived need to swing the current performance of B detection system to the target requirement because of the huge deviation, and a faster response time is evident for a swift decision to the subsequent responses. In the case of C

detection system, the need to improve from current to the target performance is apparent because a fast response time is critical in a chemical scenario for life threatening situations, where antidotes are required almost instantly. Furthermore, in a chemical situation, it is definitely more chaotic and uncontrolled as there are collapsed victims and panicked worried-wells. A quicker response time would exert less stress to the police and first responders when providing preliminary explanation to the root cause of the attack. The R system does not require any improvement in this aspect as it has surpassed the target performance requirement for response time.

Table 55: Summary of performance comparison of options with respect to response time requirements of the systems in the initial response capability.

Option	Ideal Performance	Current Performance	Ranking
C	1 minute	5 minutes	1
B	1 minute	15 minutes	1
R	1 minute	immediate	0

8.5 Tier 1 – Comparison of Definitive Identification Capability

8.5.1 Sensitivity

Table 56 summarises the performance comparison of the options with respect to sensitivity requirement of the systems in the definitive identification capability. Both C and B system performance in terms of sensitivity deviate away from the target performance. However, while the value depicted for C system is representative for Sarin, Sarin remains one of the most lethal and highly possible threats for a chemical attack. For biological incident, while *Bacillus anthracis* is highly possible, it is not the most lethal threat. There are other biological agents such as *Francisella tularaemia* which has toxicity approximately 1,000 times lower (Table 4). In this instance, the target sensitivity performance for a B system detecting *Francisella tularaemia* shifts drastically, and renders the current B

system ineffective for definitive identification. In situations like that, the need to improve the B system arises sharply. The R system does not require any improvement in this aspect as it has surpassed the target performance requirement for sensitivity.

Table 56: Summary of performance comparison of options with respect to sensitivity of the systems in the definitive identification capability

Option	Target Performance	Current Performance	Ranking
C	3×10^{-5} mg/m^3	5.7×10^{-4} mg/m^3	0.7
B	40 spores/m^3	49 spores/m^3	1
R	13 Bq/ m^3 (α) 13 Bq/ m^3 (β) 0.11 µSv/hr (γ)	5.6 Bq/ m^3 (α) 5.6 Bq/ m^3 (β) 0.1 µSv/hr (γ)	0

8.5.2 Response Time

Table 57 summarises the performance comparison of the options with respect to response time requirements of the systems in the definitive identification capability. Both B and R detector systems are able to meet the target response time, but R system is able to perform the definitive identification on site, reducing the time for information transfer. C system has the highest desire to improve from its current performance, as it deviates away from the target. Relative to C, there is little desire to improve the current performance of B system in terms of response time.

Table 57: Summary of performance comparison of options with respect to response time requirements of the systems in the definitive identification capability.

Option	Target Performance	Current Performance	Ranking
C	1 hour	1 hour 30 minutes	1
B	1 hour	1 hour	0.2
R	1 hour	0.5 hour	0

8.6 Tier 2: Weightages of KPCs

8.6.1 Frame 1: Early warning capabilities

The options with the highest desire to be improved from the current performances to the ideal target in Frame 1 are placed in comparison, with the results tabulated in Table 58.

In such an early warning capability, the most critical KPC in contributing to the successful detection is perceived to be that of response time. The purpose of early warning capability is to provide ample time for contamination avoidance, and thus the shorter the response time, the more time allocated for actions to be performed in anticipation of the incoming plume. The response time for the current B detection system is insufficient for the scenario stipulated, where at least 9 minutes (Table 45) are required for all the required responses to be performed to successfully protect the key infrastructure and VIPs. As such, immediate improvement for the response time of B system is required.

On the other hand, selectivity of the R system is as critical when compared to response time. In an early warning scenario, it is inherently difficult to pick up signals of chemical, biological or radiological attacks in the sea of numerous interferents, leading to high false alarm rates. The response towards an alert has thus been calibrated such that they are low-regret and low-burden. The acceptance for the higher false alarm rate of the detector implies a more forgiving

system towards selectivity. However, the current R system does not exhibit any inherent selectivity, and relies on human intervention via checkback with other ministries for updates. The desire to improve such a manual and inefficient process is thus as assessed to be as important as improving the response time.

At the other end, the need for sensitivity in the early warning capability is minimal due to the potential high concentration of agents present at release site for a standoff release. In addition, it has been argued (see Section 8.2.1) that the C system merely requires slight improvements to better its performances to cater for worst case scenario.

The need to swing from the current to the target requirement for range in C system is as minimal as that for sensitivity requirement. Although there is a deviation from the target performance requirement, the possibility of a small-scale terrorist attack of such nature from a long range is rather isolated. The constantly fluctuating weather conditions and the unfavourable urban conditions make it difficult for the perpetrators to accurately predict the actual dispersion pattern of the aerosols at long ranges from the target, and it is likely that they would choose to minimise the distance from the target to improve the precision of the attack.

Table 58: Comparison of options with highest desire for improvement in Frame 1.

KPC	Option	Updated Ranking
Sensitivity	C	0.3
Selectivity	R	1
Response Time	B	1
Range	C	0.3

With the above comparison, the rest of the results from Tier 1 comparison of KPC performances in Frame 1 are normalised and the interim result is tabulated in Table 59.

Table 59: Summary of interim results for Frame 1 after normalisation.

Sensitivity			Selectivity			Range			Response Time		
C	B	R	C	B	R	C	B	R	C	B	R
0.3	0	0	0.21	0.49	0.7	0.3	0.3	0	0.3	1	1

8.6.2 Frame 2: Security Screening Capability

The options with the highest desire to be improved from the current performances to the target value in Frame 2 are placed in comparison, with the results tabulated in Table 60.

Selectivity is perceived to be the most critical requirement of a biological detector in a CBR security screening scenario. The need to discriminate and distinguish biological agents from other innocent sources brought across the security checkpoint is important since minute physical quantity of *Bacillus anthracis* contributes to high potent dosage. In addition, there are a wide range of powders and liquids with fully legitimate usages inside a spectator bag. The current B system is not selective enough to pick up the traces of biological agents from the legitimate sources, and will cause false alarm at almost every case. This lack of selectivity is a critical failure point of the entire security screening system, as the consequence of a mission failure will lead to the agent dispersal. Similarly, the lack of sensitivity in a B detector system is a critical failure for the mission, as the consequence of a failed detection due to lack of sensitivity almost certainly results in a successful attack. However, the desire to improve from current level of sensitivity to the target level is not as high compared to that of selectivity, the quantity of biological agents that the perpetrator would smuggle through the custom would be relatively high enough for common biological detection system.

Comparatively, the deviation from target performance in terms of response time is not a critical failure for the entire mission because it does not contribute to an affirmative attack by the perpetrators. Instead, it heightens the possibility of a secondary attacked on the queue of spectators. In another words, without

meeting the ideal performance of response time, the system can still function, albeit at a lower efficiency and increased risk.

Table 60: Comparison of options with highest desire for improvement in Frame 2.

KPC	Option	Updated Ranking
Sensitivity	B	0.7
Selectivity	B	1
Response Time	B	0.4

With the above comparison, the rest of the results from Tier 1 comparison of KPC performances in Frame 2 are normalised and the interim result is tabulated in Table 61.

Table 61: Summary of interim results for Frame 2, after normalisation.

Sensitivity			Selectivity			Response Time		
C	B	R	C	B	R	C	B	R
0.56	0.7	0	0.8	1	0	0.4	0.4	0

8.6.3 Frame 3: Initial response capability

The options with the highest desire to be improved from the current performances to the target value in Frame 3 are placed in comparison, with the results tabulated in Table 62.

For such an initial response capability, sensitivity is perceived to be of paramount importance. The sensitivity of the current B system has performance 6,000 times worse than the target required sensitivity, implying that the current B detector will be unable to detect the minute concentration expected in such a scenario, where the first responder may not be present at the scene during the release. A swing

for the B detector in sensitivity requirement is crucial for the overall mission success for this scenario.

On the other hand, the requirement to swing to target value in both selectivity and response time aspects is not as apparent as that for sensitivity. The response time requirement of the B detector is not the mission critical determinant in this frame. While a detector with an ideal response time is able to provide timely classification, a longer response time does not constitute a consequence as catastrophic as having a poor sensitivity. The desire to improve the selectivity is assessed to be similar to that of improving the response time. The current performance of B capability is adequate in detecting most lethal bioagents with a single system.

Table 62: Comparison of options with highest desire for improvement in Frame 3.

KPC	Option	Updated Ranking
Sensitivity	B	1
Selectivity	B	0.5
Response Time	B	0.6

With the above comparison, the rest of the results from Tier 1 comparison of KPC performances in Frame 3 are normalised and the interim result is tabulated in Table 63.

Table 63: Summary of interim results for Frame 3, after normalisation.

Sensitivity			Selectivity			Response Time		
C	B	R	C	B	R	C	B	R
0.5	1	0	0.3	0.6	0.42	0.3	0.3	0

8.6.4 Frame 4: Definitive identification

The options with the highest desire to be improved from the current performances to the ideal target in Frame 4 are placed in comparison, with the results tabulated in Table 64.

As consistent with the rationale in Section 8.6.3, sensitivity is perceived to be more important than response time. A detector with highest order of sensitivity is much valued because this is often the final confirmative step to identify the species of the suspected agent. Improvement from current response time to the target level is not as desired because the current response time does not cause a critical failure in the overall mission.

Table 64: Comparison of options with highest desire for improvement in Frame 4.

KPC	Option	Updated Ranking
Sensitivity	B	1
Response Time	C	0.3

With the above comparison, the rest of the results from Tier 1 comparison of KPC performances in Frame 4 are normalised and the interim result is tabulated in Table 65.

Table 65: Summary of interim results for Frame 4, after normalisation.

Sensitivity			Response Time		
C	B	R	C	B	R
0.7	1	0	0.3	0.06	0

8.7 Tier 3: Importance of Frame

The options with the highest desire to be improved within each frame after the weight allocations (Tier 2) are listed down for comparison, to derive the importance of each frame in the overall detection architecture.

The sensitivity of a B system in the initial response capability (Frame 3) is perceived to have the most desire for improvement. The initial response capability is perceived to be extremely important in the overall detection architecture because of its direct relevance in critical life-saving countermeasures. In addition,

the deviation away from ideal sensitivity for the B system is alarming, and should require high attention. Similarly, the lack of capability in a security screening frame requires a high level of attention in improving the current performance level. Furthermore, the lack of attention to providing adequate chemical and biological detection in such a setting unveils a security loophole that must be addressed.

Improvement for response time for B systems in an early warning capability is not perceived as highly valued because the possibility of perpetrators executing an urban attack via long-range release is low. With a specific target as in this frame, the perpetrators would more likely be focused on bringing the source closer to the target so that the attack would not be affected drastically by atmospheric turbulence vertical dilution of the agents.

Similarly, the improvement for sensitivity for B system in a definitive identification is not perceived to be important, when compared to that in the initial response capability. Firstly, the current performance for the former is closer to its target performance standards. Secondly, definitive identification does not have direct influence to the main response actions towards the attack. Rather, the positive identification provides an affirmative answer to the authority of the agent, its identity, and source and concentration, which is not primarily useful in keeping the attack under control. While this capability is critical for specific medicinal and antidote therapy aid, there are other clinical tests that can identify the agent based on stool, urine or blood samples, with the compromise of a longer analysis time.

Table 66 shows the relative rating of the options placed in comparison in this section.

Table 66: Comparison of options with highest desire for improvement.

Frame	KPC	Option	Updated Ranking
1	Response Time	B	0.4
2	Selectivity	B	1
3	Sensitivity	B	1
4	Sensitivity	B	0.3

The rest of the results from the Tier 2 comparison are then normalised with the compared option in their respective frames. The overall results are tabulated in Table 67.

8.8 Chapter Conclusion

Table 67 concludes the overall results (after normalisation) of the CBR detection capabilities comparison with the SMARTS methodology.

Table 67: Overall results of comparison derived from the SMARTS methodology.

	Early Warning Capability												Security Screening Capability								
Ranking of C, B and R capability after:	**Sensitivity**			**Selectivity**			**Range**			**Response Time**			**Sensitivity**			**Selectivity**			**Response Time**		
	C	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**
- Tier 1 Analysis	1	0	0	0.3	0.7	1	1	1	0	0.3	1	1	0.8	1	0	0.8	1	0	1	1	0
- Tier 2 Analysis	0.3	0	0	0.21	0.49	0.7	0.3	0.3	0	0.3	1	1	0.56	0.7	0	0.8	1	0	0.4	0.4	0
- Tier 3 Analysis	0.12	0	0	0.08	0.2	0.28	0.12	0.12	0	0.12	0.4	0.4	0.45	0.56	0	0.64	0.8	0	0.32	0.32	0

	Initial Response Capability									Definitive Identification Capability					
Ranking of C, B and R capability after:	**Sensitivity**			**Selectivity**			**Response Time**			**Sensitivity**			**Response Time**		
	C	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**
- Tier 1 Analysis	0.5	1	0	0.5	1	0.7	1	1	0	0.7	1	0	1	0.2	0
- Tier 2 Analysis	0.5	1	0	0.3	0.6	0.42	0.3	0.3	0	0.7	1	0	0.3	0.06	0
- Tier 3 Analysis	0.5	1	0	0.3	0.6	0.42	0.3	0.3	0	0.21	0.3	0	0.09	0	0

9 RESULTS AND DISCUSSIONS

9.1 Chapter Summary

This chapter introduces the concept of sensitivity analysis and validation processes. The results of the comparison are briefly analysed in support for the proof of concept. These results highlight the different aspect of concerns that should be addressed in future, and brings about proposal of potential stop gap solutions to bridge the current inequality in the relative rankings. Limitations of the framework are discussed and further studies are recommended.

9.2 Chapter Introduction

The SMARTS method allows prioritization of our ideas according to the situational perception of both tangible and intangible KPCs. The interpretation of our perception towards the various criteria is limited by both the inherent knowledge of the fields and the cognitive challenges faced in organising the knowledge into tangible and sense-making measurements.

While the SMARTS method is capable of decision making involving conflicting intangibles, it may not necessarily pack the required confidence and robustness [205]. This is especially true when decisions must be based on competing factors at different tiers based on the hierarchy, and it may be cognitively demanding even for a subject matter expert to fully digest all the relevant factors to make a conscious decision.

Section 9.3 describes the additional layer of sensitivity analysis adopted in a systematic fashion to capture the judgements from various angles, to ensure an overall robust decision.

The remaining sections validate the result from the verified framework, and discuss the framework from different perspectives to instil the required confidence in making accurate decisions.

9.3 Sensitivity Analysis

9.3.1 Problem with the initial framework

As seen in the proposed model (Figure 7, reattached below), hereinafter referred to as Framework 1, there is a strong inter C, B and R capability comparison at the base level, as each C, B and R capability is measured with respect to each KPC within individual frames in the first tier of comparison (k=1). The second tier of comparison (k=2) analyses the importance of each KPC within a specified frame. The third tier (k=3) concludes by analysing the importance of each frame in the overall detection architecture. A matrix of C_{ijk}, B_{ijk} and R_{ijk} can be generated for every set of comparison, generalised in Figure 15, where i denotes the different frames (1 to 4) and j denotes the KPC of the detector that contributes to the success of each frame i. An example is placed alongside the matrix to illustrate the point. In this example, the selectivity of detectors in the early warning frame (i = 1) is illustrated.

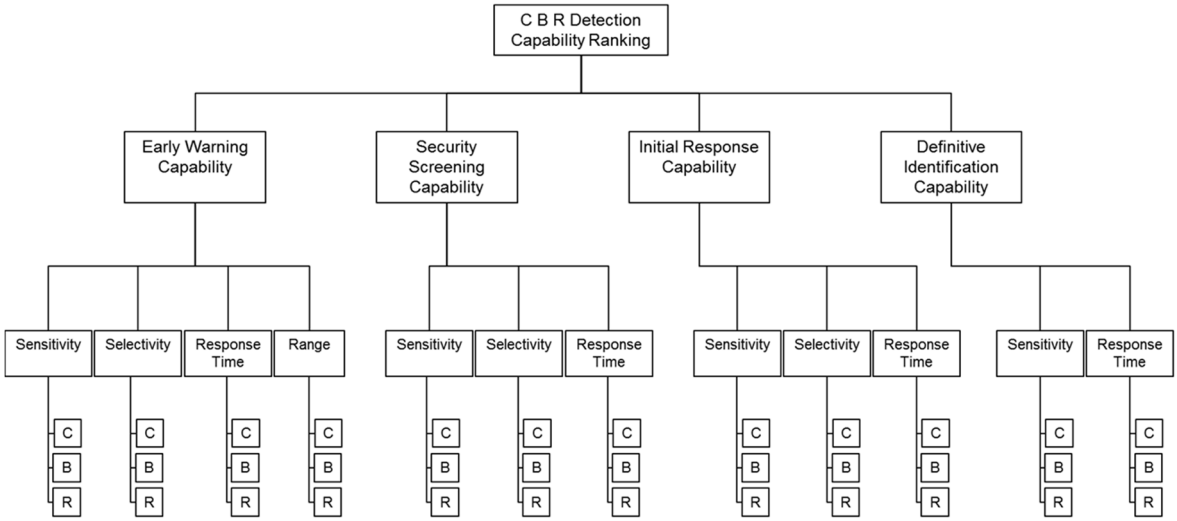

Figure 7: Framework 1

	Comparison with respect to each KPC			***Example: Selectivity in Frame 1 (****Table 67****)***		
Base comparison	C_{ij1}	B_{ij1}	R_{ij1}	*0.3*	*0.7*	*1*
Second tier comparison	C_{ij2}	B_{ij2}	R_{ij2}	*0.21*	*0.49*	*0.7*
Highest tier comparison	C_{ij3}	B_{ij3}	R_{ij3}	*0.08*	*0.2*	*0.28*

Figure 15: Matrix representing the three tiers of comparison in the model.

This method of categorising has flaws. As the comparison progresses into the next tier, it must be noted that the ratio of C, B to R values within each level of comparison is kept constant, as illustrated in the equations below:

$$\frac{C_{ij1}}{B_{ij1}} = \frac{C_{ij2}}{B_{ij2}} = \frac{C_{ij3}}{B_{ij3}} \quad , \quad \frac{C_{ij1}}{R_{ij1}} = \frac{C_{ij2}}{R_{ij2}} = \frac{C_{ij3}}{R_{ij3}} \quad \& \quad \frac{B_{ij1}}{R_{ij1}} = \frac{B_{ij2}}{R_{ij2}} = \frac{B_{ij3}}{R_{ij3}}$$

This is further illustrated using the figures in the example given in Figure 15.

$$\frac{0.3}{0.7} = \frac{0.21}{0.49} = \frac{0.08}{0.2} = 0.4 \quad , \quad \frac{0.3}{1} = \frac{0.21}{0.7} = \frac{0.08}{0.28} = 0.3 \quad \& \quad \frac{0.7}{1} = \frac{0.49}{0.7} = \frac{0.2}{0.28} = 0.7$$

This implies that the first level of comparison between the C, B and R detection capabilities must be extremely robust, taking into account not only the performance differences within the said KPC, but should also accord the relative differences in the importance of the different KPCs within a chemical, biological and radiological incident (frame), and the disparity in emphasis of the different frames towards the success in different chemical, biological and radiological detection architectures. While these may not be entirely impossible, the increased cognitive requirement tends to lead the decision maker into overlooking certain aspects. For instance, in the midst of determining the difference in KPC comparison within each frame, critical criteria such as importance of the KPC in determining the success of the frame or the role of each frame in contributing to the success of the overall CBR defence may be neglected as the secondary concern. In order to uphold the intended integrity of the comparison model, additional models focusing on different aspects are proposed to be implemented in the sensitivity analysis phase.

9.3.2 Framework 2: Focus on comparison of KPC within a domain

Figure 16 shows the illustration of the proposed Framework 2. Framework 2 focuses on the baseline comparison of the KPC within the individual domain detection system at the bottom tier to derive the relative importance of each KPC in their respective environment, before comparing the relative weights of each detection system within a frame. Ultimately, the importance of each frame towards the success of the overall detection architecture is defined. Similar to Framework 1, the ratio of each pair of base comparison is maintained as the comparison progresses through the different tiers. The difference from Framework 1 lies in the arrangement of the hierarchy elements, where in this case, the main emphasis resides in the investigation of the KPC within the individual C, B and R domain as the base comparison.

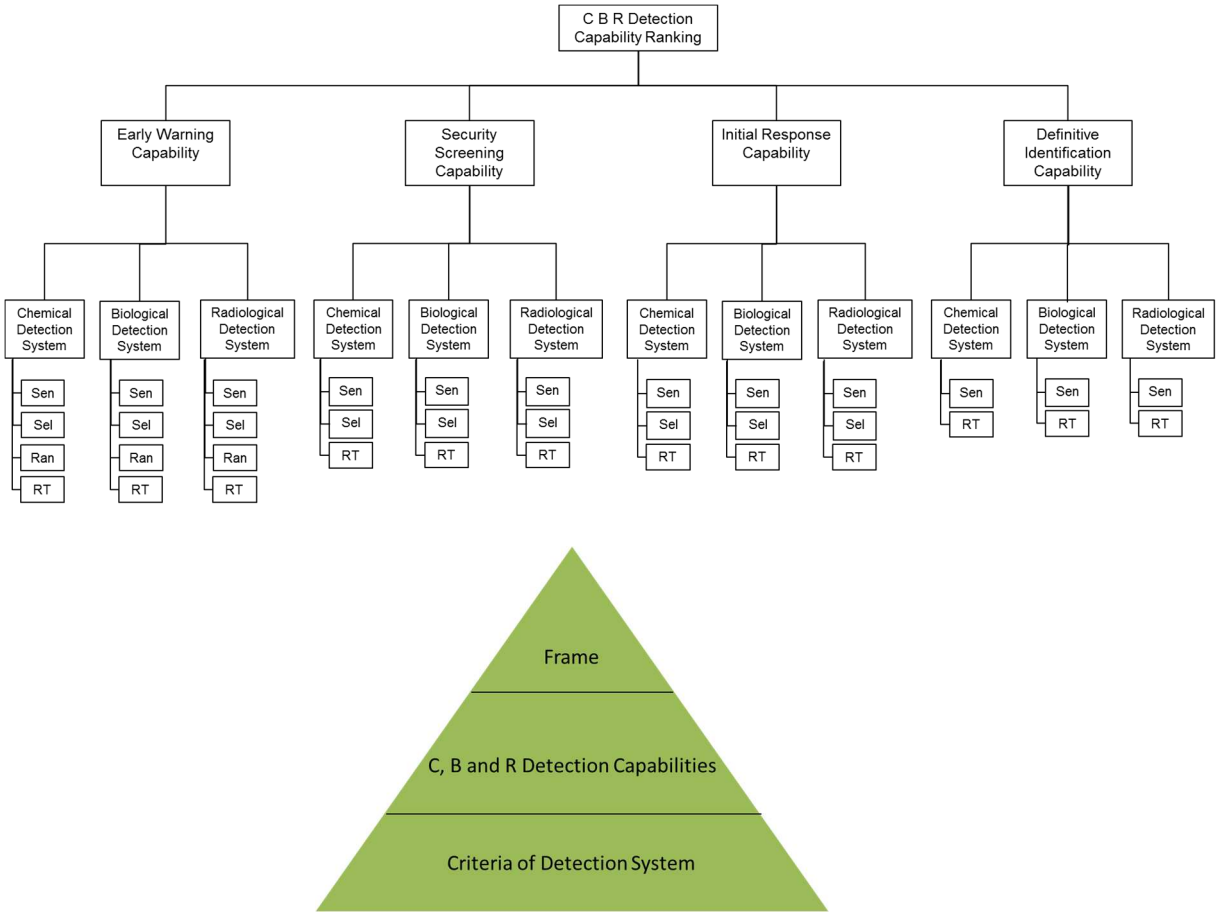

Figure 16: Proposed Framework 2.

9.3.3 Framework 3: Focus on domain capability performances

The hierarchy is then remodelled to Framework 3, as shown in Figure 17, where in Framework 3, the performance of each domain detection capabilities in terms of their individual KPC are first compared.

The different KPCs of each domain detection capability are compared in terms of their importance in each frame. Next, the importance of each KPC towards the success of detection in each domain is measured, before the individual domains are finally compared at the final stage.

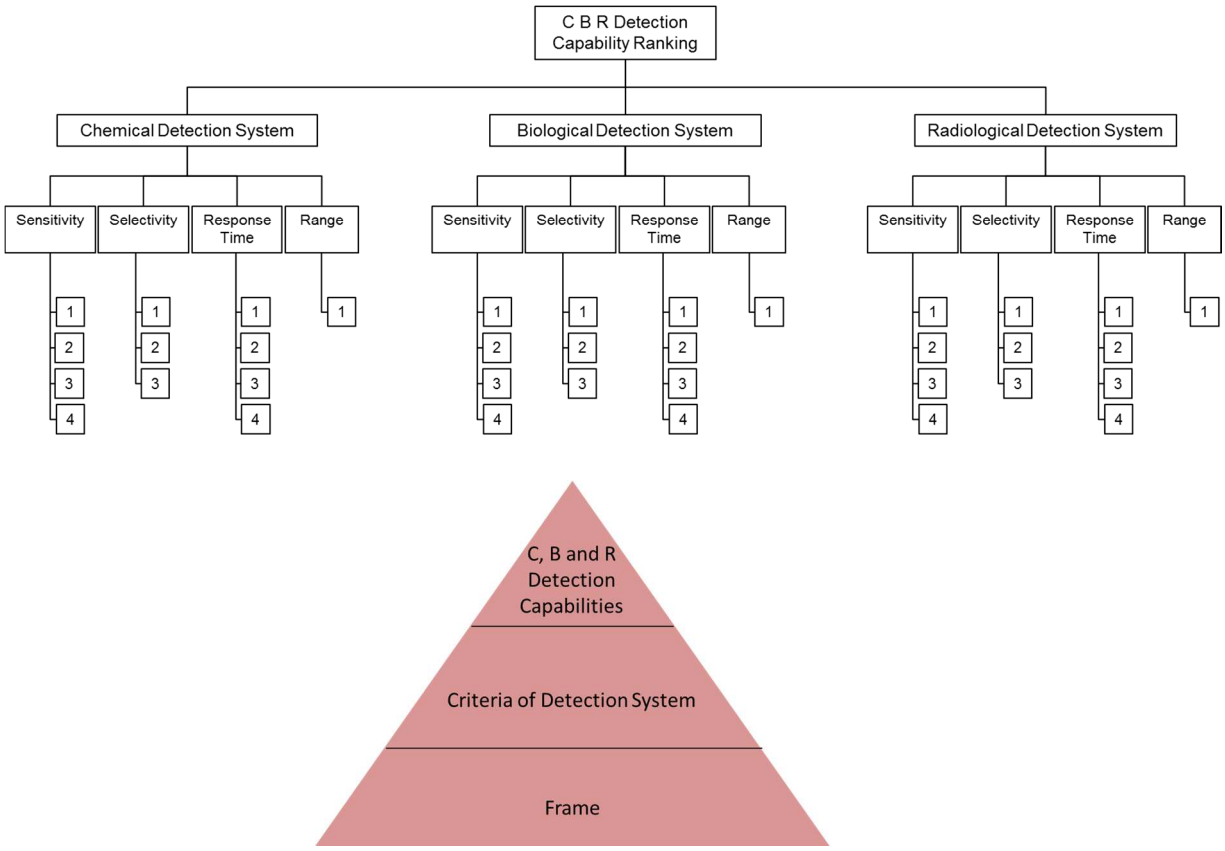

Figure 17: Proposed Framework 3.

9.3.4 Framework iteration

As seen, the three frameworks complement each other in the pursuit of an accurate C, B and R detection capability ranking. The original Framework 1 is designed to provide the most comprehensive inter C, B and R capability

comparison at the base comparison, explicitly relating the decision maker to the main objective. Framework 2 scopes the comparison to focus on the importance of the KPC performance in the individual domain environment. Lastly, Framework 3 bases the discussion on the importance of each frame in different domain environments. Although the three framework targets the comparison from three different facets, the output converges towards the same C, B and R detection capability ranking, relying on the same experts' judgements. Since all three framework leverages on the opinion of the same set of experts with the same set of scenario, it is implied all three framework should narrow to the same results. However, by phrasing the analysis in a different manner, it leaves the experts open to approach the comparison from different facets, and thus, initial answers may have slight variations.

For the comparison to be fully encompassing, a sanity check based on iterative approach is adopted, as shown in Figure 18. It is proposed that the decision maker attempts all three frameworks. Once the first attempt is performed, the finalised individual weightages of each KPC should be reconciled with the corresponding weightage values in the other two frameworks.

The comparison of the individual weightages across the three frameworks encourages the decision maker to pick up disparities and to revisit the initial rationalisations and alter the base comparisons with a clearer perception. Such iterations are performed until the following is satisfied:

- The ranking from the three frameworks converge to a common answer.
- The individual weightages in each framework, derived after the three tiers of comparisons, are within acceptable deviation from their corresponding values in the other two frameworks.
- The decision maker is convinced that the weightages in the three frameworks are representative of his final perception from various facets

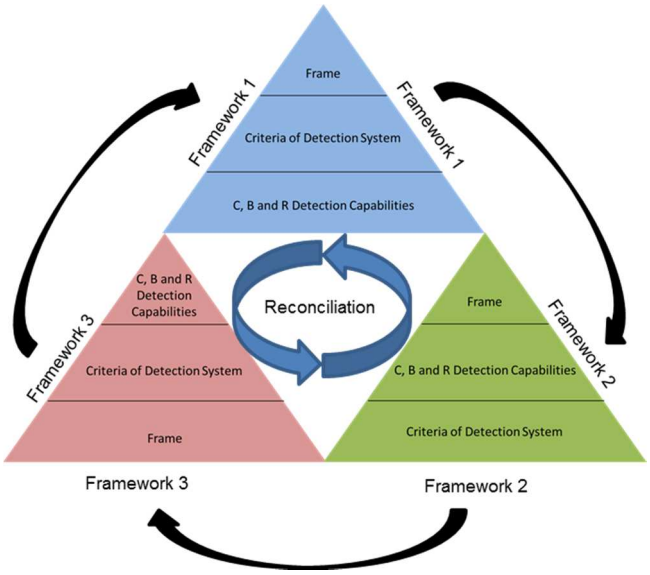

Figure 18: An iterative approach is adopted to derive at a robust solution. The approach relies on three frameworks that are derived to draw perceptions from different facets.

9.3.5 Updated Results

The initial results obtained in Table 67 were compared alongside the initial results from Framework 2 and 3. Collectively, they formed the first iteration in attempts to arrive at an undisputed conclusion. The details of the various iterations are deliberately left out in this dissertation. The iterated results from three frameworks are appended in Appendix A. The final result from Framework 1 after the iteration is placed in comparison with the original Framework 1 (Chapter 8), and the comparison is depicted from Table 68 to Table 76. The overall updated result after the sensitivity analysis is summarised in Table 77.

Table 68: Comparison of results before and after sensitivity analysis for Frame 1.

	Frame 1: Early Warning Capability							
	Sensitivity		Selectivity		Range		Response Time	
	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
C	1	1	0.3	0.3	1	1	0.3	0.3
B	0	0	0.7	0.6	1	1	1	1
R	0	0	1	1	0	0	1	1

Table 69: Comparison of results before and after sensitivity analysis for Frame 2.

	Frame 2: Security Screening Capability					
	Sensitivity		Selectivity		Response Time	
	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
C	0.8	0.6	0.8	0.8	1	1
B	1	1	1	1	1	1
R	0	0	0	0.2	0	0

As seen in Table 69, the desire to swing the selectivity of the current R detection system in Frame 2 changes from 0 to 0.2 after the sensitivity analysis. The change was reflected as a result of analysis from Framework 2 (Refer to Appendix A, Table A-2), where selectivity was perceived as one of the most critical area of improvement when compared to sensitivity and response time of a R detection system within the personnel security screening capability. The change of perspective from a different facet brought attention to the initial perception in Framework 1.

Table 70: Comparison of results before and after sensitivity analysis for Frame 3.

	Frame 3: Initial Response Capability					
	Sensitivity		**Selectivity**		**Response Time**	
	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
C	0.5	0.5	0.5	0.5	1	0.8
B	1	1	1	1	1	1
R	0	0	0.7	0.7	0	0

From Table 70, the response time of the chemical detection capability was initially perceived to be as desired to be improved as that for the biological detection capability in an initial response frame. However, as seen in Appendix A, Table A-2 (Tier 2 comparison), when the chemical response time in the initial response frame was compared with the biological sensitivity in the same frame, it was perceived that the desire to improve the chemical response time is only 0.5 that of the desire to improve the biological sensitivity. However, when the biological response time was compared to the biological sensitivity (Tier 1 comparison), it was desire to improve was perceived to be 0.6. This alluded to the misalignment of perception from the two different frameworks[49], and triggered the need for re-evaluation of the perception in Framework 1.

[49] In framework 1, chemical response time: biological response time = 1: 1. In framework 2, chemical response time: biological response time = 0.5: 0.6.

Table 71: Comparison of results before and after sensitivity analysis for Frame 4.

	Frame 4: Definitive Identification Capability			
	Sensitivity		Response Time	
	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
C	0.7	0.7	1	1
B	1	1	0.2	0
R	0	0.1	0	0

As seen in Table 71, the desire to swing the selectivity of the current R detection system in Frame 2 changes from 0.2 to 0 after the sensitivity analysis. The change was reflected as a result of analysis from Framework 3 (refer to Appendix A, Table A-3, Framework 3) where response time of biological detection systems for all four frames were placed in comparison. In this comparison, it was then perceived that all three biological response times from frame 1, 2 and 3 deviates from the ideal, and require improvements. However, it was perceived that the biological response time in the definitive identification frame (1hr) is similar to the target value (1hr) and thus no requirement for improvements. The differences in perception between Framework 1 and Framework 3 after the first iteration leads to another analysis and thus brought about the change of perception in the biological response time in frame 4, under Framework 1.

Table 72: Comparison of results before and after sensitivity analysis for alternatives with highest desire for improvement in Scenario 1 (early warning capabilities).

KPC	Alternative	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
Sensitivity	C	0.3	0.3
Selectivity	R	1	1
Response Time	B	1	1
Range	C	0.3	0.3

Table 73: Comparison of results before and after sensitivity analysis for alternatives with highest desire for improvement in Scenario 2 (personnel security screening).

KPC	Alternative	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
Sensitivity	B	0.7	0.7
Selectivity	B	1	1
Response Time	B	0.4	0.4

Table 74: Comparison of results before and after sensitivity analysis for alternatives with highest desire for improvement in Scenario 3 (initial response capability).

KPC	Alternative	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
Sensitivity	B	1	1
Selectivity	B	0.5	0.5
Response Time	B	0.6	0.6

Table 75: Comparison of results before and after sensitivity analysis for alternatives with highest desire for improvement in Scenario 4 (laboratory confirmation capability).

KPC	Alternative	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
Sensitivity	B	1	1
Response Time	C	0.3	0.3

Table 76: Comparison of results before and after sensitivity analysis for alternatives with highest desire for improvement in each frame.

Scenario	KPC	Alternative	Ranking Before Sensitivity Analysis	Ranking After Sensitivity Analysis
1	Response Time	B	0.4	0.35
2	Selectivity	B	1	1
3	Sensitivity	B	1	1
4	Sensitivity	B	0.3	0.3

Table 77: Updated overall results of comparison, after sensitivity analysis.

	Early Warning Capability												Security Screening Capability								
Ranking of C, B and R capability after:	**Sensitivity**			**Selectivity**			**Range**			**Response Time**			**Sensitivity**			**Selectivity**			**Response Time**		
	C	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**
- Tier 1 Analysis	1	0	0	0.3	0.6	1	1	1	0	0.3	1	1	0.6	1	0	0.8	1	0.2	1	1	0
- Tier 2 Analysis	0.3	0	0	0.3	0.6	1	0.3	0.3	0	0.3	1	1	0.42	0.7	0	0.8	1	0.2	0.4	0.4	0
- Tier 3 Analysis	0.11	0	0	0.11	0.21	0.35	0.11	0.11	0	0.11	0.35	0.35	0.42	0.7	0	0.8	1	0.2	0.4	0.4	0

	Initial Response Capability									Definitive Identification Capability					
Ranking of C, B and R capability after:	**Sensitivity**			**Selectivity**			**Response Time**			**Sensitivity**			**Response Time**		
	C	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**	**C**	**B**	**R**
- Tier 1 Analysis	0.5	1	0	0.5	1	0.7	0.8	1	0	0.7	1	0.1	1	0	0
- Tier 2 Analysis	0.5	1	0	0.25	0.5	0.35	0.48	0.6	0	0.7	1	0.1	0.3	0	0
- Tier 3 Analysis	0.5	1	0	0.25	0.5	0.35	0.48	0.6	0	0.2	0.3	0.03	0.09	0	0

9.4 Results

Through the iterative process, the comparison of C, B and R detection capabilities can be decomposed and quantified. This section aims to verify the rigour of the framework by analysing and validating its derived results.

Table 78 is derived from the rearrangements of the final tier analysis (Tier 3) from Table 77, in descending order. These figures are termed as Desire Ratings (DR) as they signify the Author's perceived desire for the KPC to be improved from the current performance level to the target performance level. As seen, the sensitivity and selectivity of a biological detection system in the CBR security screening and initial response capability have the highest DR. The highest DR for the chemical domain is the selectivity in the CBR security screening frame, while that for the radiological domain is the selectivity of the initial response phase. Seen in Table 78, the results are conveniently categorised into three distinct categories. The first category (DR > 0.4) lists the different KPCs that must be addressed to obtain a visible improvement in the detection capability. The next category (0.4 > Dr > 0.1) lists the KPCs that do not need to be improved urgently, although improvements will enhance the overall capability. The last category (DR < 0.1) shows the KPCs that are already performing relatively at the peak, and no further improvements are required. There are a total of 7 KPCs for a radiological domain that has a DR of 0, while 2 for biological and 0 for chemical domains.

Table 78: Results of subjective analysis after iteration, presented in descending rank order.

Desire rating > 0.4				0.4 > Desire rating > 0.1				Desire rating < 0.1			
Domain	Scenario	KPC	Rating	Domain	Scenario	KPC	Rating	Domain	Scenario	KPC	Rating
B	2	Selectivity	1	R	1	Selectivity	0.35	C	4	Response time	0.09
B	3	Sensitivity	1	B	1	Response time	0.35	R	4	Sensitivity	0.03
C	2	Selectivity	0.8	R	1	Response time	0.35	B	1	Sensitivity	0
B	2	Sensitivity	0.7	R	3	Selectivity	0.35	R	1	Sensitivity	0
B	3	Response Time	0.6	B	4	Sensitivity	0.3	R	1	Range	0
C	3	Sensitivity	0.5	C	3	Selectivity	0.25	R	2	Sensitivity	0
B	3	Selectivity	0.5	B	1	Selectivity	0.21	R	2	Response time	0
C	3	Response Time	0.48	C	4	Sensitivity	0.21	R	3	Sensitivity	0
C	2	Sensitivity	0.42	R	2	Range	0.2	R	3	Response time	0
C	2	Response Time	0.4	C	1	Sensitivity	0.105	B	4	Response time	0
B	2	Response Time	0.4	C	1	Selectivity	0.105	R	4	Response time	0
				C	1	Range	0.105				
				B	1	Range	0.105				
				C	1	Response time	0.105				

The statistical results are organised in Figure 19 as a stacked plot of DR against the KPCs for the four distinct frames. This graph provides a clear comparison of the C, B and R detection capabilities improvement desires in terms of the specific KPC in each frame. The data is re-arranged in Figure 20 as a comparison within each domain, emphasising on the trend of frame dependant importance of each domain in achieving success in the overall CBR detection architecture. The two different plots yield specific findings targeted to different groups of professionals. Specific findings on Figure 19 and Figure 20 are depicted in the preceding subsections.

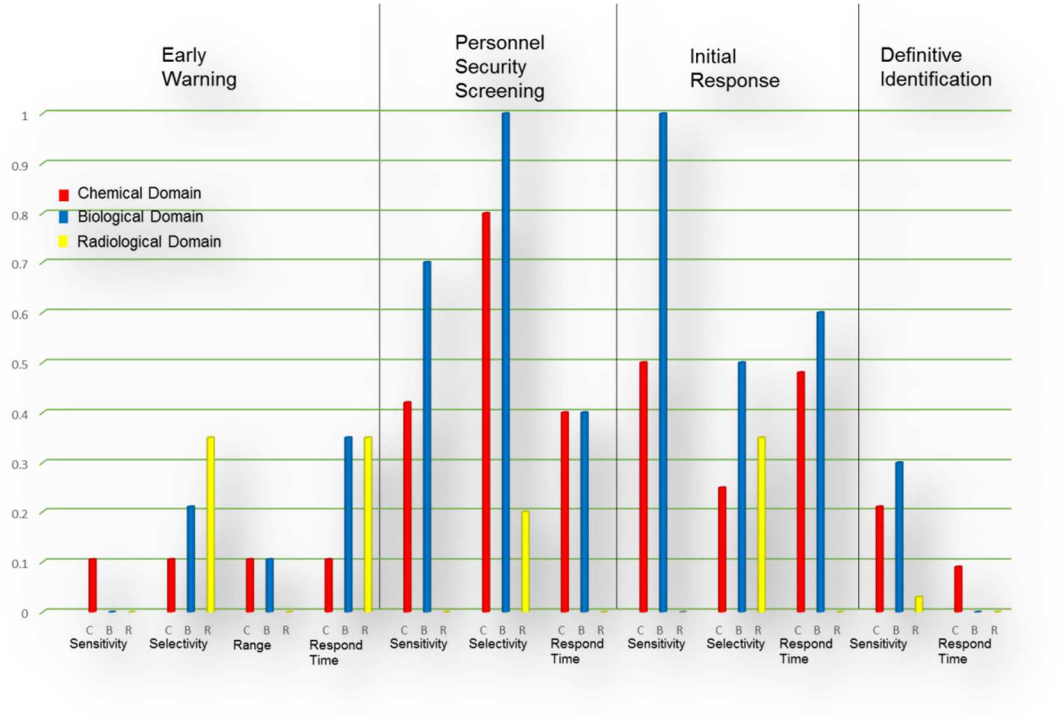

Figure 19: Plot of Desire Ratings (DRs) against KPCs within each frame.

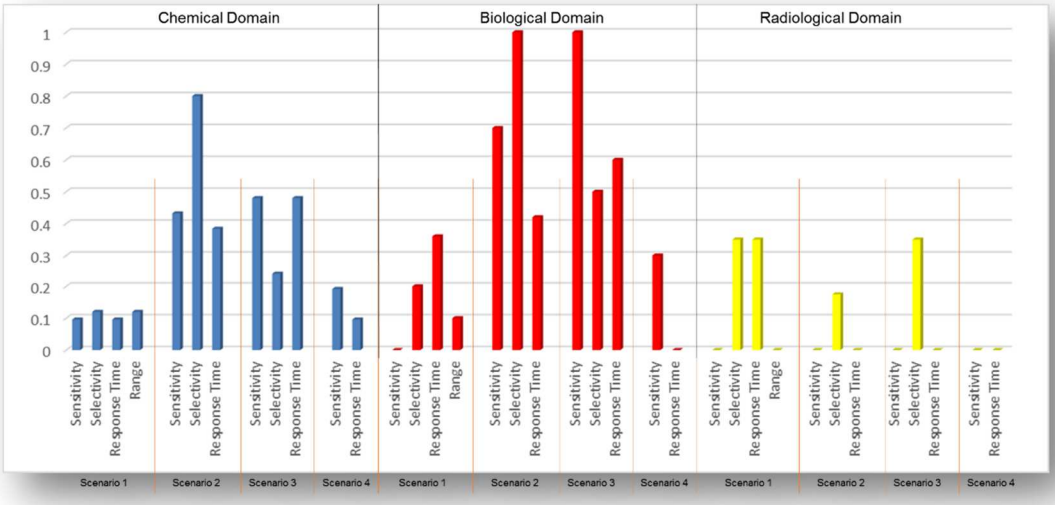

Figure 20: Plot of DRs vs KPCs within each domain.

9.4.1 Findings on early warning capability

In the early warning capability, it is implied from Figure 19 that there is the strongest perceived desire to improve the radiological capability, based on the fact that the current R standoff detection system is fundamentally rudimentary and not specific enough for any response actions. There is a strong desire to incorporate the ability of detecting all three alpha, beta and gamma radiation dispersion in aerosol form, at a response time fast enough for any response initiations. In contrast, chemical standoff detection system is relatively efficient and useful in all aspects to enable an acceptable level of contamination avoidance actions. However, when compared to the overall scheme, it was shown in Figure 19 that although within the early warning frame comparison there were indications to improve the radiological standoff (early warning) capabilities, the desire was less pronounced when compared to other frames. The success of long range attacks via aerosol dispersions is highly reliant on the plume dispersion pathways, which are dependent on the meteorological conditions and urban architecture layout, amongst many other factors. Such dispersions towards a specified target also require a huge amount of agents depending on the distance to the target, and can be easily detected. The battery of constraints adds logistical burden to the planning, and hinders the success of the attacks. With a

lower possibility of long-range attacks, the reliance on standoff detection capabilities reduces. The relative high tolerance of false alarm may also be the reason for the lower desire to improve the current standoff capabilities.

Except for the need to improve the response time, generally the desire to improve biological standoff capability is low, and this lack of desire is postulated to the nature of the standoff detection capability, which generally generate high false positive alarms to deny significant actions (such as full evacuation or full response). This shifts the reliance onto the other 3 frames in the overall scheme of detection architecture.

9.4.2 Findings on CBR personnel security screening capabilities

From Figure 19, in the CBR security screening capabilities, the biological capability is perceived to require the most attention to improve to the target performance level due to a myriad of factors revolving around the currently limited biological screening capability. Although the chemical screening capabilities are limited to the same extent, Figure 19 shows a lesser desire for chemical improvements, possibly due to the lower perceived consequences[50] of chemical agents relative to biological agents. Radiological detection capabilities, on the other end, are less required for improvements in all aspects with the prevalent technological capabilities displayed in current security arenas. Figure 20 revealed that such a capability in the chemical and biological domains generally require a higher relative attention, implying the lack of focus and the importance as the last layer of the detect-to-warn mechanism.

9.4.3 Findings in initial response capability

Figure 19 shows a strong desire (1) to improve the current biological sensitivity and response time. This is attributed to the inability to detect biological agents at realistically low concentration within the required time, causing problems to the operator onsite. Comparatively, chemical detection capabilities in such a frame

[50] Threat analysis is not within the scope of the dissertation. There is a further need to study the consequence and likelihood of C, B and R attacks to better encompass the threat element.

are more effective, possibly due to the higher focus developers and procurers have placed in dealing with the more probable threat. Chemical threats are generally fast-acting and thus a finer response protocol coupled with better detection mechanism is required to tackle its imminent problem. Again, radiological detection capability is comparatively ranked lowest in the improvement desire, indicating that it is generally accepted as a good performer amongst the C, B and R detector in the initial response phase.

9.4.4 General trend of C, B and R detection capability

It is implied in Figure 20 that both the C and B domains show similar trends in the areas of improvements in the security screening and initial response capabilities. While the inherent technologies to equip both domains with the necessary capabilities are different, the trend is promising to synergise research findings from chemists and microbiologists in attempt to uncover potential improvement measures from different perspectives.

However, the desire to improve the KPC in radiological detection is fundamentally different. As seen in Figure 20, there are several KPCs that are not required for any improvements from the current performance levels. However, almost all radiological scenarios prompt for the improvement in selectivity, which in specific terms, refers to the need to detect all forms of radiation amidst the background interference. It defies the hypothesis that radiological detection systems are adequate in detecting all forms of radiation threat effectively. Capability improvements in the form of standoff detection and alpha-beta detection in response to post incident management are required for an all-round solution against radiological incidents.

9.4.5 Comparative Analysis

To improve the comparative analyses required from first responders, the results can be rearranged and displayed as a comparison between two capabilities (X-Y plot) or all three capabilities (X-Y-Z) plot, the former having the ability to provide analysis in a clearer view. Figure 21 shows the comparative analysis for C & B, C & R and B & R detection systems in a clockwise fashion, and highlights the

important ways in which one domain differs in its KPC capability from another domain. Each graph can also be segregated into four quadrants to indicate the maturity of the KPC traits for each domain. The X=Y line distinctly displays the superiority of one domain capability over the other, and gives the first responders an idea of their current capability at a glance. As an example, the first graph shows that in general, most of the KPCs for biological detection capability require more improvements compared to chemical detection capability as most of the data is skewed above the Y=X line. The graph also identified two data points (selectivity in security screening and sensitivity in initial response) at the upper right quadrant, which indicates strong desires to improve in both chemical and biological capabilities. The overall aim is to understand the various KPCs and their weaknesses, in attempt to improve them towards the lower left quadrant.

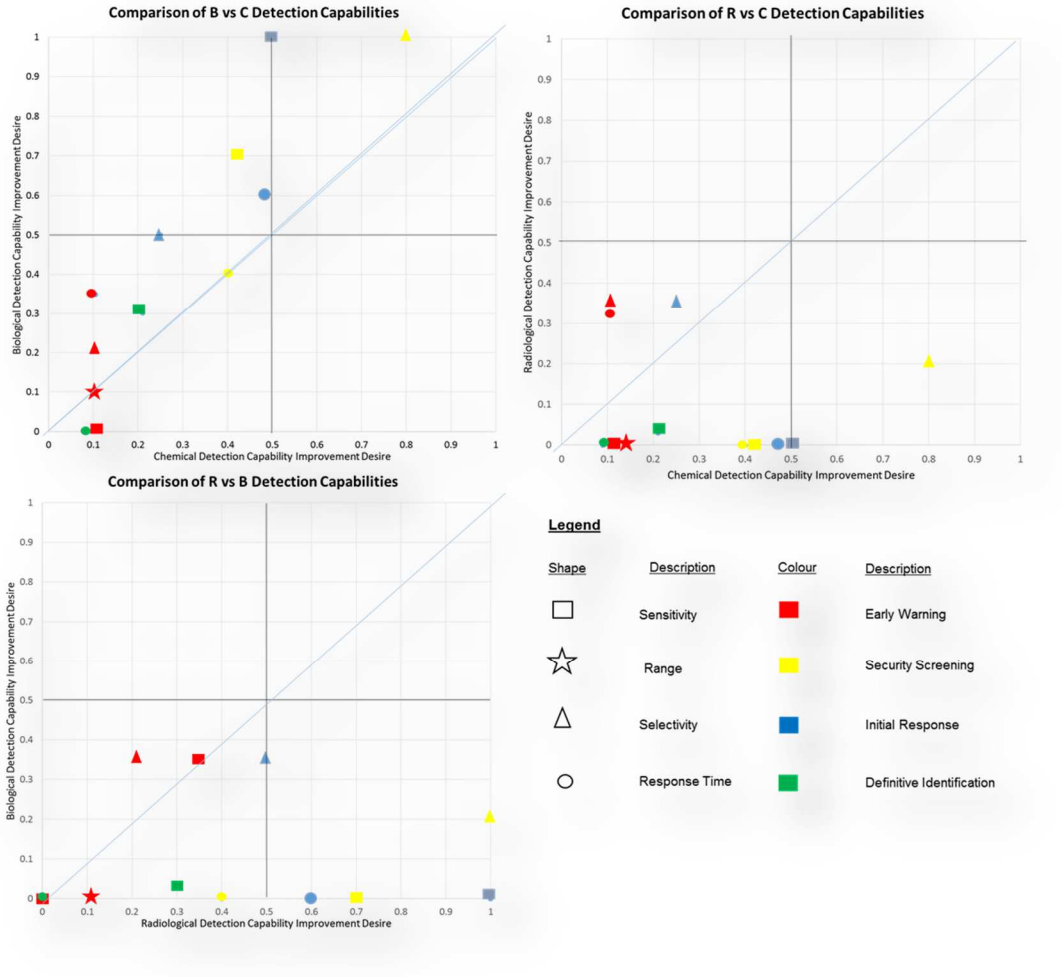

Figure 21: Comparative analysis of B vs C (top left), R vs C (top right) and R vs B (bottom left).

9.4.6 Validation of overall results

9.4.6.1 Validation of results with literature

Table 79 shows the summation of the individual weightages for C, B and R (extracted from Table 77) for all domains. It can be seen that the overall desire to improve biological systems is much higher compared to that for radiological detection systems, inferring a highest level of challenge faced in biological detection, followed by chemical, and radiological detection.

Table 79: Overall summated results for CBR detection comparisons.

Domain	Score	Percentage
Biological	5.17	51.6%
Chemical	3.57	35.63%
Radiological	1.28	12.77%

This result is well reflected in real world research and report findings performed by many official bodies, as depicted in this paragraph. Dr. Price [206] consolidated the contracts[51] for CBRN equipment for FY2009, as depicted in Figure 22.

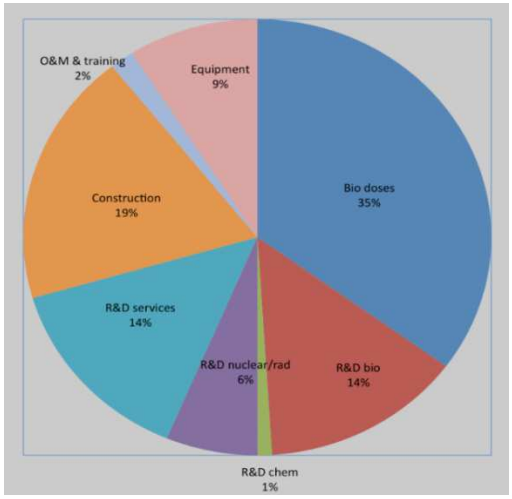

Figure 22: Pie chart for US CBR contracts by category in FY 2009 [206].

The data from Figure 22 that are of direct relevance to the dissertation are the CBR R&D spending, as they imply the amount of emphasis placed on improving the capabilities. These data are extracted and normalised, and placed in comparison with the dissertation findings as shown in Figure 23.

[51] It is documented by Dr. Price that the consolidated listing is imperfect due to the difficulty faced in gathering the resources.

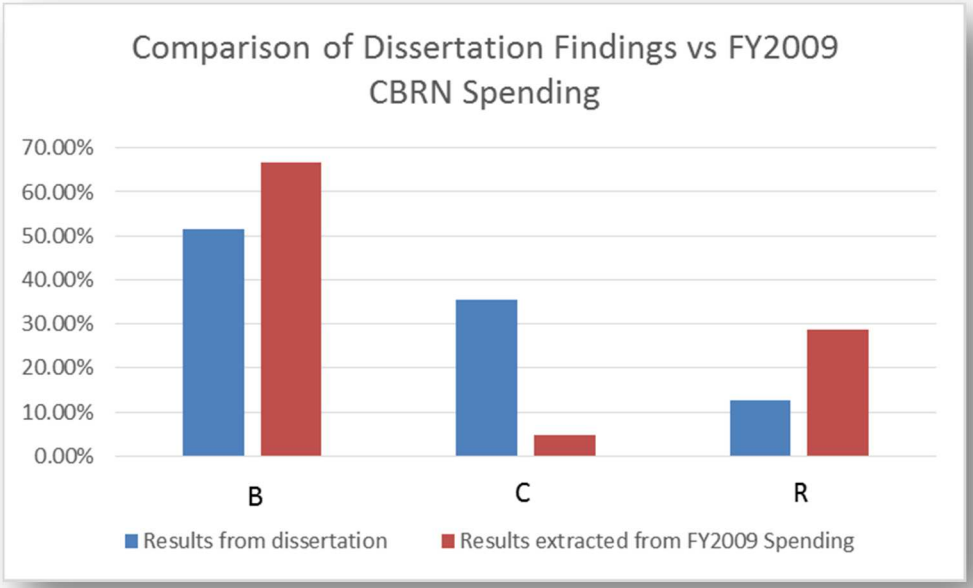

Figure 23: Comparison of dissertation findings vs FY2009 CBR spending.

It is noted that in FY2009, US had spent 14% out of the total CBR contract expenditure (66.67% out of the total R&D spending) on R&D for biological defence, compared to 1% (4.76% out of the total R&D spending) for chemical and 6% (28.57% out of the total R&D spending) for radiological and nuclear (R&N). This has implied the acknowledgement of heavy investment required for B over C and R defence capabilities. The disparity in the C and R research expenditure with the dissertation findings (as seen in Figure 23) could possibly be accounted by the addition of nuclear research investment in the overall R&N spending, where enormous efforts are often placed in countering nuclear threats due to the high consequential effects of a nuclear attack.

In another report, US Government Accountability Office (GAO) conducted a review [207] in 2008 to assess the limitations of CBRN detection equipment for first responder use. The report started with the aim of addressing concerns in all aspects of C, B, R and N detection deficiencies, but concluded with the results that C and B detection systems are highly ineffective in supporting the roles of the first responders. A short section was dedicated to the deficiency of radiological and nuclear detection system in the detection of dispersed releases

in the atmosphere. This is consistent with the dissertation findings, where capability in radiological systems is ranked to require the most improvement in terms of early warning capabilities (Refer to Figure 19).

In another finding, the GAO also reported that their findings from the National Institute of Justice (NIST) [208] that it takes generally 3 to 5 years for a C and B detector standard to achieve full consensus, while it only takes 12 to 18 months for the same process in R detector standards to achieve similar recognition. This is postulated to the matured knowledge inherited in radiation technology and relatively well established protocols to the responses for incidents of such nature.

Lastly, the GAO summarised a report to the National Security on the nuclear and radiological capabilities for emergency responses [209]. The technology of the physical radiological detection systems were not mentioned within the investigation findings, instead the outcome of the capability investigated focused on the underutilisation of aerial background radiation survey systems. GAO suggested the allocation of funds to the equipping of more integrated logistic supports for more radiation surveys to be performed, without mention of technology research focus. This resonates with the dissertation, where radiological capabilities are perceived to be established and well defined for many applications, including the defence industry [210].

9.4.6.2 Validation of results with focus group discussions

Two focus group discussions were also held in Cranfield Shrivenham Campus. The participants covered the main group of first responders, CBR combatants, scientists, procurers and researchers from the CBR field. The main issue discussed during the first meeting revolved around the participants' perception of the current C, B and R detection capabilities specific to the four frames mentioned throughout the dissertation. This was complemented in the second meeting with the introduction of the SMARTS framework and the derivation of the results based on the Author's perception of the characteristic performance of the KPC relating to each domain capability. The discussions provided real life insights to detection capability deficiencies and welcomed feedbacks to the validation of the results.

The outputs are scattered over this dissertation, but the supporting points to the results validation are summarised below.

1. Radiological capabilities are perceived as a well-balanced capability. This resides well among the results from the methodology. Most of the participants agreed that relative to the C and B capabilities, the R capability received few fine-tunings in terms of the specified KPCs in the respective frames.

2. Chemical and biological capabilities must be improved. There were mixed responses to identifying the capability that require the most improvements. The debate on this arises from the diversified background of the participants. The chemists believed that chemical detection capabilities are insufficient to tackle the highly probable attacks compared to biological agents. The biologists, on the other hand, focused on the magnitude of deviation away from ideal capability performances in every aspect of a biological scenario. However, the armed forces and first responders generally have a common consensus that they face a larger challenge in ensuring the success of a biological incident compared to a chemical incident, and they generally faced little issues with radiological incidents compared to the former two.

9.5 Discussions

9.5.1 Reliance of the Study on a Single Decision Maker

Utilising the author's perception towards C, B and R detection capabilities as the basis of this work made it possible to examine the complex relationship between each of these domain capabilities in the timeframe for this project. The author's perceptions were to some extent supported by both subject matter experts and volunteers with knowledge in the field of CBRN. However, the strength of the conclusion from these studies is limited mainly to the accuracy of the author's judgement of the input and parameters of the framework, and such a method has often been scrutinised for its solidarity view and the extent of generalisability to other decision makers' viewpoint. Regardless of how objective and specific an individual believes he conduct the research, it remains to be subjected to

interpretation of influence by personal background, experiences and biases. However, while the results may be questionable to some, the framework is built in a modular manner to accommodate perceptions from a larger pool of decision makers to derive a more comprehensive and robust output. In anticipation of a robust comparison, the output of the comparison is validated with numerous literatures and reports, as well as consensus from focus group discussions. The framework is also subjected to intensive sensitivity analysis to pick up conflicting perceptions from the author's perception. Amidst the checks in place, this method is still contentious to objectivists whom require facts and figures to substantiate the claim. To mitigate the subjectivity of personal influences, future research would thus benefit more from the use of a larger sample of participants from different aspects of the industry, for instance, the government agencies, operators, researchers and the industry manufacturers.

9.5.2 Selection of the Representative Agents

In Chapter 6, one agent from each of the C, B and R domain is selected as a representation in studying the performance of the CBR detection capabilities with respect to specific KPCs. On a wider scheme, such a representation may undermine the full potential of the comparison methodology, failing to capture other aspects of the system that is not exposed when compared to the non-selected agent. For instance, the dominant chemical early warning capability (FTIR) functions well with chemicals that responds only to the selected bandwidth. Although the selected agent (Sarin) is detectable, there are other common agents such as Chlorine and Phosgene, which cannot be detected. Similarly, flame photometry cannot be used in identifying toxic industrial chemicals without phosphorous or sulphate groups. On the other hand, the selection of radiological agent results in the use of a gamma source in the comparison, which limits the comparison to only one type of radiation detector.

Next, the selections in this report are based on a method that works adequately to predict agents that are likely to be utilised by the perpetrators. This method, similar to the SMARTS, required the careful decomposition of criteria that reflects the thought process of the perpetrators. However, no one can accurately predict

their next move, as the psychology of terrorism is marked more by theory and opinion than good science [211]. As such, the prediction and evaluation based on the criteria selection are seldom 100% accurate. Criteria relating to intent, shift of motivation, psychology, capability and vulnerability are explicitly left out in a deliberate attempt to simplify the model. Full research on risk and threat warrants a separate study and thus does not fall within the scope of this dissertation.

9.5.3 Limitations due to Assumptions

In order to perform comparison based on swing method, several assumptions are made to establish the current and target performance of the CBR detection systems. These assumptions are direct contributors to potential sources of error, which may affect the decision makers' judgement.

Some conditions stipulated in an attempt to derive the target value (Chapter 7) for the detection criteria are posed to challenge the limits of the detection systems. For instance, in a CBR personnel security screening frame, the minimum sensitivity required of any detection system is based on the notion that the perpetrator is smuggling a minimum quantity of agents sufficient to only harm a small group of people. In most situations, the detection criteria could be more relaxed if the intent of the perpetrator is to target a larger pool of people. In yet another example, the sensitivity of the early warning capability may not be required to be challenged to the limit as the scenario is stipulated as such that the source concentration is higher, or the source is released nearer to the target. Such assumptions tend to err on the side of caution, but by doing so, may inevitably increase the deviation from the target performances of the detection system, affecting the decision maker's judgement in the swings.

Next, in deriving the target performance (Chapter 7), complex theories are deliberately substituted with simpler logic or worst-case scenarios. An obvious example is the stipulation of sensitivity requirement for detection systems under the initial response capability. The target is set to STEL for chemical and biological environment, and background values for radiological environment. These values are realistic, yet demanding. They are several magnitudes lower than the potential release concentration to anticipate the dilution effect as a result

of atmospheric conditions. Such a simplistic approach, however, yields considerable limitations in terms of accuracy and validation, but it provides the answer in the quickest manner. To derive the most precise answer, usage of complex physical theory is required. In the former example, the aerosol must be modelled statistically to understand its behaviour under specific temporal and spatial fluctuations of wind velocity, temperature, moisture content and many other weather conditions. In addition, the size distribution, density, viscosity, collision efficiency, geometrical shape and other physical traits are required to understand the molecular diffusion rate in the atmosphere. Lastly, the resuspension rate may also affect the overall concentration at the time of response, as particles that have settled may rise again due to wind and wake of any moving person beyond 0.2m/s [212]. There are other instances where more attention to scientific theories and calculation could improve the accuracy of the derived values, such as determining the required sensitivity in early warning and definitive identification frames. The compromise of detail to enable speed allowed more effort to be allocated other areas of the study, increasing the overall breadth of the research. However, the overarching framework was created in a transparent and robust manner, so that new input data or new concept that is of value can replace components in the current framework as they become available.

9.5.4 KPCs Used in the Comparison of C, B and R Detection Capabilities

The comparisons are performed with the assumption that the KPCs selected as a common performance indicator are representative and adequate. The rationale of selecting these KPCs is elaborated in Section 5.4, where the number of KPCs is minimised to mitigate comparison bandwidth. However, it has been contested that there are several more KPCs that are worth exploring to generate a more robust comparison. One of these KPCs is the training requirement of the systems in all four frames. First responders and CBR militants in the discussions have pointed out that their main ergonomic barrier with the detection systems are the sophistication of the equipment and their user-friendliness, affecting their ability to efficiently utilise the equipment. Another KPC capable of influencing the results

is the total life cycle cost of the equipment, where cost influences the unit procurement, hence spatial distribution, and practical response times.

The potential of more KPC inclusions to improve the results are acknowledged, but each inclusion must be weighed against the impact in the overall analysis to maintain the integrity of the comparison.

9.6 Recommendations

9.6.1 Further Studies

Section 9.5 revealed several limitations of the study, many arising due to the time constraints within an MSc timeframe. In order to maximise the potential of this research, it is recommended to allocate the relevant expertise to focus efforts in fine-tuning the research in the areas identified with limitations.

In addition, to achieve more insights based on the methodology proposed, further research is recommended to incorporate multifaceted inputs from relevant subject matter experts. For example, scientists can compare the detection systems from a scientific and technological angle, and the end users can provide feedback on the ergonomics comparison of the various detection systems. Industrial manufacturers can then contribute by discussing the difficulties in miniaturising the technologies into field-able capabilities, while the government intelligence can compare the urgency of improving the current systems from a political angle.

The research is only targeted at understanding the detection limitation, which is a small subset of the entire CBR defence framework. In order to fully appreciate the different segments of CBR defence architecture, further studies on protection, medical countermeasures and decontamination should be performed, leveraging on the same methodology protocol in the studies.

9.6.2 Interim solutions to capability gaps

The analysis in Section 9.4 leads to the understanding of the current capability limitations. While the CBR community acknowledges these limitations and is actively developing solutions through technological researches, capability gaps are still evident in many sections. Leveraging on the results from this analysis, it is possible to identify weak spots that must be addressed in the interim period, while the community continues in search for the required breakthroughs. The interim solutions should be implemented to improve the capability without the need to invest more effect than the current technological research.

9.6.2.1 Raman technology for security screening

At security screening points, the need for high throughput and a non-intrusive identification has pushed the limits of many chemical and biological agent detection technologies, rendering most of them unsuitable for such usages. The need to improve these capabilities is evident and urgent. Many European airports [213] utilises Raman spectroscopy at border security, but such capabilities are rarely seen in other border controls and security screening areas. One of the plausible explanations is for the overwhelming concern for conventional and homemade explosive security requirements in air transport, coupled with the stigma of CB detection being slow and intrusive, such that they are relegated to only the secondary line of defence. Such thoughts and actions generate vulnerability to CB agents and knowledgeable perpetrators. Mending this loophole in security against C and B defence may not require leaps and bounds of technology innovations, but deploying the right equipment to do the right job.

Ramen spectroscopy has been studied extensively and used as a laboratory tool for analytical chemistry for many years, reaching a level of maturity that transit from laboratory use to several field applications. The in-depth discussion of the theory behind Raman spectroscopy is beyond the scope of this dissertation. Raman Spectroscopy targets the molecules of chemical agents and amino acids that make up proteins of biological agents, and do so without physical contact with the sample, preserving sample integrity and poising it as a suitable candidate for many homeland security applications [214].

Relating to Figure 19, the C and B detection capabilities in the security screening frame requires improvement in terms of selectivity (DR = 1.0 for B, DR = 0.8 for C), sensitivity (DR = 0.7 for B, Dr = 0.42 for C) and response time (DR = 0.4 for C and B). The introduction of Raman technology into personnel security screening capability will reduce the desire for improvement with the enhancement of the detection capability.

Raman technologies fit in airport security like it does in most other personnel security processes. It is fast and versatile, and does not interfere with the current screening procedures. It has the potential to detect trace amount of chemical and biological agents without contact. At the entry border of a major event, Raman spectroscopy either as a point detector or a man-portable table equipment could be deployed alongside conventional X-ray equipment, where liquid and powders can be surrendered separately to undergo screening processes. A typical scan takes seconds and the entire automated analysis process can be achieved in under a minute, comparable to the X-ray analysis time.

The disadvantages and potential blind spot of Raman Spectrometry to security screening will not be covered in this dissertation. For a start, it will bring about immediate improvement in terms of sensitivity, selectivity and response time to the chemical and biological detection capability, without the need for hefty research investment. A mere off the shelf purchase or resource re-deployment would yield significant shift in the improvement desires throughout the comparison of the overall CBR detection capabilities.

9.6.2.2 Improving sampling efficiency for biological detection

One of the obstacles to an effective biological detection capability at an initial response to a suspected biohazard is the current sensitivity limitation (DR = 1.0, referenced from Table 78). There are two direct methods of overcoming this obstacle. The most obvious method is the continual indulgence in research on newer and better state-of-the-art technology to lower the detection limit. However, the return of investments in terms of sensitivity improvements have been marginal compared to the amount of emphasis placed. As seen in the analyses, the current

sensitivity (DR = 1.0) remains inadequate for individual protection, especially in the biological domain.

The second avenue to venture is the improvement in sampling efficiently. The improvement in bio sampling does not directly improve the sensitivity of the detection capability, but presents a potential larger concentration of analyte to the detector, which reduces the need for sensitivity improvement.

The current approved [215] sampling method involves surface sampling by form-based swabs. The residual powder on hard surfaces are wiped down with swabs (or wipes) of moisture with buffered solutions such as potassium phosphate and presented to detectors. This method of agent recovery does not currently provide statistical confidence to the responder. A study [216] has revealed that the recovery yield for common swab based sampling is 24 to 32% for non-lab incidents, a figure that is not favourable for response to biohazards.

A more efficient method deployed in point detection sampling technique is to direct large volumes of air through a HEPA filter to disperse the agent particles into small volumes of buffer solutions to form a concentrated mixture. This method is limited by the efficiency of the pump, low doses of agents and electrical power constraints of hand-held samplers in the field.

From a different perspective, the overall desire to improve the sensitivity of the biological detection capability could be reduced by improving the efficiency of the sampling method.

The shift of research effort into sampling technology may result in a more cost-effect solution for the overall detection capabilities at a fast time, and the result is the potential overall reduction in improvement desire in terms of sensitivity. By deriving a better sampler, the current detection systems that cannot detect the biological agents in low doses have a better chance to detect them in the higher concentrated mixture.

An interim solution is to deploy higher powered HEPA samplers with greater pump efficiency to collect the analyte in a shorter amount of time. Although this

shifts the strain towards the logistical and electrical burden, it greatly reduces the need for a more efficient sensor.

On the other hand, a more easily deployable solution is to implement a longer sampling time, which shifts the burden towards the overall response time of the biological incident. While such a procedure will result in a longer response time for biological detection capability (DR for response time may potentially increase), the commander must be able to weigh his game and derive at a compromise between sensitivity and response time, but theoretically, the latter is deemed less important as biological agents have delayed effects and thus are more forgiving towards a ‘slower’ response.

9.7 Chapter Conclusion

It is implied from the results in Section 9.4 that biological detection capability is the weakest link in the overall CBR detection architecture, especially selectivity in the personnel security screening frame and sensitivity in the initial response frame. However, referenced to Figure 19 and Figure 20, there are other areas of the chemical and radiological detection capabilities that should be improved to attain an overall enhancement to the defence capability. For instance, the selectivity of the chemical detection capability in security screening is limited due to the lack of deployment of a functional solution. These enhancements, however, do not need to be derived from technological breakthroughs, but simple and implementable procedural adjustments to reduce the desirability of improvements. The framework could also benefit in its depth through future involvements of subject matter experts from the CBR field.

The methodology proposed pinpoints the capability gaps in the CBR detection architecture. The researcher and designer could leverage on the outputs of the framework to work towards enhancing the detection architecture, but trade-off analysis must be performed. For instance, it is generally understood that an improved sensitivity often results in a longer response time of the detector. Before

any enhancement is proposed, the capability should be re-evaluated against the framework to ensure that other attributes are not compromised.

10 CONCLUSION

10.1 Chapter Introduction

The study was set up to explore the comparison of the current C, B and R detection capabilities. While it is not common for such inter-comparison to be performed, it brings about new insights to the understanding of our current limitations.

To achieve the aims, the study sought to complete the following tasks:

1. Derivation of methodology to provide a platform for successful comparison

2. Leveraging on discussed framework to perform preliminary analysis

10.2 Comparison Methodology

Several decision analysis tools were evaluated in search of a robust model for such multifaceted comparison.

The AHP method was assessed suitable for the selection of a representative C, B and R agent for the comparison. While AHP comprises tedious pairwise comparisons of criteria to arrive at a conclusion, these comparisons were heavily supported by the vast availability of literature on the inherent properties of the various agents, enhancing the ability of the decision maker in performing informed comparisons. The AHP analysis revealed that the agents that are most likely to be used in a CBR attack are Sarin (C), *Bacillus Anthracis* (B), and Cobalt-60 (R). These agents were selected as the representative agents for the capability comparison.

SMARTS was chosen for the capability comparison due on its simplicity in capturing the author's judgement into quantitative outputs for an objective comparison. A realistic scenario non prejudicial to C, B or R was created and decomposed into four distinct frames – early warning frame, personnel security

screening frame, initial response frame and definitive identification frame. The four frames are created to represent the chronological progression of detection mechanism across the timeline of the scenario, where all four frames contributed to the success of the overall detection architecture. The C, B and R capabilities were then analysed with respect to the KPCs most applicable to the frames. The SMARTS framework constructed applied both published CBR detection capabilities and the author's judgement of the target requirement to derive the relative ranking of the C, B and R capabilities.

However, the sensitivity analysis (Section 9.3) revealed that the original framework set out lacked the ability to sufficiently capture the required information processed in the decision maker's mind. The comparison of detection capabilities is multi-dimensional, and under each node or criteria, there are different considerations in a chemical, biological or radiological environment. A single framework was thus assessed to be inadequate in accommodating such a multi-dimensional problem.

Such a shortcoming was overcome by the introduction of several similarly structured frameworks that drew the focus to other aspects that was not apparent from the original framework. These frameworks together formed a pyramid of iterations that greatly enhanced the credibility of the results with cognitively less demanding strategies.

10.3 Comparison Analysis

The extreme toxicity of biological agents and the ease of acquisition (amongst many other concerns) made biological agents favourable for small scale attacks by non-state organisation. Coupled with the lack of distinctive detection features, biological detection systems have been concurred by many literatures to be the 'weakest link' of all CBR detection systems. The findings of this dissertation resonated with these literatures, indicating that in general, biological detection system ranked the highest for need to be improved to ideal conditions (Table 79). Such a finding echoed the huge disparity between the current performance and

ideal conditions, especially in point detection technologies. Firstly, bio-threats are prevalent and harmful, compared to chemical and radiological counterparts, and this leads to the need (DR = 1.0, from Table 78) for the highest sensitivity for the biological detection system. The presence of numerous background interferences echoed the need for a selective detection system with lowest false alarms. Coupled with the fact that naturally, biomolecules possess few properties that are distinguishable by handheld detection systems, it is a challenge for current technology to progress by quantum leaps to reach its ideal conditions. The large disparity between current and ideal target performances was postulated to be the reason behind its weak link.

This dissertation complemented the real-world findings by analysing the problem into different frames within the detection architecture. In this manner, the different layers of detection was examined between domains, and the study revealed that biological detection system may require more urgent attention on specific portions of detect-to-warn and detect-to-treat scenarios. For the detect-to-warn phase, personnel security screening for illicit CB material should be improved from the current capability that is almost non-existent. It was also proposed to improve the point detection technologies under the initial response phase for a more sensitive and faster preliminary identification of attacks. The early warning capabilities against biological and chemical threats were perceived effective compared to radiological early warning capability. There is currently no fielded true radiation standoff detection system that can detect particulate radiation at distance long enough for full contamination avoidance purposes, as most radiation detection technology can only sense the radiation upon ‘contact’. The radiological standoff detection technology for early warning capability is definitely one area that is severely lacking for an encompassing protection against radiological attack.

10.4 Recommendations on Further Research

This study presented like-minded researchers with a leveraged starting step in attempt to quantify detection capabilities from a multi-faceted level. Due to time

constraint, it was not as extensive as intended, and thus further exploration in the research strategies would aid in crystallising the ultimate goal of CBR detection capability comparison. The overarching aim of fine-tuning the CBR defence framework could also be achieved by similar methodology, with the inclusion of much higher level of operational, situational, technological and political thinking.

10.5 Summary

To sum up, this dissertation provided an encompassing method for comparing chemical, biological and radiological detection capability, and presented a preliminary result based on the author's judgement. The imperative to improve biological detection in all aspects featured strongly within the findings, while radiological detection did not. To develop a well-rounded CBR sensing capability for a major event, it was recommended for emphasis to be placed on radiological detection in early warning capability, chemical and biological detection in personnel screening capability and lastly, chemical and biological detection in initial response capability.

The ability to perform such inter-comparison based on the modular and transparent methodology also brought about a new world of possibility in deeper research regarding the wider CBR operations.

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Appendix A DETAILS OF COMPARISON RESULTS AFTER ITERATION APPROACH IS ADOPTED

A.1 Chapter Summary

As summarised in Section 9.3, the introduction of self-checks enhance the accuracy of decision making. In this dissertation, three different frameworks are proposed, allowing the decision maker different avenues to crystallise the perceptions from different facets. The iteration approach then provides a platform for reconciliation of the outputs as an additional means of sanity check.

A.2 Derivation of three frameworks

The first framework is modelled in Figure A- 1. The first (lowest) tier focuses on the comparison of C, B and R detection capabilities in terms of the respective KPCs in each frame. The second tier of comparison defines the importance of each KPC to the success of the respective frame, while the third (highest) tier discusses the importance of each frame to the overall success of the detection architecture.

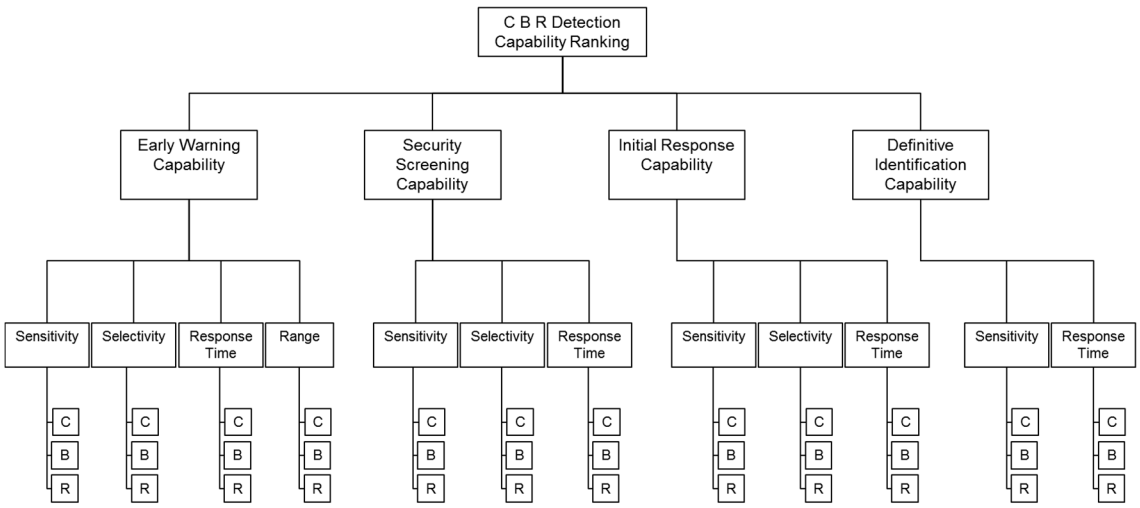


Figure A- 1: Hierarchy for Framework 1.

The second framework is modelled in Figure A- 2. The first (lowest) tier focuses on the importance of each KPC to each domain detection capability. The second tier compares the relative importance of each domain in the respective frames. The last (highest) tier discusses the importance of each frame to the overall success of the detection architecture.

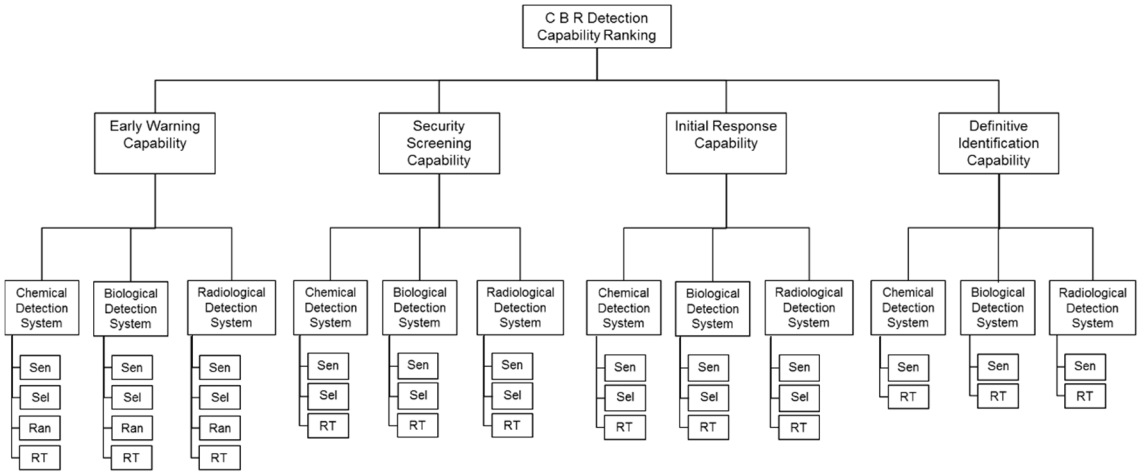


Figure A- 2: Hierarchy for Framework 2.

The third framework is modelled in Figure A- 3. The first (lowest) tier focuses on the performance of each domain detection capabilities in terms of the individual KPCs. The second tier compares the relative importance of each KPC within each domain. The last (highest) tier discusses the importance of each domain to the overall success of the detection architecture.

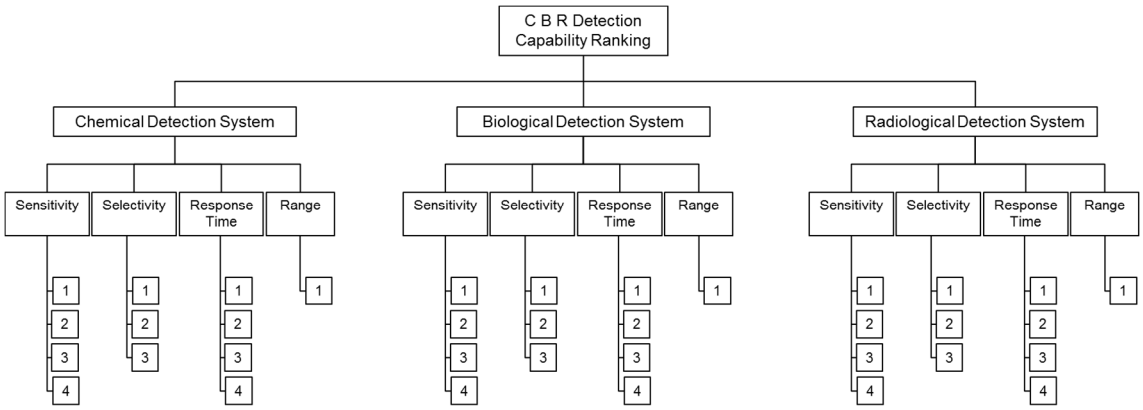


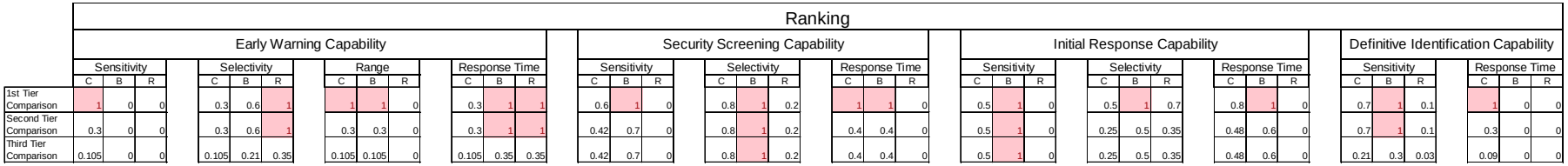
Figure A- 3: Hierarchy for Framework 3.

A.3 Output of iteration

A sanity check based on the iterative approach is adopted. Once the first round of iteration is completed, the finalised individual weightage of each criterion is reconciled with the corresponding weightages in the other two frameworks. The process of iteration continues until the results converge to an acceptable value. Table A-1 to A-3 shows the output from the three frameworks after the final iteration. In each table, the normalised output from the three tiers of comparisons is shown.

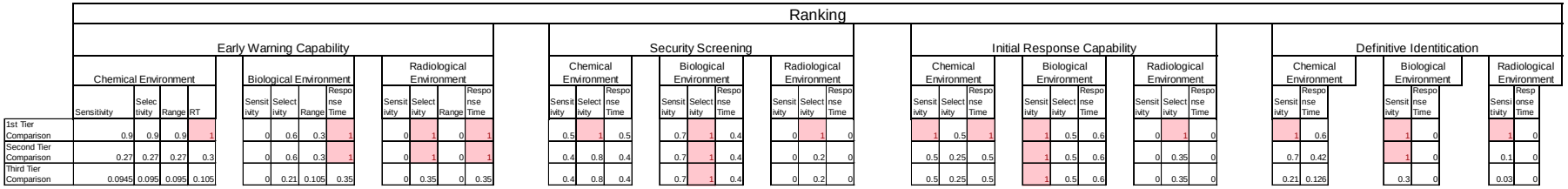
The scores after the final iteration are presented in Table A-4. As a benchmark, the original output of Framework 1 is placed in comparison.

Table A- 1: Output from Framework 1 after iteration.



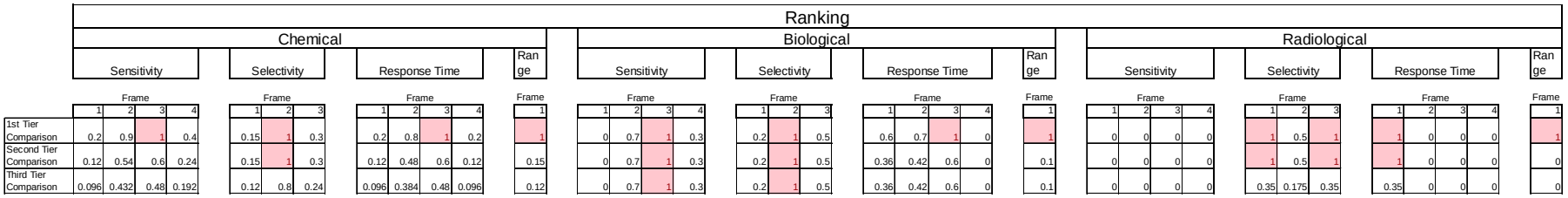
	Ranking																																			
	Early Warning Capability												Security Screening Capability									Initial Response Capability									Definitive Identification Capability					
	Sensitivity			Selectivity			Range			Response Time			Sensitivity			Selectivity			Response Time			Sensitivity			Selectivity			Response Time			Sensitivity			Response Time		
	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R	C	B	R
1st Tier Comparison	1	0	0	0.3	0.6	1	1	1	0	0.3	1	1	0.6	1	0	0.8	1	0.2	1	1	0	0.5	1	0	0.5	1	0.7	0.8	1	0	0.7	1	0.1	1	0	0
Second Tier Comparison	0.3	0	0	0.3	0.6	1	0.3	0.3	0	0.3	1	1	0.42	0.7	0	0.8	1	0.2	0.4	0.4	0	0.5	1	0	0.25	0.5	0.35	0.48	0.6	0	0.7	1	0.1	0.3	0	0
Third Tier Comparison	0.105	0	0	0.105	0.21	0.35	0.105	0.105	0	0.105	0.35	0.35	0.42	0.7	0	0.8	1	0.2	0.4	0.4	0	0.5	1	0	0.25	0.5	0.35	0.48	0.6	0	0.21	0.3	0.03	0.09	0	0

Table A- 2: Output from Framework 2 after iteration.



	Ranking																																			
	Early Warning Capability												Security Screening									Initial Response Capability									Definitive Identification					
	Chemical Environment					Biological Environment				Radiological Environment			Chemical Environment			Biological Environment			Radiological Environment			Chemical Environment			Biological Environment			Radiological Environment			Chemical Environment			Biological Environment			Radiological Environment	
	Sensitivity	Selectivity	Range	RT		Sensitivity	Selectivity	Range	Response Time	Sensitivity	Selectivity	Range	Response Time	Sensitivity	Selectivity	Response Time	Sensitivity	Selectivity	Response Time	Sensitivity	Selectivity	Response Time	Sensitivity	Selectivity	Response Time	Sensitivity	Selectivity	Response Time	Sensitivity	Selectivity	Response Time	Sensitivity	Response Time		Sensitivity	Response Time		Sensitivity	Response Time
1st Tier Comparison	0.9	0.9	0.9	1		0	0.6	0.3	1	0	1	0	1	0.5	1	0.5	0.7	1	0.4	0	1	0	1	0.5	1	0	0.5	0.6	0	1	0	1	0.6		1	0		1	0
Second Tier Comparison	0.27	0.27	0.27	0.3		0	0.6	0.3	1	0	1	0	1	0.4	0.8	0.4	0.7	1	0.4	0	0.2	0	0.5	0.25	0.5	1	0.5	0.6	0	0.35	0	0.7	0.42		1	0		0.1	0
Third Tier Comparison	0.0945	0.095	0.095	0.105		0	0.21	0.105	0.35	0	0.35	0	0.35	0.4	0.8	0.4	0.7	1	0.4	0	0.2	0	0.5	0.25	0.5	1	0.5	0.6	0	0.35	0	0.21	0.126		0.3	0		0.03	0

Table A- 3: Output from Framework 3 after iteration.



	Ranking																																			
	Chemical												Biological												Radiological													
	Sensitivity				Selectivity				Response Time				Range	Sensitivity				Selectivity				Response Time				Range	Sensitivity				Selectivity				Response Time				Range
	Frame				Frame				Frame				Frame	Frame				Frame				Frame				Frame	Frame				Frame				Frame				Frame
	1	2	3	4	1	2	3		1	2	3	4	1	1	2	3	4	1	2	3		1	2	3	4	1	1	2	3	4	1	2	3		1	2	3	4	1
1st Tier Comparison	0.2	0.9	1	0.4	0.15	1	0.3		0.2	0.8	1	0.2	1	0	0.7	1	0.3	0.2	1	0.5		0.6	0.7	1	0	1	0	0	0	0	1	0.5	1		1	0	0	0	1
Second Tier Comparison	0.12	0.54	0.6	0.24	0.15	1	0.3		0.12	0.48	0.6	0.12	0.15	0	0.7	1	0.3	0.2	1	0.5		0.36	0.42	0.6	0	0.1	0	0	0	0	1	0.5	1		1	0	0	0	0
Third Tier Comparison	0.096	0.432	0.48	0.192	0.12	0.8	0.24		0.096	0.384	0.48	0.096	0.12	0	0.7	1	0.3	0.2	1	0.5		0.36	0.42	0.6	0	0.1	0	0	0	0	0.35	0.175	0.35		0.35	0	0	0	0

Table A- 4: Illustration of output comparison from the three frameworks. The original output of Framework 1 before iteration is presented on the left.

Framework 1				Framework 2		Framework 3	
Original		Final		Final		Final	
*Description	Score	*Description	Score	*Description	Score	*Description	Score
3-sen-b	1	2-sel-b	1	2-sel-b	1	3-sen-b	1
2-sel-b	0.8	3-sen-b	1	3-sen-b	1	2-sel-b	1
2-sel-c	0.64	2-sel-c	0.8	2-sel-c	0.8	2-sel-c	0.8
3-sel-b	0.6	2-sen-b	0.7	2-sen-b	0.7	2-sen-b	0.7
2-sen-b	0.56	3-rt-b	0.6	3-rt-b	0.6	3-rt-b	0.6
3-sen-c	0.5	3-sen-c	0.5	3-sen-c	0.5	3-sel-b	0.5
2-sen-c	0.45	3-sel-b	0.5	3-rt-c	0.5	3-sen-c	0.48
3-sel-r	0.42	3-rt-c	0.48	3-sel-b	0.5	3-rt-c	0.48
1-rt-b	0.4	2-sen-c	0.42	2-sen-c	0.4	2-sen-c	0.432
1-rt-r	0.4	2-rt-c	0.4	2-rt-c	0.4	2-rt-c	0.384
2-rt-c	0.32	2-rt-b	0.4	2-rt-b	0.4	2-rt-b	0.42
2-rt-b	0.32	1-sel-r	0.35	1-rt-b	0.35	1-sel-r	0.35
3-sel-c	0.3	1-rt-b	0.35	1-sel-r	0.35	3-sel-r	0.35
3-rt-c	0.3	1-rt-r	0.35	1-rt-r	0.35	1-rt-r	0.35
3-rt-b	0.3	3-sel-r	0.35	3-sel-r	0.35	4-sen-b	0.3
4-sen-b	0.3	4-sen-b	0.3	4-sen-b	0.3	1-rt-b	0.36
4-rt-c	0.3	3-sel-c	0.25	3-sel-c	0.25	3-sel-c	0.24
1-sel-r	0.28	1-sel-b	0.21	1-sel-b	0.21	1-sel-b	0.2
1-sel-b	0.2	4-sen-c	0.21	4-sen-c	0.21	4-sen-c	0.192
4-sen-c	0.2	2-sel-r	0.2	2-sel-r	0.2	2-sel-r	0.175
1-sen-c	0.12	1-sen-c	0.105	4-rt-c	0.126	1-sel-c	0.12
1-rt-c	0.12	1-sel-c	0.105	1-rt-c	0.105	1-ran-c	0.12
1-sel-c	0.08	1-ran-c	0.105	1-ran-b	0.105	1-ran-b	0.1
4-rt-b	0.06	1-ran-b	0.105	1-sen-c	0.0945	1-sen-c	0.096
1-sen-b	0	1-rt-c	0.105	1-sel-c	0.0945	1-rt-c	0.096
1-sen-r	0	4-rt-c	0.09	1-ran-c	0.0945	4-rt-c	0.096
1-ran-c	0	4-sen-r	0.03	4-sen-r	0.03	1-sen-b	0
1-ran-b	0	1-ran-r	0	1-ran-r	0	1-ran-r	0
1-ran-r	0	1-sen-b	0	1-sen-b	0	1-sen-r	0
2-rt-r	0	1-sen-r	0	1-sen-r	0	2-rt-r	0
2-sel-r	0	2-rt-r	0	2-rt-r	0	2-sen-r	0
2-sen-r	0	2-sen-r	0	2-sen-r	0	3-rt-r	0
3-rt-r	0	3-rt-r	0	3-rt-r	0	3-sen-r	0
3-sen-r	0	3-sen-r	0	3-sen-r	0	4-rt-b	0
4-rt-r	0	4-rt-b	0	4-rt-b	0	4-rt-r	0
4-sen-r	0	4-rt-r	0	4-rt-r	0	4-sen-r	0

*Description is written as frame-KPC-domain.