NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(SAS-060)TP/252

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RTO TECHNICAL REPORT **TR-SAS-060**

Non-Lethal Weapons Effectiveness Assessment Development and Verification Study

(Etude d'évaluation, de développement et de vérification de l'efficacité des armes non létales)

Final Report of Task Group SAS-060.

Published October 2009

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RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Non-Lethal Weapons Effectiveness Assessment Development and Verification Study

(RTO-TR-SAS-060)

Executive Summary

During the 1999 Washington summit, the North Atlantic Council (NAC) identified Non-Lethal Weapons (NLW) as a "critical, additional capability needed in order to meet the demands of future operations." Recent and ongoing operations have confirmed this need. Lessons from peace support and anti-/counter-terrorism operations have highlighted the need to accomplish tasks while minimizing undesired or collateral effects, which is key to the very nature and definition of non-lethal weapons[1]:

> *Non-Lethal Weapons are weapons which are explicitly designed and developed to incapacitate or repel personnel, with a low probability of fatality or permanent injury, or to disable equipment, with minimal undesired damage or impact on the environment.*

Although the need for NLW has been formally recognized, NATO and its member nations still must determine which capabilities to develop and field and how best to employ them. Understanding NLW effectiveness is vital to supporting such decisions. SAS-060's purpose was to develop a common, agreed approach for assessing effectiveness. In line with the study's specific objectives, SAS-060 formed three working groups that:

- Collected and applied NLW data to test the system effectiveness methodology developed by SAS-060's predecessor study (SAS-035);
- Extended the methodology to account for aggregation of results, at a point in time and over multiple scenario phases, and variability/uncertainty; and
- Enhanced NLW awareness and integrated with other NATO efforts.

Conclusions – SAS-060 partly verified the system effectiveness methodology (with some issues remaining but confidence they can be resolved), extended the methodology (with multiple aggregation methods identified and implemented) to include assessments across phases of a scenario, and increased NLW awareness.

Recommendations – The new NATO NLW Roadmap calls for a SAS-060 Follow-On Study. SAS-060 discussed the merits of the recommendation. Continued work on the effectiveness methodology was not viewed as the best course – as the work has already progressed beyond the availability of data to support verification/validation. SAS-060's two highest priority topics for study are:

- Capabilities Assessment – Addressing NATO operational requirements, gaps between capabilities and requirements, and wargaming/cost-benefit analyses of candidate solutions to gaps; and
- Experimentation – Developing NATO-common protocols for NLW experiments, conducting experiments to generate data, and addressing data shortfalls identified in previous studies.

In October 2007, the Conference of National Armaments Directors (CNAD) approved a NLW Defence Against Terrorism (DAT) initiative, which may also require follow-on support.

[1] *NATO Policy for Non-Lethal Weapons*, 27 September 1999.

Etude d'évaluation, de développement et de vérification de l'efficacité des armes non létales

(RTO-TR-SAS-060)

Synthèse

Lors du Sommet de Washington de 1999, le Conseil de l'Atlantique Nord (NAC) a identifié les armes non létales (NLW) comme « une capacité critique supplémentaire indispensable pour satisfaire aux exigences des futures opérations ». Les opérations récentes ou en cours ont confirmé ce besoin. Les leçons tirées des opérations anti-terroristes et de soutien de la paix ont fait apparaître clairement la nécessité d'accomplir les missions tout en limitant les effets non désirés ou collatéraux, ce qui est indissociable de la définition et de la nature même des armes non létales[2] :

> *Les armes non létales sont des armes discriminantes qui sont explicitement mises au point et principalement utilisées pour frapper d'incapacité le personnel et le matériel, avec un minimum de risque mortel, de lésions permanentes au personnel et de dommages indésirables aux biens et à l'environnement.*

Bien que la nécessité des NLW ait été officiellement reconnue, l'OTAN et ses nations membres doivent encore déterminer quelles capacités développer et employer sur le terrain et comment les utiliser de manière optimale. La compréhension de l'efficacité des NLW est cruciale lors de telles décisions. Le but du SAS-060 était donc de développer une approche commune et convergente d'évaluation de cette efficacité. Conformément aux objectifs spécifiques de l'étude, le SAS-060 a constitué trois groupes de travail, qui :

- Ont recueilli et appliqué les données relatives aux NLW en vue de tester la méthodologie d'efficacité du système développée lors de l'étude du SAS-035, prédécesseur du SAS-060 ;
- Ont étendu la méthodologie afin qu'elle intègre l'agrégation des résultats, à un moment précis dans le temps et lors de multiples phases de scenarios, ainsi que la variabilité et l'incertitude ; et
- Ont renforcé la sensibilisation aux NLW et l'ont ajouté aux autres efforts de l'OTAN.

Conclusions – Le SAS-060 a partiellement vérifié la méthodologie d'efficacité du système (certains problèmes demeurent, mais il existe un bon espoir de les résoudre), étendu cette méthodologie (par l'identification et la mise en œuvre de plusieurs méthodes d'agrégation) pour inclure des évaluations lors des différentes phases d'un scenario, et amélioré la sensibilisation aux NLW.

Recommandations – La nouvelle feuille de route de l'OTAN relative aux NLW prévoit une étude de suivi du SAS-060. Le SAS-060 a examiné le bien-fondé de cette recommandation. Un travail continu sur la méthodologie d'efficacité n'est pas considéré comme étant la meilleure option – dans la mesure où les travaux ont déjà progressé au-delà de la disponibilité de données venant à l'appui de la vérification et de la validation. Les deux sujets d'étude prioritaires du SAS-060 sont :

- L'évaluation des capacités – Déterminer les exigences opérationnelles de l'OTAN, les écarts existants entre les capacités et les exigences, et réaliser des jeux de stratégie et des analyses de rendement des solutions envisagées pour combler ces écarts ; et

[2] *Politique de l'OTAN sur les armes non létales*, 27 septembre 1999.

- Expérimentation – Développer des protocoles communs à l'OTAN pour les expériences relatives aux NLW, réaliser des expériences en vue de générer des données, et tenter de combler le manque de données identifié dans les études précédentes.

En octobre 2007, la Conférence des Directeurs Nationaux de l'Armement (CDNA) a approuvé une initiative de défense contre le terrorisme (DAT) par NLW, qui pourrait également nécessiter soutien et suivi.

Chapter 1 – INTRODUCTION

1.1 STUDY CONTEXT

The challenges presently confronting NATO are very different from those that prevailed throughout the Cold War. As demonstrated in ongoing peace support and anti-terrorism/counter-terrorism operations, NATO is facing new types of threats, undertaking new kinds of missions, performing a broad range of military tasks within difficult operating environments, and conducting these tasks subject to a variety of policy and operational constraints. Lessons learned during these operations have highlighted the need for non-lethal weapons (NLW). The need to accomplish tasks while minimizing undesired or collateral effects speaks to the very nature and definition of non-lethal weapons[1]:

> *Non-Lethal Weapons are weapons which are explicitly designed and developed to incapacitate or repel personnel, with a low probability of fatality or permanent injury, or to disable equipment, with minimal undesired damage or impact on the environment.*

Table 1-1 summarizes several challenges identified in recent and ongoing operations and associated implications (and opportunities) for NLW.

Table 1-1: Lessons Learned and the Need for NLW

Challenge	Implication/Opportunity for NLW
Minimize undesired casualties: – When uncertain if a target is hostile. – When others (non-combatants or friendly forces) are near a target. – When the desired target effect/ response is temporary (i.e., not desired dead or destroyed).	Offer ***reversible*** means to act that will: – Help discern intent (also allowing for earlier use of lethal force upon determining hostile intent). – Dissuade, delay, or defeat the target. – Isolate threats from human shields.
Minimize undesired collateral effects: – On infrastructure and facilities (especially if civilian/dual-use or of symbolic importance). – Which have an environmental impact.	Provide ***limited duration*** effects that: – Deny adversary's use or access while preserving for later use. – Minimise re-construction needs.
Act when lethal force may not be allowed or may be counter-productive: – Policy, treaty/legal, or operational constraints. – Potential 2nd and 3rd order effects.	Tailor ***effects*** (type and magnitude) to: – Accomplish task requirements. – Satisfy constraints. – Avoid undesired consequences (negative perceptions or reactions).

NATO has clearly recognized the potential offered by non-lethal weapons. During the 1999 Washington Summit, the North Atlantic Council identified NLW as a "critical, additional capability needed in order to meet the demands of future operations" and established NLW as a Defence Capabilities Initiative item (Item EE 2(i)). Since then, NLW needs have been reinforced in peace support operations (as highlighted in

[1] *NATO Policy for Non-Lethal Weapons*, 27 September 1999.

conclusions from SAS-041/SAS-048) and in anti-terrorism/counter-terrorism efforts (as discussed in MC472). In order to meet these needs, NATO has conducted a variety of activities. Past work includes development and approval of a NATO NLW Policy, development of an initial NATO NLW Roadmap, multiple studies conducted under the auspices of the Research and Technology Organisation[2], standardization efforts by a Team of Experts within a NATO Army Armaments Group (NAAG) Land Group, an Advanced Research Workshop, a NLW Exhibition sponsored by the Conference of National Armaments Directors (CNAD), and a NAAG Quick Reaction Team (QRT) which has just developed a new NATO NLW Roadmap.

Although the need for NLW has been formally recognized and supporting activities begun, NATO and its member nations still must determine which non-lethal capabilities to develop and field and how best to employ them. Understanding NLW effectiveness is vital to supporting such decisions and to ensuring that commanders and troops in the field will be comfortable employing these capabilities.

1.2 SAS-060'S PURPOSE

SAS-060's predecessor study (SAS-035) developed a proposed framework for measuring NLW system effectiveness[3], and the SAS Panel chartered SAS-060 to verify and extend the SAS-035 methodology, with the following objectives, as identified in the study's Terms of Reference (included as Annex A):

1) Verify the Measures of System Effectiveness (MoSE) Methodology:
   - Identify necessary data types and experiments or experimental guidelines for generating them.
   - Make explicit the process for describing required responses.
   - Verify the methodology, with realistic data for actual system(s) in an operational context, and provide worked example(s).

2) Extend the MoSE Methodology:
   - Address potential uses and associated methods of aggregation.
   - Address confidence levels, including an examination of potential sources of variation and how variations propagate through the methodology's calculations.

3) Explore development of Measures of Operational Effectiveness (MoOEs):
   - Assess the feasibility of extending the methodology to account for operational effectiveness (i.e., the simultaneous and/or sequential use of one or more systems – non-lethal and/or lethal – to achieve a desired outcome).
   - Develop and explore concepts for assessing operational effectiveness.

4) Enhance awareness of NLW work and integrate with other NATO efforts:
   - Engage with organisations identified in the NATO NLW Roadmap.
   - Conduct briefings for Allied Command-Operations and Allied Command-Transformation and others as appropriate and develop and conduct a seminar/workshop if warranted.

[2] Studies include SAS-035 (NLW Effectiveness Assessment, the predecessor of SAS-060), SAS-040 (Long Term Scientific Study), and HFM-073 (Human Effects).

[3] Non-Lethal Weapons Effectiveness Assessment (SAS-035 RTO-TR-085), published October 2004.

1.3 STUDY TEAM

SAS-060 included participants from 12 nations (eleven alliance members and one partner nation):

- Belgium
- Canada
- Denmark
- France
- Germany
- Italy
- Netherlands
- Norway
- Spain
- Sweden
- United Kingdom
- United States

In addition SAS-060 conducted significant information exchange with Allied Command Transformation (ACT), including holding a SAS-060 Study Team meeting at ACT, which included an exchange of briefings and information materials.

A listing of individual SAS-060 participants is provided in Annex B.

1.4 WORKING GROUPS

The SAS-060 Study Team met twice per year to oversee and integrate study efforts.

The Study Team formed three working groups to carry out the detailed work of the study. Each working group met as needed to carry out assigned responsibilities. The Task 1 working group was responsible for objective 1 from the Terms of Reference, the Task 2 working group for objectives 2 and 3, and the Task 3 working group for objective 4, with an overview of work packages as follows:

- Task 1 – ***Methodology Verification and Refinement***, which focused on testing and refining the SAS-035 system effectiveness methodology with data from a variety of NLW technologies (vehicle arrestor nets, optical disrupters, high-power microwaves, kinetic devices, and flash-bangs).
- Task 2 – ***Aggregating Results for System and Operational Effectiveness***, which examined a range of scenarios and addressed aggregation of results at a point in time (system effectiveness) or across phases of a scenario (operational effectiveness).
- Task 3 – ***Enhancing Awareness and Coordinating with Other NATO NLW Efforts***, which developed presentation materials (including for the SAS-060 display at the CNAD NLW Exhibition), conducted liaison with other NATO efforts such as ACT and the NAAG Quick Reaction Team, and developed a NLW Workshop for NATO Defence College.

1.5 REPORT ORGANISATION

The main body of the report includes an overview of the three tasks and results developed by their respective working groups, followed by conclusions and recommendations:

- **Chapter 2** describes the efforts of the Task 1 working group, presenting the approach and results for testing and refining the NLW system effectiveness methodology.
- **Chapter 3** describes the efforts of the Task 2 working group regarding aggregation of results and implications for system and operational effectiveness.
- **Chapter 4** describes the efforts of the Task 3 working group to enhance NLW awareness and coordinate with other NATO efforts.
- **Chapter 5** presents conclusions and recommendations, including SAS-060's proposed response to the NAAG QRT recommendation for a SAS-060 Follow-On Study.

A series of annexes provide additional detail.

Chapter 2 – METHODOLOGY VERIFICATION AND REFINEMENT

2.1 INTRODUCTION

In 2004, NATO's Research and Technology Organisation published the final report of SAS-035[1]. This report proposed an effectiveness methodology, starting with physical weapon characteristics and calculating in turn Measures of Performance (MoP), Measures of [target] Response (MoR), Measures of System Effectiveness (MoSE), and finally Measures of Operational Effectiveness (MoOE).

2.1.1 Objectives

The aim of Task 1, as stated in the SAS-060 Terms of Reference[2], was to verify the Measures of System Effectiveness (MoSE) methodology:

- Identifying necessary data types and experiments or experimental guidelines for generating them;
- Making explicit the process for generating required responses; and
- Verifying the methodology, with realistic data for actual system(s) in an operational context, and providing worked examples.

2.1.2 Work Packages

The Task 1 working group investigated the following NLW technologies and specific weapon systems:

1) **Vehicle Arrestor Nets**

   A vehicle arrestor net, placed on the roadway, will bring a vehicle to a halt rapidly but without injury to occupants. Vehicle arrestor nets are in use by several armed forces, and they have been deployed operationally. Extensive trials data is available, in terms of stopping distances against a wide range of vehicle types under varied environmental conditions, and some data is available on performance in operational use.

2) **Optical Disrupter**

   An optical disrupter shines a light beam or flash into the eye, at an intensity which will cause disorientation to the subject but with no risk of permanent damage to the eye. Based on a conceptual design, experimental data was postulated.

3) **High Power Microwave (HPM) Weapon**

   A HPM weapon uses a non-nuclear electromagnetic pulse (NNEMP) to cause temporary or permanent damage to electronic equipment. No weapon of this type is currently commercially available, but experimental data on potential effectiveness of such a weapon is available.

4) **Kinetic Energy Weapons**

   These are weapons which throw a projectile, such as a blini or baton round, the impact of which will temporarily incapacitate a person without causing permanent damage. Experimental performance, range, accuracy and impact data was available for several kinetic energy weapons.

[1] NATO RTO Technical Report TR-085, AC/323(SAS-035)TP/44 dated October 2004.

[2] See the Terms of Reference and Technical Activity Proposal Activity Ref RTG-020 dated August 2004.

5) **Flash-Bangs**

Flash-bangs are pyrotechnic devices, typically in the form of grenades, which produce a loud bang and brilliant flash; they incapacitate people within some radius of the burst point, without permanent damage to sight or hearing. Experiments have shown the effect of flash-bangs on the ability of subjects to carry out simple tasks (such as aiming weapons).

Table 2-1 presents a summary of NLW systems and types of data available.

Table 2-1: Summary of NLW Assessments

Technology	Data Status
Vehicle Arrestor	Extensive experimental data on stopping distances (MoR) Some operational data
Optical Disrupter	Physical characteristics (PWC) and some experimental data (MoP)
High-Power Microwave	Experimental results on performance and effect on electronic hardware (MoP/MoR)
Kinetic Energy Weapons	Experimental results on performance (MoP)
Flash-Bangs	Results of experiments on human subjects (MoP/MoR)

2.2 APPROACH

The approach involved working through the steps of the SAS-035 methodology and evaluating MoSEs for a range of NLW across military tasks drawn from a common scenario. A detailed description of the SAS-035 methodology is given in Section 3 of the SAS-035 Final Report. Figure 2-1 provides an overview.

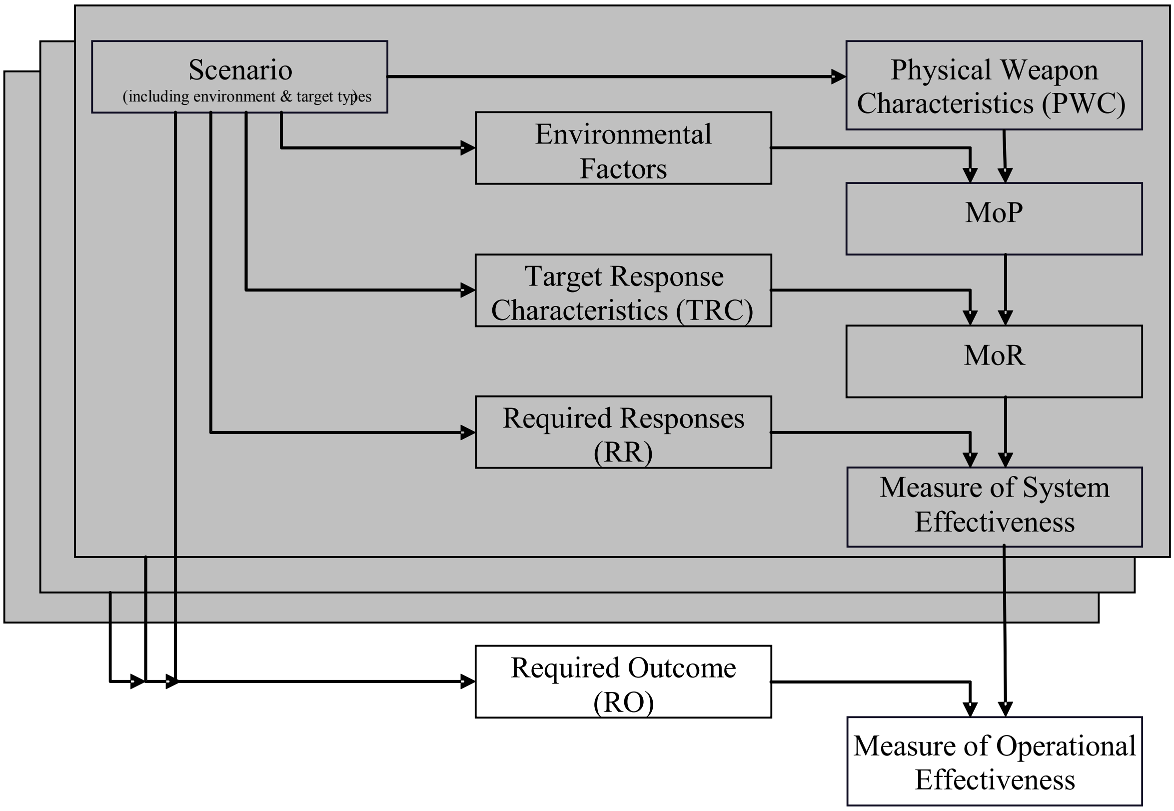


Figure 2-1: The SAS-035 Methodology.

The methodology consists of the following steps:

1) A scenario is defined in terms of an operational situation and military tasks.

2) Physical weapon characteristics (PWCs) – such as weight, calibre, muzzle velocity, and power requirements of the weapon(s) – are determined.

3) Measures of Performance are derived from PWCs and environmental factors, with typical MoPs including:
   - Terminal momentum of a baton round;
   - Optical intensity of a flash-bang;
   - Area coverage of a net; and
   - Field strength of a directed energy weapon.

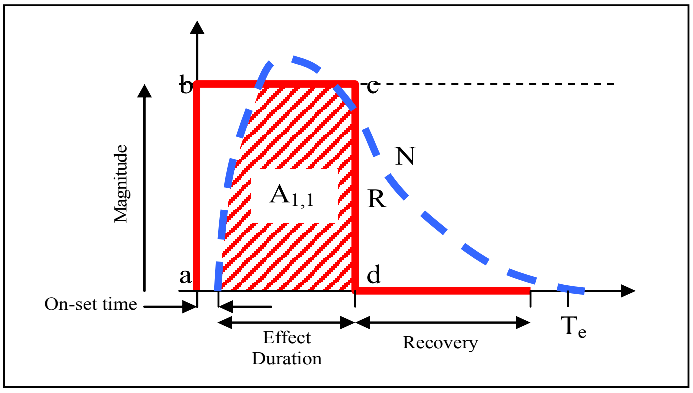
4) Required Responses (RRs) specify three time profiles:
   - Task accomplishment (effects on intended targets);
   - Target constraint satisfaction (effect reversibility and target recovery); and
   - Collateral constraint satisfaction (reversibility/recovery for own forces, non-combatants, infrastructure, etc.).

   RRs are expressed in terms of seven Basis Response (BR) variables: Mobility, Communication, Physical Function, Sense and Interpret, Group Cohesion, Motivation, and Identification.

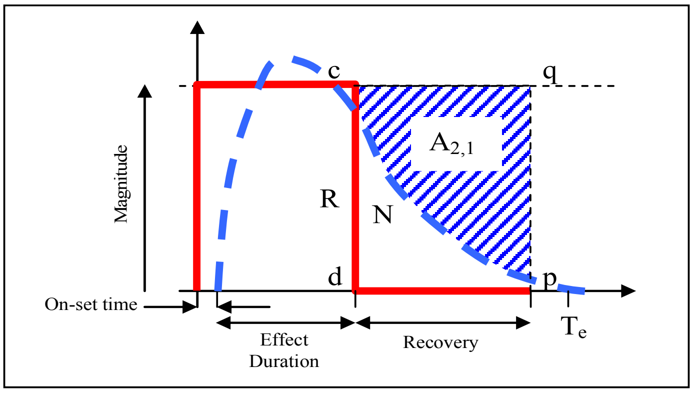
5) MoPs, together with Target Response Characteristics, are then used to estimate the actual target response. These Measures of Response (MoRs) are time profiles of the same Basis Response as used for the RRs.

6) RR vs. MoR time profiles are graphically compared to calculate the degree to which the measured response meets the required response in terms of:

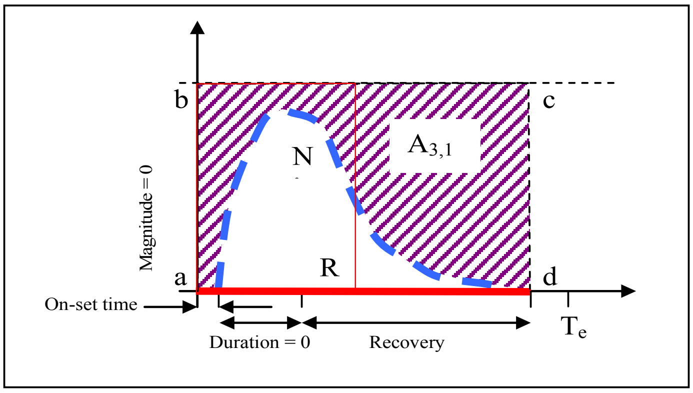
- Task accomplishment (designated P_1)



- Target constraint satisfaction (designated P_2)



- Collateral constraint satisfaction (designated P_3)



These comparisons are made for each of the 7 Basis Response variables, to give 21 Measures of System Effectiveness (MoSE) elements; more details on the comparison process are given in Annex C.

7) The MoSE are then fed into a model of the scenario, and compared to a measure of Required Outcome to arrive at a Measure of Operational Effectiveness. However, this step in the process is outside the scope of Task 1.

The aim of Task 1, therefore, was to verify the practicability of carrying out Steps 1) through 6) for real weapon systems.

2.3 SCENARIO

The scenario used for the Task 1 verification exercise involved protection of a Brigade and Battalion HQ, depicted in Figure 2-2, in a UN Peace Enforcement operation. The overall mission required restoring law and order in the area of responsibility and providing general area security. The specific military objective was to maintain security of the camp and freedom of movement of own troops.

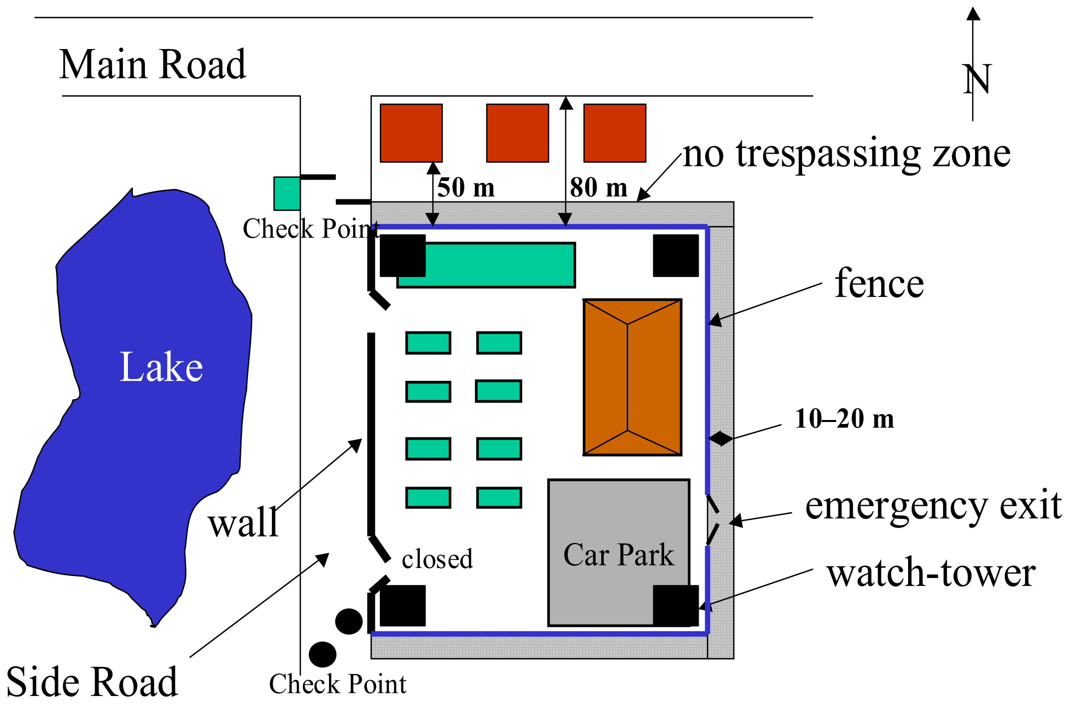


Figure 2-2: Scenario Layout.

Two possible threats to the HQ were considered:

- A low intensity threat involving a local population wanting to break into the camp to steal material and food supplies; and
- A higher intensity threat (considered only for the HPM Weapon), with the scenario extended to include organised warring factions equipped with mortars, grenades, and automatic weapons, with a command post 1 km from the camp.

The scenario was divided into four phases corresponding to the progress of an attack on the HQ compound, with military tasks identified for each phase. The MoSEs, for each of the weapon systems considered in Task 1, were then evaluated in the context of the military tasks associated with defeating these possible threats.

A more detailed description of the scenario is given in Annex C.

2.4 VEHICLE STOPPER EXAMPLE

This example made use of data available on an already fielded device that can rapidly be deployed to arrest a suspect vehicle in a controlled, non-lethal manner. In applying the methodology, the Task 1 assessment included the following assumptions:

NLW Characteristics and Employment Considerations

- Sufficient resources are available at all times to deploy the vehicle stopper on the inside of the northern checkpoint covering the whole width of the road.
- Three seconds have been allowed for the time from the decision to stop the vehicle to the completion of system deployment.

Target (Approaching Vehicle) Characteristics

- The vehicle is not able to swerve around the vehicle stopper, and vehicles aim to have a similar speed on both sides of the checkpoint.
- In this analysis, non-intended targets are our vehicles.
- In line with trials data, the driver will keep his foot on the accelerator, even after the system has engaged the front tyres, until the vehicle is stopped.

Weapon-Target Interactions

- The system will not stop a vehicle travelling above 110 kph (70 mph).
- Due to the puncturing of target vehicles' tyres, ten minutes has been allowed for the vehicle to start moving again, and it is assumed those vehicles are only capable of reaching half their initial speed after being cut free (the 70 mph vehicle remains at the same speed, as this vehicle stopper does not affect it).
- Knock on effects of deploying the vehicle stopper have not been examined.
- Sample trials data has been used, and it is assumed the speeds assessed within the trials data are achievable in the scenario.
- Two minutes has been allowed to detain the occupants of the stopped target vehicle.

2.4.1 Scenario Factors

Given the scenario, the vehicle stopper will be deployed in the following military tasks:

- **Phase 2 – Task 1**: Stop or divert unauthorised personnel and vehicles from reaching the perimeter fence and main entrance.
- **Phase 2 – Task 7**: Stop unauthorised vehicles from reaching the camp main entrance and apprehend occupants.
- **Phase 4 – Task 8**: Prevent enemy from escaping.

Due to the similarity of the above tasks, the rest of this assessment focuses on the first task, with the results assumed to be applicable to the other tasks.

The mode of deployment is:

- The Military Commander sees an approaching target vehicle and gives the signal to deploy the vehicle stopper (which takes 3 seconds for operators to deploy).

- The system engages the vehicle which should ideally come to a standstill 50 metres away from the cut off team standing ready to apprehend occupants.

2.4.2 Basis Response (BR) Variables

The basis response variables to which the vehicle stopper contributes are:

- **Mobility**: The system arrests vehicles, bringing them to a controlled stop. In trials it has successfully stopped Front Wheel Drive (FWD), Rear Wheel Drive (RWD), Four Wheel Drive (4WD) and vehicles equipped with run-flat tyres. The target response will be measured by reduction in speed over time.
- **Physical Function:** The impact on Physical Function is due to the NLW's ability to ensure vehicles work at reduced efficiency – for example, the system could immobilise a vehicle, allowing the arrest of the driver or passenger.

The vehicle stopper is not regarded as having any effect on the other Basis Response variables.

2.4.3 Required Response and MoR

It is assumed that the Military Commander wants the vehicle to come to a standstill as close to his cut off team (50 metres away) as possible. The RR curve is as shown in Figure 2-3.

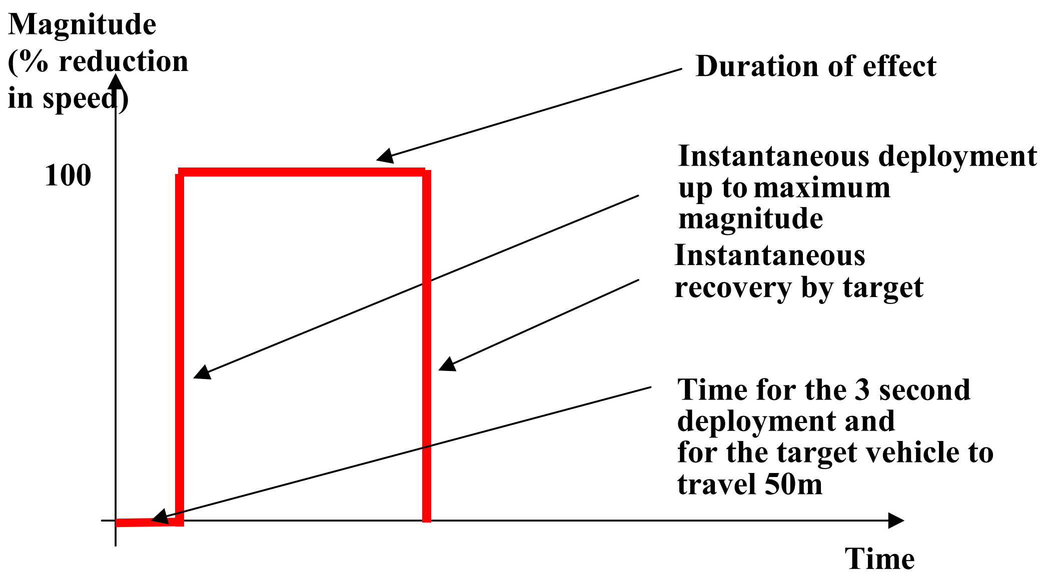


Figure 2-3: Required Response (RR) Curve.

To examine the flexibility of the methodology, three cases were assessed:

1) A vehicle at 30 mph (13.41 m/s);
2) A vehicle at 49 mph (21.90 m/s); and
3) A vehicle at 70 mph (31.29 m/s), which is not slowed at all by this vehicle stopper.

The MoR curves for these cases, derived from trials data are shown in Figure 2-4 – Figure 2-6, which also show the RR curve for comparison.

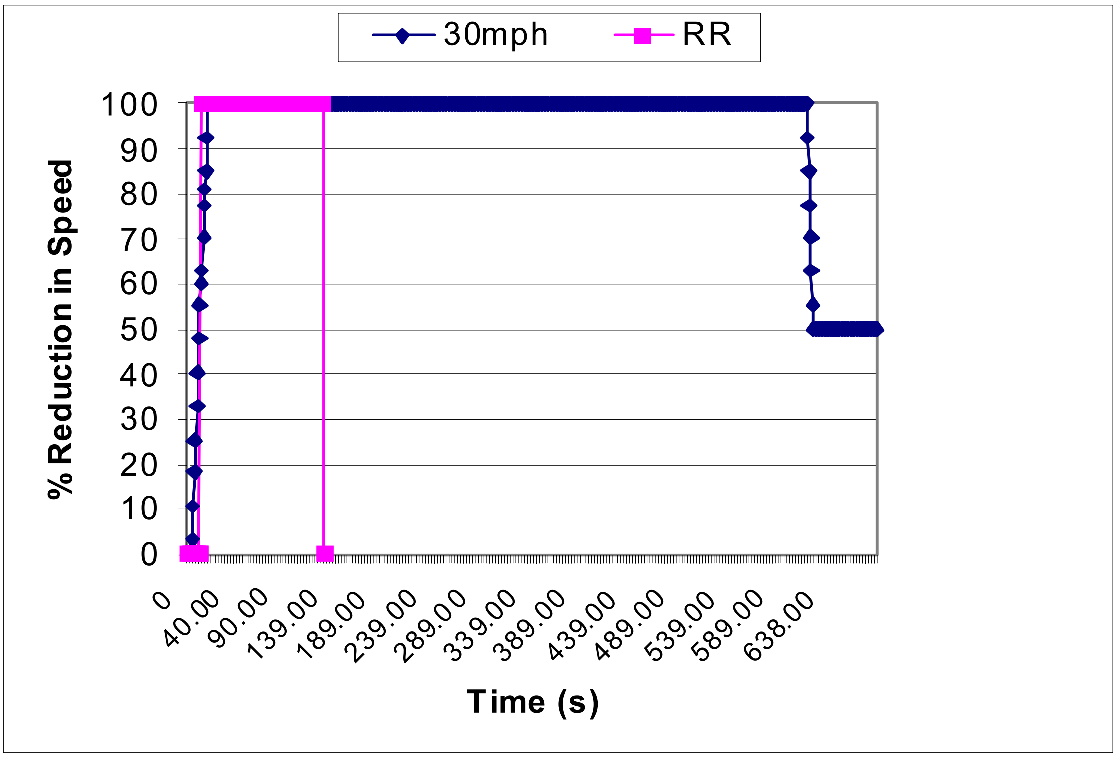


Figure 2-4: MoR for 30 mph Case.

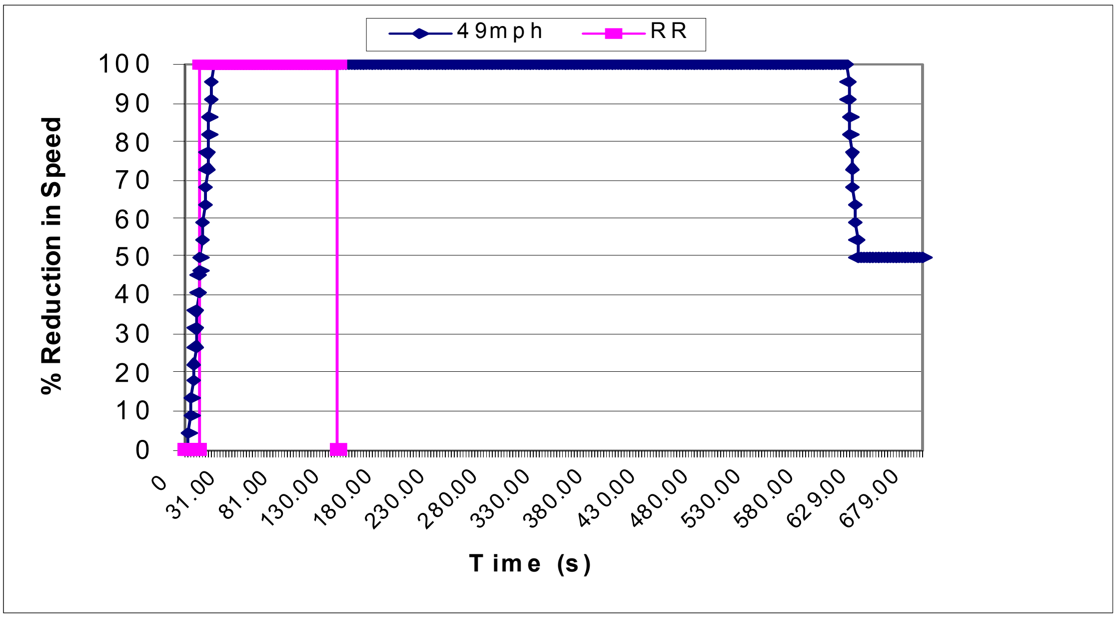


Figure 2-5: MoR for 49 mph Case.

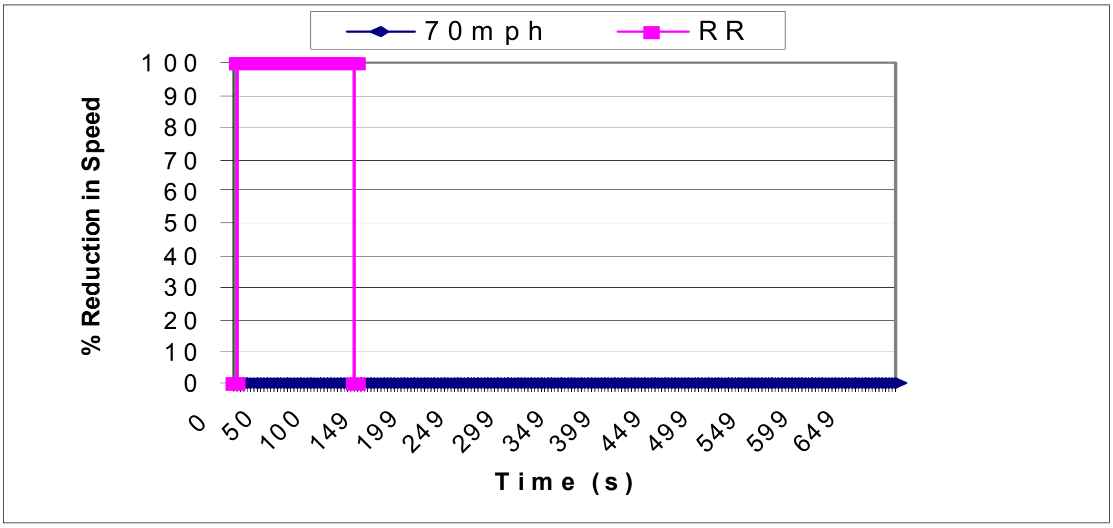


Figure 2-6: MoR for 70 mph Case.

2.4.4 Measures of System Effectiveness (MoSE)

Based on these results, and using the method described in Annex C, values for P_1, P_2 and P_3 were derived for the two Basis Responses – Mobility and Physical Function; because the same quantity was used to measure both Responses the results are the same. The results are shown in Table 2-2; the values for P_3 are based on the assumption that no non-target vehicles would be affected by the vehicle stopper in this scenario.

Table 2-2: MoSE Results

Case	P_1	P_2	P_3
30 mph	0.9959	Tends to 0.5	1
49 mph	0.9748	Tends to 0.5	1
70 mph	0	1	1

2.4.5 Sensitivity Analyses

The following sensitivity cases were examined:

- A required response with a constant rate of deceleration.
- Varying the distance between the vehicle stopper and the cut off team with a required response that is based on:
  - An instantaneous reduction in speed to zero.
  - A constant rate of deceleration.

P_1 values were calculated for the above for both the 30 mph and 49 mph cases. Table 2-3 compares the results for the constant deceleration case with the base case.

Table 2-3: Comparison of MoSEs for Alternative Required Responses

Case	Instantaneous P_1	Constant Deceleration P_1
30 mph	0.9959	0.9899
49 mph	0.9748	0.9677

P_1's variation with stopping distance for the two cases is shown in Figure 2-7 and Figure 2-8. Figure 2-7 shows results for varying distances between vehicle stopper deployment and the cut-off team, based on the required response for the vehicle stopping instantaneously. Figure 2-8 shows similar results for constant deceleration.

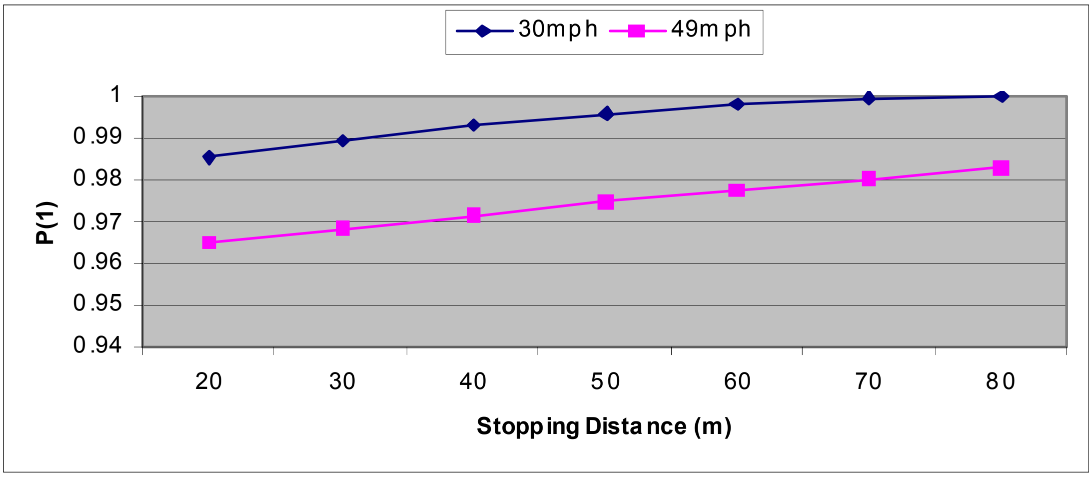


Figure 2-7: P_1 Values (Instantaneous Stopping).

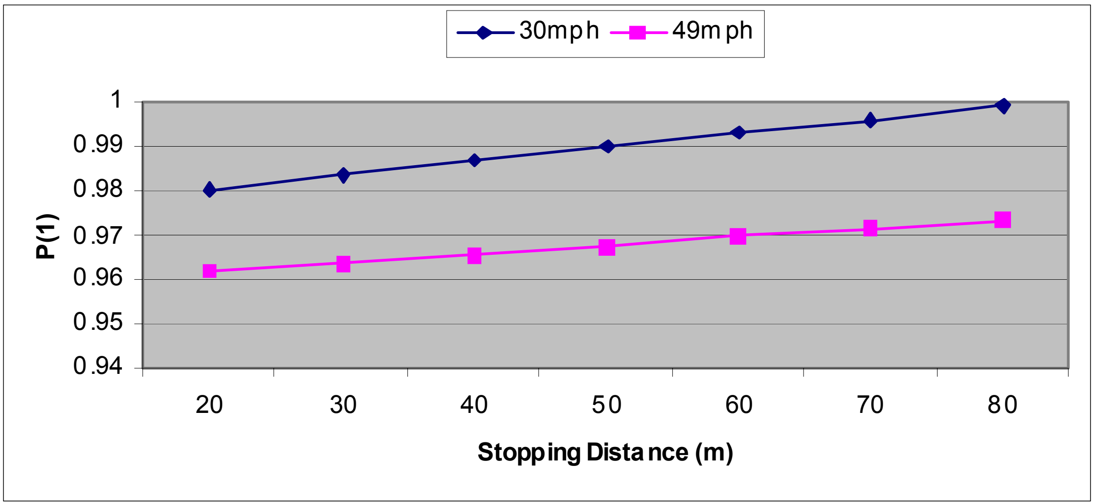


Figure 2-8: P_1 Values (Constant Deceleration).

2.4.6 Summary from Vehicle Stopper Assessment

The Task 1 working group concluded that:

- The proposed effectiveness methodology can be successfully applied (and defining a realistic Required Response is key to this success).
- The methodology has been proved to be sensitive to changes in inputs.

Issues identified in the course of this exercise were:

- Several assumptions were required to limit the scope of work so the methodology could be applied.
- Calculation of P_1 values is clear; P_2 and P_3 required some interpretation, and a cut-off time was used otherwise graph areas were unbounded. (This issue was also identified in the other NLW assessments, and proposed refinements to the methodology – revising the P_2 calculation and eliminating P_3 – are discussed later in this chapter.)
- Required Responses are based on Military stakeholder opinion, which might vary between individuals.
- Further issues might be identified when comparing multiple NLW options.

2.5 FLASH-BANG EXAMPLE

The military tasks (please see Annex B for more details) in which it was assumed that flash-bangs could be applied were:

Phase 2 – Task 2: Disperse personnel or vehicles in the No Trespass Zone

Phase 2 – Task 4: Disorientate personnel

Phase 3 – Task 2: Disperse personnel or vehicles in the No Trespass Zone or Side Road

Phase 3 – Task 4: Disorientate personnel

Phase 4 – Task 2: Incapacitate vehicles and individuals

The available data is not applicable to the tasks in which a group of people is dispersed by means of a flash-bang device. For the purpose of this investigation the decision was made to take Phase 2 – Task 4 and Phase 3 – Task 4 as starting points. The difference between the selected tasks is found in the associated constraints. During Phase 2 the actions against individuals must have no permanent effect, whereas Phase 3 permits for some permanent effect.

2.5.1 Weapon Performance

Two different flash-bang hand grenades (Type A and Type B) were taken as candidate systems. Physical Weapon Characteristics (PWC) are provided in Table 2-4 and Table 2-5. The data is obtained from measurements in the open field at ground level.

Table 2-4: PWC of Flash-Bang Hand Grenade Type A

Distance to source [m]	–	1.25	2.5	5.0	10.0
Peak light intensity [cd/sr]	$8 \cdot 10^5$				
Peak sound level [kPa]		35	12	5	3
Sound intensity level [dB(A)SEL]		143	136	129	122

Table 2-5: PWC of Flash-Bang Hand Grenade Type B

Distance to source [m]	–	1.25	2.5	5.0	10.0
Peak light intensity [cd/sr]	$2 \cdot 10^5$				
Peak sound level [kPa]		5	3	2	1
Sound intensity level [dB(A)SEL]		128	125	119	115

The delivery characteristics of flash-bang hand grenades are essentially no different from other types of hand grenades. The following values can be used for both types of flash-bangs to characterise the throwing performance:

- Radius of 50% deliveries from aimpoint, distance 15 m, horizontal target area: 1 m.
- Radius of 50% deliveries from aimpoint, distance 25 m, horizontal target area: 2 m.
- Maximum throwing distance: 30±5 m.

Scenario conditions are such that the difference between PWC and MoP are negligible.

2.5.2 Target Response

Permanent ocular damage and temporary blindness are deemed to be the most important physiological responses resulting from bright flashes of light. For 'normal', visible radiation and an exposure of 0.1 s it is possible to define threshold values for ocular damage and temporary flash blindness. The results are summarised in Table 2-6.

Table 2-6: Target Response Thresholds for Flashes of Light

Target Response	Value [cd/m^2]
Ocular damage (night-time, foveal perception)	$8.5 \cdot 10^7$
Ocular damage (daytime, foveal perception)	$2.5 \cdot 10^8$
Flash blindness for 5 s (night-time, foveal perception)	$3.1 \cdot 10^4$
Flash blindness for 5 s (daytime, foveal perception)	$4.7 \cdot 10^7$

Generally applied threshold values for impulse sounds to prevent hearing loss are 140 dB sound pressure level and 125 dB(A) sound energy level. Regarding the required effective intensity of a single impulse sound there are three basic types of responses, namely startle, escape and freeze behaviour. It is possible to produce relationships expressing the probability of each of these responses as function of the intensity of the stimulus. It is also possible to produce relationships expressing the duration of the responses as function of the intensity of the stimulus. These are the target response relationships, yielding MoR.

2.5.3 Weapon Effectiveness

Suppose the RR is stated as follows:

- The primary military intent for employing the flash-bang device is to degrade the target's ability to produce aimed fire.

- 100% probability for a 5 s degraded hostile performance.
- 2% probability of serious injury (i.e., loss of eyesight and/or hearing loss) in Phase 2.
- 20% probability of serious injury (i.e., loss of eyesight and/or hearing loss) in Phase 3.

The Basis Response that is affected by the flash-bang device, as far as the military intent is concerned, is Sense and Interpret. Other Basis Responses that can be directly affected are Motivation and Group Cohesion. However, the corresponding target response relationships are not available.

With the data provided thus far, it is possible to perform effectiveness simulations. The assessment of P_1 and P_2, according to the definition of SAS-035, is provided in Table 2-7. Regarding P_3, one may argue that, as a worse case, a non-combatant can be just as close to a detonating flash-bang hand grenade as the intended target. Hence, P_3 equals P_2.

Table 2-7: MOE Assessment of Flash-Bang Hand Grenades

Flash-Bang	P_1	P_2	P_3
Type A in Phase 2	0.95	0.62	0.62
Type A in Phase 3	0.95	0.62	0.62
Type B in Phase 2	0.90	0.99	0.99
Type B in Phase 3	0.90	0.99	0.99

2.5.4 Issues

From the P_2 assessment one can conclude that the flash-bang Type B is almost compliant with the military requirements (namely 99%). However, one can see that Type B is in fact *fully* compliant. P_2 over time is a constant within the relatively short engagement timeframe considered, and the probability of hearing damage is about 1 percent (1 – 0.99). Furthermore, the definition of P_2 does not result in a different value for both types of hand grenades. This constitutes a problem since it can be shown that Type A can intuitively be rated as 'becoming more compliant in Phase 3 as opposed to Phase 2'. These observations call for a review of the P_2 definition.

2.6 RESULTS FROM OTHER NLW ASSESSMENTS

The results from applying the methodology for the optical disrupter, HPM weapon, and kinetic energy weapons are included as Annex C.

2.7 IMPLICATIONS AND ISSUES

As noted previously, the Task 1 working group identified several issues associated with the P_2 and P_3 calculations. Figure 2-9 depicts the proposed revision to P_2 for the intended target (or, using the typical designator, Red). Instead of calculating the shaded area above the Measured Response curve A within the rectangle bounded by the points *cdpq*, P_2 is now calculated 1 minus the area beneath curve A bounded by the new rectangle cdpq, where c and q no longer are at the same magnitude as the required response but rather at the level of the measured target response at time T_1.

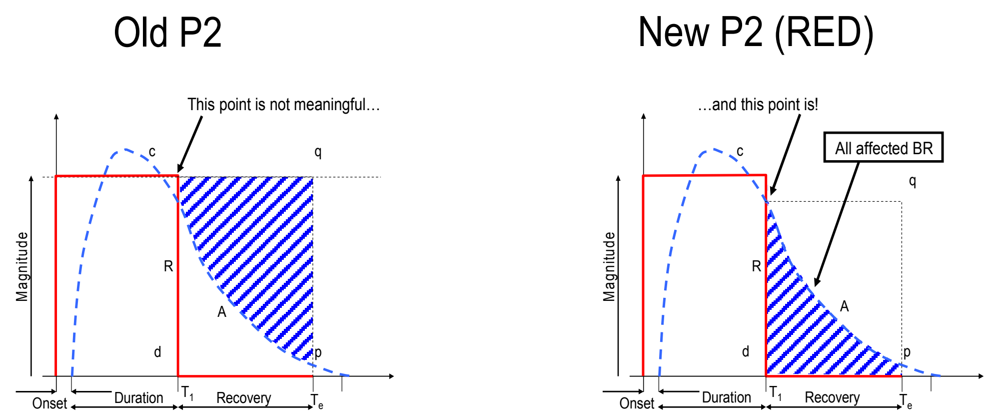


Figure 2-9: Old Approach for Calculating P_2 versus New Proposed Approach.

This change was deemed necessary because P_1 and P_2 are viewed as two distinctly different characteristics describing NLW effectiveness. The choice to define the shared area from $T = T_1$ onwards by a magnitude related to P_1 is simply not correct. While the new P_2 definition is viewed as an important improvement, there is also an issue with the new P_2 that needs to be addressed. In the new approach to P_2 the upper bound of the shared area is defined by the magnitude of the actual response. Since the actual response is in fact variable, this may complicate the process of comparing the performance of one NLW's P_2 to another.

Moreover, the working group proposed eliminating the P_3 collateral constraint, and replacing it with two calculations – one for own forces (Blue) and one for non-combatants (White) – as depicted in Figure 2-10. This measure would calculate the shaded area under the curve from the onset of the (undesired) response until an operationally relevant recovery time, T_e.

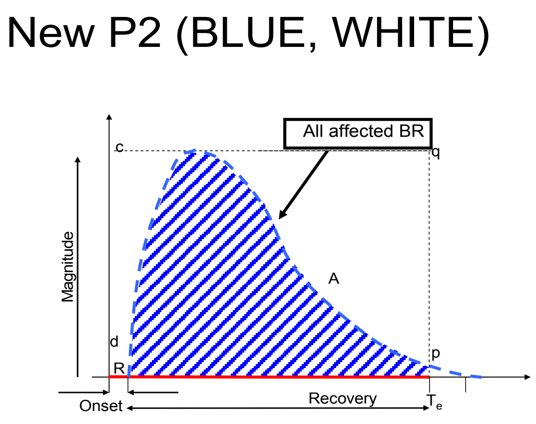


Figure 2-10: Replacement of P_3 with P_2 (Blue) and P_2 (White).

A number of issues about the use of the methodology either arose in the course of the verification exercise or had been previously identified and were not fully resolved by the exercise. These include the following:

1) **Lack of Orthogonality of the Basis Response Variables**. By this is meant the fact that there is a risk of overlap between different variables in terms of what they are measuring, leading to double-counting some of the benefits of a given weapon. This problem arose in the cases of the vehicle stopper – where the estimated effects on Mobility and Physical Function measure exactly the same thing – and the Optical Disrupter. It is recommended that this problem should be met through a combination of care in the formulation of Basis Response variables and accounting for any remaining non-orthogonality in the process of aggregating across BRs.

2) **Choice of Appropriate Basis Response**. A related issue is the difficulty in some cases of selecting the right Basis Response variable to measure the effect of a weapon. This arose in the case of the High Power Microwave weapon, where the effect could equally well be defined in terms of the Communication or Sense and Interpret responses, and arguably in terms of Physical Function as well. A more orthogonal and explicit definition of the Basis Responses is a partial solution.

3) **Provision of Required Response**. The RR specifies the Commander's requirement for the weapon, and should ideally come from military sources. All the RR used in this exercise came in fact from scientists, and the exercise has not fully verified that it is possible to carry out the methodology using RR from military sources. It was agreed in the course of the study that the RR needs to be specified in terms of physically meaningful and measurable variables conforming to the description of the methodology in the SAS-035 report, in terms of time profiles of effect on the Basis Responses. It was felt that, typically, commanders will state their desired effect on target behaviour, and the methodology should be able to translate this statement into a combination of Basis Response levels. Note that more than one combination of levels may achieve the desired effect. The demonstration of such a process has not been achieved in SAS-060.

4) **Coupled Effects**. The possibility was identified that, where more than one weapon was used in achieving the same task the effects might interact, with the result that the overall effect would be more than the sum of the individual effects. For example, in the use of a paintball and vehicle stopper sequentially to stop a car, a partly obscured front window leaves the driver with less opportunity to counter-act the next obstacle. The initial performance of the car-plus-driver is partly disrupted, and this reduced level of performance is the starting point for the next engagement (e.g., vehicle stopper deployment).

   This issue can be assigned to the MoOE part of the methodology. However, it is equally possible to think of two weapon effects acting simultaneously, during a 1-on-1 engagement, making it a MoSE issue.

5) **Derivation of MoR from MoP**. MoP were available for all the weapons examined in this exercise, but it is noticeable that the only ones for which complete MoR were available were those – vehicle stopper and HPM – whose effect is on equipment rather than people. Deriving MoRs for human subjects requires either a validated theory – which is not known to exist in most cases – or experiments – which raise ethical and practical problems. One possible exception is flash-bangs, where much experimental data is available. Because of ethical and experimental problems, in some cases, e.g., kinetic energy weapons, field data (post-use audits) may be the only means of assessing effectiveness. In general the exercise cannot be said to have shown that MoR data will usually be available.

6) **Issues Related to MoSE**. These issues include:

   - MoSE normalisation – in order to calculate the MoSE measures and normalise them to lie in [-1,1] the methodology requires specification of a total time period for the scenario, and upper limits to the effects achieved by the weapon. If the weapon effect does not return to zero in some reasonable time then (as demonstrated by the case of the vehicle stopper) the values of

P_2 and P_3 will depend on the time period selected as the length of the scenario, and an agreed method of defining the scenario cut off point is needed.

Setting the upper limit to the effect did not in practice cause problems in the exercise, but there are at least three issues here:

- In the case of P_1, how to account for cases where the weapon has a greater effect than the specified upper limit.
- In the case of P_2, where the aim is to eliminate the effect as quickly as possible when it is no longer needed, a strong argument can be made that excess effects should be included; but this could lead to a value of $P_2 < -1$.
- In the case of P_3, there is no obvious way of setting the upper threshold, and so it is not obvious how to set an upper limit to, and hence normalise, collateral effects.

- Whether the methodology should continue to incorporate P_3. In the course of the study concerns arose that P_3 (collateral MoSE) was almost immeasurable in its current form. It was suggested that a better approach would be to repeat an analysis of P_1 and P_2 for Red, Blue and White actors. In this way a series of acceptable effect magnitudes, durations and recovery times could be specified for all actors. This removes the arbitrariness of the "upper magnitude comparison limit" and makes all calculations more logical and defensible.

  These issues, about normalisation and the definition of P_3, resulted in recommendations for the redefinition of P_2 and P_3, as previously discussed.

7) **Sensitivity Analyses**. Whilst the vehicle stopper exercise has demonstrated the feasibility of sensitivity analyses within the methodology, the more general use of sensitivity analyses remained an issue at the end of Task 1, as it depends on estimates being available of the relative uncertainty in the various data – RR, MoR and the thresholds used in calculating P_1, P_2 and P_3 – and the feasibility of getting such estimates has not been demonstrated.
8) **Software Implementation**. The SAS-035 report envisioned the implementation of the methodology as a computer model. However, the experience of Task 1, applying the methodology to a diverse range of weapons, suggests that something simpler and less formalised is needed. The methodology is best viewed as a thought process for carrying out one stage in the process of assessing and comparing non-lethal weapons, to be adapted as appropriate to the particular set of weapons being studied. No single computer tool would meet the needs of all weapon types. Given the ability to specify the MoP, MoR and RR in agreed formats, then a calculation engine could be created which would perform the various MoSE calculations. However, the uncertainty over the data sets and fields makes the creation of such a tool difficult.
9) **Use of Combat Modelling**. The possibility was identified that aggregation methods of deriving MoSE from MoOE would not adequately capture the impact of effects to individual targets on the course of the scenario as a whole – that, for instance a small effect on one key enemy activity may have a major effect on later events. In that case, the MoSE measures could only be integrated adequately into a meaningful high level measure of operational success by formal modelling or wargaming of the overall sequence of events in a scenario in which the weapon(s) are used.

2.8 TASK 1 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions emerged from Task 1:

1) The exercise has shown that the methodology is verifiable by the process adopted – that is, that there is no reason to believe the process could not be verified if it were completely carried through. In fact:

- A number of issues with the methodology have been identified, but at present none are believed to be "show-stoppers".
- The feasibility of carrying out sensitivity analysis has been demonstrated for one weapon system.

2) The methodology should currently be regarded as a thought process, which should be adapted to the needs of assessing specific weapon systems, rather than a formal model which should be implemented in software.

3) Issues remain with:
   - The lack of orthogonality of the Basis Response variables.
   - Choice of appropriate Basis Response for some weapon types.
   - Provision of Required Response from military sources.
   - Derivation of Measures of Response from Measures of Performance.
   - Issues related to Measures of System Effectiveness – including normalisation, definition of scenario endpoint and how to measure collateral effects.
   - Sensitivity analyses.
   - Software Implementation.
   - Coupled effects.
   - The possible use of combat modelling as an aggregation method.

It is recommended that the SAS-035 framework should be modified, that a modified version of the P_2 measure of undesired effects should be applied universally to Blue, Red and White participants, and that the P_3 measure should be removed from the methodology.

Chapter 3 – AGGREGATING RESULTS FOR SYSTEM AND OPERATIONAL EFFECTIVENESS

3.1 INTRODUCTION

The Task 2 working group had two linked objectives, extending the Measures of System Effectiveness methodology and exploring development of Measures of Operational Effectiveness. Supporting objectives included:

- Addressing issues carrying over from Task 1 regarding the MoSE methodology (as refined).
- Analysing additional scenarios.
- Identifying distinctions between system and operational level measures of effectiveness.
- Determining potential methods of aggregating results – at a single point in time and across phases of a scenario – and comparing the methods.
- Analysing potential sources of variation and confidence levels.

3.2 INPUTS FROM TASK 1

The starting point for Task 2 efforts were the outputs from the Task 1 working group:

- The refined MoSE methodology as documented in a Task 1 report.
- System effectiveness data generated as part of the Task 1 assessments:
  - Vehicle Arrestor,
  - Optical Disrupter,
  - High-Power Microwave Weapon,
  - Kinetic Energy Weapons,
  - Flash-Bangs.
- Key issues identified (see Section 2.7).

3.3 SCENARIO ANALYSES

The Task 2 working group analysed additional scenarios:

- ***Urban Operations 2020 Warfighting Scenario*** – This was a fairly high intensity scenario with factions fighting in the aftermath of a government collapse and a mission to stabilise the country and restore territorial integrity, reduce potential for regional conflict, and ameliorate a humanitarian crisis. NLW-related tasks were associated with limiting collateral damage and reconstruction requirements as well as security operations in conjunction with humanitarian efforts.
- ***Urban Operations 2020 Contingency Response Operation Scenario*** – This had many similar elements to the previous scenario but with a cease fire agreement and Chapter VII UN Security Council Resolution in place. The NLW-relevant tasks were the same as in the warfighting scenario.
- ***Peace Enforcement*** – This scenario involved NATO Peace Enforcement in a non-permissive environment, with relevant tasks including NLW use as part of offensive operations, crowd dispersal, area denial to personnel, and crowd and riot control (with specific tasks to incapacitate, control movement/repel/employ barriers, and mark/identify).

- ***Deny Use of WMD*** – In a two-sided civil war having the threat of chemical weapons use, the mission is to prevent WMD use, ameliorate the humanitarian crisis, and minimise loss of life and chance of CW release. Given the risk of a chemical release, NLW may apply in many tasks, including: prevent the manufacture of chemical agents, render CW facilities inoperable, locate and distinguish combatants and non-combatants, neutralise hostile and potentially hostile troops, clear CW facility of personnel, deny enemy access to CW facility and deny areas, disrupt communications, disperse non-combatants and clear areas, and provide personnel and facility security.
- ***Urban Operations (Military Disaster Relief)*** – Following a major earthquake, the mission is to conduct non-combatant evacuation opeations, distribute emergency supplies, and evacuate/ relocate refugees and displaced persons. Specified NLW-relevant tasks are crowd and riot control, distinguish between hostile and non-hostile, erect barriers, control movement, and deny areas.
- ***Urban Operations (Peacekeeping)*** – In the aftermath of extended conflict over autonomy, the mission is to maintain order and a secure environment, confiscate weapons, provide security for NGOs, and safeguard citizens while minimising civilian casualties and collateral damage.
- ***Urban Operations (Urban Combat)*** – This was a high intensity scenario involving a powerful state pursuing regional hegemony including through subversion of its neighbors. This scenario indicates an important role for NLW as the mission explicitly cites the need to minimise casualties and collateral damage while regaining control of the government capital.
- ***Humanitarian Assistance*** – Following governmental collapse a third world country faces spreading famine and chaos. The mission is to maintain general and local area security, distribute essential supplies, and facilitate logistics with the following specified NLW-relevant tasks: open and maintain ingress/egress routes; control movement, ability to act/shoot, etc.; deny areas/deny access to individuals and vehicles; incapacitate individuals; stop and/or neutralise vehicles; mark targets; restrict communications (leader to crowd); and minimise civilian casualties and collateral damage.

For each scenario, the Task 2 working group analysed the mission, threats, environmental factors, specified tasks, task-target combinations, linkages (**P**rimary and **S**econdary) to Basis Responses (depicted in Table 3-1), desired response characteristics, and engagement characteristics.

Table 3-1: Linkages from Tasks to Basis Responses (BRs)

		Mobility	Communications	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identification
Anti-Personnel Task-Target Combinations	Deny Area/Deny Access to Individuals	P				S	P	
	Secure and Defend Against Individuals	S		P	S		S	
	Contain, Isolate, Separate Individuals	S	S		P			P
	Delay Individuals	P		P				
	Incapacitate Individuals	S	S	P		S	S	
	Disperse Individuals	S			P		S	
	Distract and/or Disorient Individuals					P	S	
	Degrade/Suppress Individuals			P		S	P	
	Canalize Individuals	P			S		S	
	Clear Buildings/Facilities/Structures of Individuals	P					S	S
	Clear Vessels/Aircraft of Personnel	P					S	
	Interrogate Intent of Individuals		S					P
	Deceive/Demonstrate to Individuals					P	S	

Anti-Materiel Task-Target Combinations	Disable Vehicles, Vessels, and Aircraft	P		P		S		
	Render Inoperable/Deny Use of Vehicles, Vessels, and Aircraft	P		P		S		
	Stop/Interdict Vehicles/Vessels/Aircraft	P		P		S		
	Render Inoperable/Deny Use of Weapons			P				
	Degrade/Suppress Weapon Systems and Ammunition		S	P		S		
	Render Inoperable/Deny Use of Vehicles, Vessels, and Aircraft	P		P		S	S	
	Contain/Isolate/Separate/Delay Movement from Buildings, Facilities, and Structures	P					S	S
	Deny Area/Deny Access to Vehicles, Vessels, and Aircraft	P					S	
	Render Inoperable/Deny Use of Buildings, Facilities, and Structures			P				
	Render Inoperable/Deny Use of Buildings, Facilities, and Structures			P			S	
	Contain/Isolate/Separate Vehicles, Vessels, and Aircraft	P			P			P
	Delay Vehicles, Vessels, and Aircraft	P				S	S	
	Canalize Vehicles and Vessels	P				S	S	
	Deny Area/Deny Access/Render not Trafficable to Vehicles, Vessels, & Aircraft	P		P				

Anti-Capability TTCs	Render Inoperable/Deny Use of WMD	S	S	P				
	Render Inoperable/Deny Use of C4ISR		P			P		
	Render Inoperable/Deny Use of Buildings/Facilities/Structures			P				
	Degrade/Suppress C4ISR		P			P		

3.4 MoSE AND MoOE DEFINITIONS/DISTINCTIONS

The Task 2 working group sought to identify distinctions between MoSEs and MoOEs by examining differences between tactical and operational level tasks, with the underlying intent to facilitate development of MoOEs. However, there were no major differences in the types of tasks as illustrated in Table 3-2.

Table 3-2: Operational and Tactical Level Task Comparisons

	Task Categories
Operational Level	Conduct Operational Movement/Manoeuvre Employ Operational Firepower Provide Operational Logistics/Personnel Support Provide Operational Force Protection
Tactical Level	Deploy/Conduct Manoeuvre Employ Firepower Provide Combat Service Support Protect the Force

The differences between operational and tactical level tasks are not in the nature of the tasks but rather their scope and scale. In defining required outcomes (and MoOEs) as opposed to required responses (and MoSEs), Table 3-3 shows useful distinctions.

Table 3-3: MoSE vs. MoOE Distinctions

Required Response/MoSE	Required Outcome/MoOE
Single Task	Multiple Tasks
Single Target	Multiple Targets
Single NLW	Multiple NLW
Single Phase	Extended Duration (across phases)

3.5 AGGREGATION APPROACHES AND EXAMPLES

3.5.1 Methods and Description

The methods proposed, studied, and implemented for aggregating effectiveness can be classified into the following categories:

- **ANALYTICAL FORMULATION**
  - SAS-035
  - Weighted Euclidean Distance
    - Generalization: Weighted Minkowski Distance
    - Particularization: Root Mean Square
- **MULTI-CRITERIA**
  - Scoring Model
  - Pairwise Comparison Weighted
    - Variant: Random Weights Generation averaged
  - Analytic Hierarchy Process
- **ARTIFICIAL NEURAL NETWORK**
  - Supervised Radial Basis Function Network

All the methods are normalized in order to obtain aggregated values between 0 and 1, allowing for direct comparisons among methods.

3.5.1.1 Analytical Formulations

3.5.1.1.1 SAS-035 Proposed Formula

SAS-035[1] anticipated the need to aggregate effectiveness results (whether for task accomplishment, P_1, or constraint satisfaction, P_2) across basis responses. An example analytical formulation was expressed as follows:

$$P^* = \left\{ 1 - \prod_{i=1}^{7} \left[1 - \left(\frac{P_i + |P_i|}{2} \right) \right] \right\} + \left\{ -1 + \prod_{i=1}^{7} \left[1 + \left(\frac{P_i - |P_i|}{2} \right) \right] \right\}$$

[1] SAS-035 final report, pp. 3-19.

This formula is easy to use. However, the formulation has an important limitation: saturation. If any $P_i = 1$ (and all are non-negative), then the aggregated P* = 1, making the other basis response (BR) values irrelevant. Nevertheless, this method is included for comparison purposes.

3.5.1.1.2 Weighted Euclidean Distance (WED)

The Weighted Euclidean Distance in a seven-dimensional space (number of BRs) is a simple and straightforward method to solve the aggregation problem. This method takes into account BRs' relative importance through a vector of weights w_i (i = 1, 2, … ,7). Weighting is determined by the user and the sum of all the weights must add up to one.

The mathematical formulation of this aggregation method is as follows:

$$\sum_{i=1}^{7} w_i = 1; \text{ With } w_i \geq 0$$

$$P^* = \frac{d(O,P)}{d(O,E)} = \frac{\sqrt{\sum_{i=1}^{7} w_i P_i^2}}{\sqrt{\sum_{i=1}^{7} w_i}} = \sqrt{\sum_{i=1}^{7} w_i P_i^2}$$

where:

w_i: vector of normalized weights;

O (0,0,0,0,0,0,0): origin with all effectiveness values of the BRs equal to zero; and

E (1,1,1,1,1,1,1): maximum value (all effectiveness values of the BRs equal one).

When the relative importance is the same for all the BRs, then the aggregation equation (called Averaged Euclidean Distance) is equal to the **Root Mean Square (RMS)**. The RMS, utilized in many research areas, is a measure of the magnitude of a set of numbers that gives a sense of the typical size of the numbers. The RMS aggregated value (P*) for the effectiveness of the seven Basis Responses $\{P_1, P_2, \ldots, P_7\}$ is:

$$P^* = \sqrt{\frac{1}{7}\sum_{i=1}^{7} P_i^2} = \sqrt{\frac{P_1^2 + P_2^2 + \cdots + P_7^2}{7}}$$

The RMS is an appropriate aggregation method when the user is not interested in the relative priority of different Basis Responses. When the user wants to rank the importance of the BRs, RMS is not a suitable method.

The WED is a particularization of the Weighted Minkowski Distance. The WMD of order k can be used as an aggregation method:

$$P^* = \left(\sum_{i=1}^{7} w_i P_i^k\right)^{\frac{1}{k}}$$

When the Minkowski factor for the norm k (order) is set as 2, the expression is the WED. When k is set to 1, the formula is a linear weighting model (Scoring Model).

3.5.1.2 Multi-Criteria Decision Models (MCDM)

Multi-Criteria Decision Models (MCDM) are methods for solving decision problems. In this section, MCDM are used to aggregate effectiveness and rank alternatives (NLW). Hence, BRs are weighted by coefficients that measure relative importance based on decision makers' experience.

3.5.1.2.1 Scoring Model (SM)

The Scoring Model (SM) is a simple and fast method to solve the aggregation problem. The critical step is determining appropriate weights for the BRs for different situations (scenario, phase of engagement, requirements, etc.). The relative weights must be assigned based on the concrete objectives of each operation, with the sum of all the weights must be equal to one (aggregated values are bounded to one).

The steps of the SM are the following:

1) Identify the main goal → Choose the best NLW.
2) Identify the alternatives → Different NLW.
3) List the criteria to apply in making the decision → Different BRs.
4) Assign the weights for the different criteria → Weights Vector.
5) Calculate the Score for each alternative.
6) Rank the alternatives according to the Score. The NLW with the highest Score is the best.

The scoring formula for j types of NLW is:

$$P_j^* = \sum_{i=1}^{7} w_i \bullet P_{ij}$$

Where:

P_{ij} = Effectiveness value of the BR_i of the NLW_j

w_i = weight for the BR_i

P^*_j = Aggregated value for the NLW_j

Therefore, the SM is a basic method to aggregate effectiveness when the relative importance of Basis Responses matters. When the relative importance is the same for all BRs, then the outcome is an average (arithmetic mean).

3.5.1.2.2 Pairwise Comparisons Weighted (PCW)

The PCW method compares pairs of input values (referred to as pairwise comparisons), subtracting one from all the others. Then weights must be assigned, with knowledge from experts used to build the Weights Vector (WV).

The pairwise dominance might be checked with the following LP models used to make the aggregation:

$$P_j^* = \max\left(\sum_{i=1}^{7} w_i \left(P_{ji} - P_{ki}\right)\right)$$

Where: P_{ji} is the effectiveness value of the NLW_j with respect to BR_i and the maximization is over the subindex k.

The weights take values between 0 and 1 and they must add up to 1. So, the aggregated results are bounded by 1. Every specific case has a different Weights Vector related to it, and the experience of working with the WV is very important.

A method based on the PCW formulation, is the **Random-Weights Generation averaged (RWG)**. This method does not apply user criteria. Instead, weights are generated using random uniform distributions for the simulation of additive i-criteria decision models (i is the number of BRs). In the procedure, *i-1* random numbers are first selected from a uniform distribution on (0, 1) independently. Then, the numbers are ranked. Suppose the ranked numbers are $1 \geq v_{i-1} \geq \ldots \geq v_2 \geq v_1 > 0$. The first differences of these ranked numbers (including the bounds 0 and 1) can be obtained as:

$$w_i = 1 - v_{i-1}$$
$$w_{i-1} = v_{i-1} - v_{i-2}$$
$$\ldots$$
$$w_1 = v_1 - 0$$

In this case, the set of numbers $(w_1, w_2, \ldots, w_7)$ will clearly add up to one. Once the weights have been generated, the aggregation PCW formula is applied.

Moreover, the aggregated value for each j must be calculated T times (Monte Carlo simulations) to obtain an average outcome:

$$\widetilde{P}_j^* = \frac{1}{T}\sum_{r=1}^{T} P_{jr}^*$$

If the value of T is high enough, then the relative importance given to all BRs tends to be the same. Therefore, the results of both methods are the same when RWG is calculated with a high T and the weights vector gives the same importance to all BRs in the PCW case.

When knowledge from experts is not available, the RWG can be used to generate stochastic aggregation results for comparison purposes.

3.5.1.2.3 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) can be used in single or multi-dimensional decision-making problems. It is a methodology suitable for aggregation and for determining weights. AHP is based on decomposing a complex MCDM problem into a system of hierarchies (with an example presented in Annex D).

Owing to its simplicity and ease of use, the AHP has found ready acceptance by decision-makers. It helps structure thoughts and organise problems in a manner that is simple to follow and analyse. Basically the AHP helps in structuring the complexity, measurement and synthesis of rankings, features that make it suitable for our purposes.

The matrices are *(7xN)*, seven being the number of criteria (BRs) and *N* the number of alternatives (NLW), for a specific P_k.

This matrix is constructed by using the relative importance of the NLW in terms of each BR. The vector $(a_{1j}, a_{2j}, a_{3j}, \ldots, a_{7j})$ for each *j* is the principal eigenvector of a 7×7 reciprocal matrix which is determined by pairwise comparisons of the impact of the *N* NLW on the *i-th* BR.

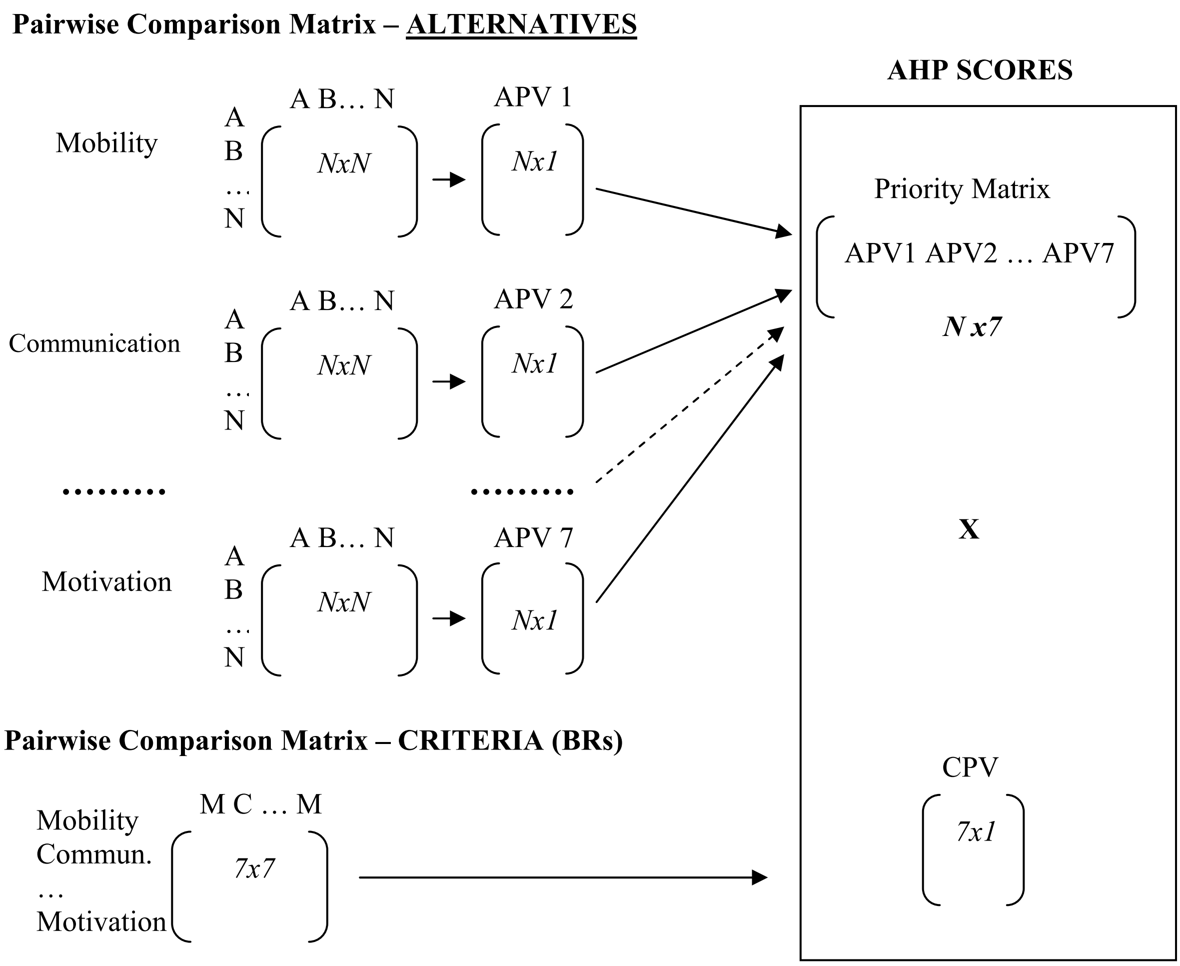


Figure 3-1: AHP Diagram.

The matrix *(7xN)* is aggregated in a *(Nx1)* vector. This vector represents the specific P_k aggregated for the *N* different types of NLW.

The AHP produces weight values for each alternative based on the judged importance of one NLW versus another[2] with respect to a common basis response. Its main value resides in the easy and logical method of obtaining the weights.

3.5.1.3 Artificial Neural Networks (ANN)

Artificial Neural Networks (ANNs) have been used in multiple research areas and can be adapted to aggregation (see Annex D for a detailed description).

Several options were studied and analyzed to solve our problem of aggregation considering unsupervised and supervised nets. Finally the net proposed and implemented to solve the problem of aggregation was a supervised radial basis function network.

[2] Knowledge from experts/commanders is needed to build the Criteria Comparison Matrix. Every specific case has a Criteria Comparison Matrix related to it, and experience is very important.

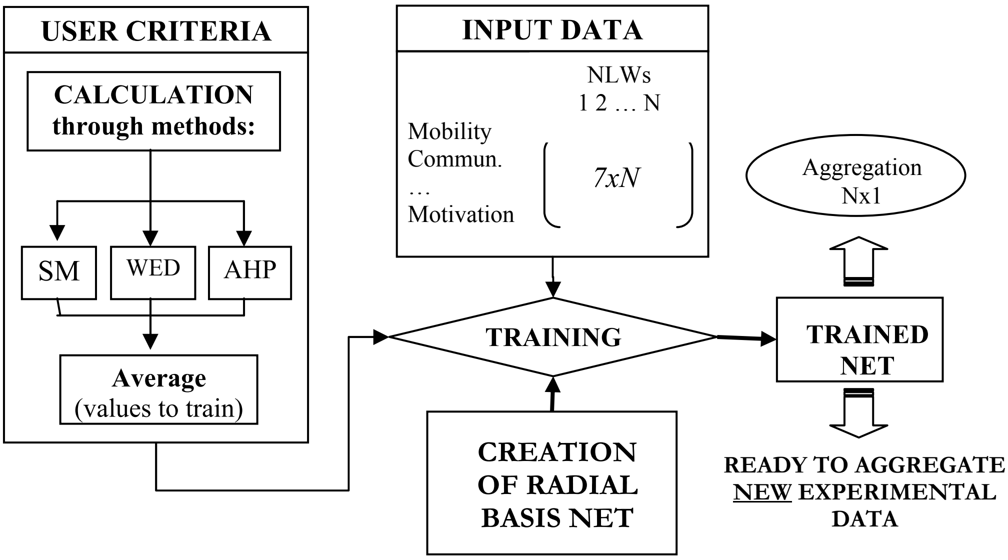


Figure 3-2: Supervised Radial Basis Net Block Diagram.

The target (known goal output state) to train the net is obtained by aggregation methods which need user criteria. The net is supervised because the criteria are taken into account when obtaining the corresponding target to train the net. This target is an average among all the results obtained by the other "weighted" methods (SM, WED, and AHP). Thereby, the ANN results are "combinations" of the other weighted methods' aggregated values.

Once there is a trained net, the ANN method easily calculates results for different scenarios, engagement phases, etc. The SM, WED, and AHP are no longer required because the net is already trained, and results can be obtained directly.

Given an input matrix *(7xN)*, the network yields an output vector Nx1 with the aggregated values.

3.5.2 Comparison of Methods

3.5.2.1 Comparison of Results

The MoSE are split into three different types: intended target (Red), our own forces (Blue) and non-combatants/others (White). Every colour is treated in the same way but independently from each other. The results presented in the comparison are only for P_1 for Red.

The following table (Table 3-4) presents data on six NLW-target combinations: Optical Disrupter, vehicle stopper (30, 49 and 70 mph), and kinetic weapons (Blinis and 12 gauge). The six P_1 matrices *(7x2)* available (colour red) are:

Table 3-4: NLW Input Data

RED	NLW 1: Optical Disrupter		NLW 2: Vehicle Stopper (30 mph)		NLW 3: Vehicle Stopper (49 mph)		NLW 4: Vehicle Stopper (70 mph)		NLW 5: Kinetic (Blinis)		NLW 6: Kinetic (12 gauge)	
BR	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2	P_1	P_2
Mobility	0.8	0.6	0.9959	0.5	0.9748	0.5	0	1	0.75	0.6	0.4	1
Communication	0	1	0	0	0	0	0	0	0.2	1	0.1	1
Physical Function	0.8	0.6	0.9959	0.5	0.9748	0.5	0	1	0.5	1	0.8	1
Sense/Interpret	1	0.75	0	0	0	0	0	0	0.95	0.65	0.4	1
Group Cohesion	0.75	0.75	0	0	0	0	0	0	0.75	0.8	0.6	0.9
Identification	0	1	0	0	0	0	0	0	0	0	0	0
Motivation	0	0	0	0	0	0	0	0	0.4	1	0.4	0.9

In order to compare the different aggregation methods, the effectiveness values of the BRs are equally weighted when user weights are needed.

Results obtained by the different methods are shown in order to clarify the conclusions:

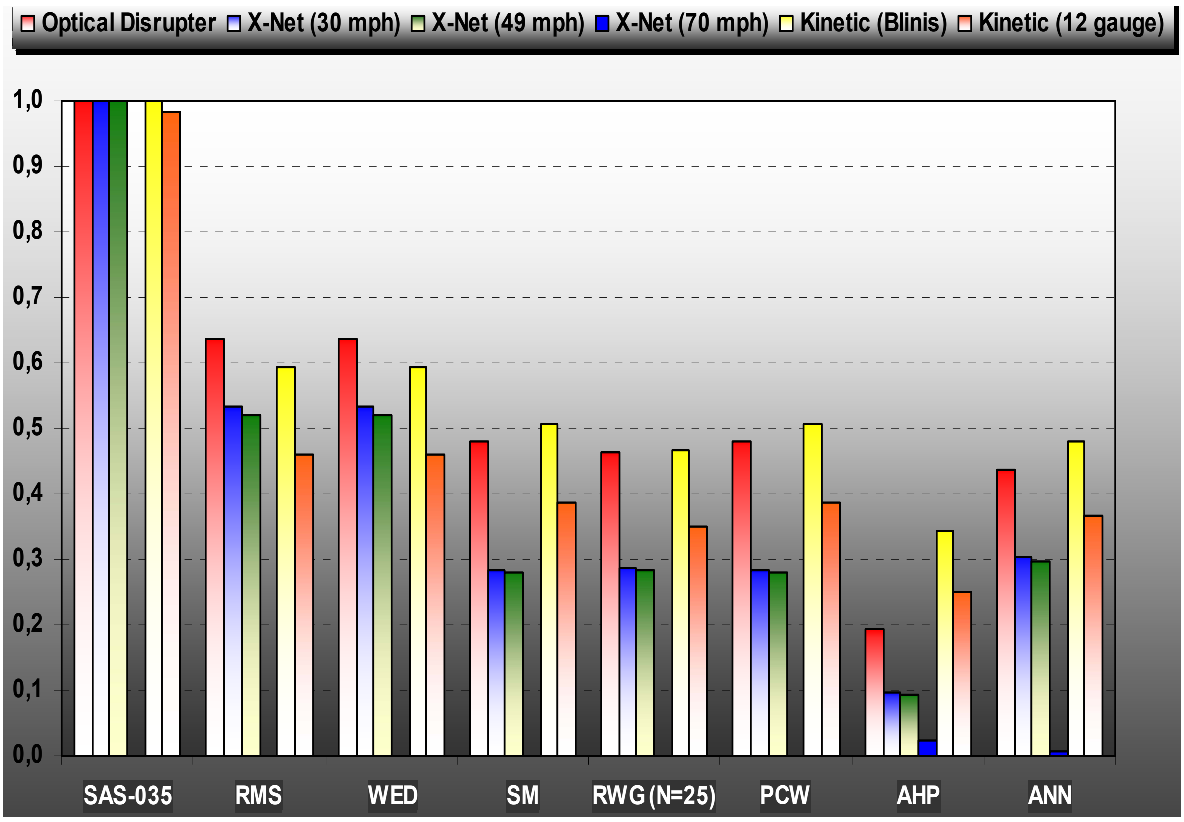


Figure 3-3: Comparison of Results.

Table 3-5: Methods' Results

P^*_1	SAS-035	RMS	WED	SM	RWG (N = 25)	PCW	AHP	ANN
NLW 1: Optical Disrupter	1.0000	0.6372	0.6372	0.4786	0.4617	0.4786	0.1933	0.4364
NLW 2: Vehicle Stopper (30 mph)	1.0000	0.5323	0.5323	0.2846	0.2881	0.2846	0.0958	0.3043
NLW 3: Vehicle Stopper (49 mph)	0.9994	0.5211	0.5211	0.2786	0.2820	0.2786	0.0943	0.2980
NLW 4: Vehicle Stopper (70 mph)[3]	0	0	0	0	0	0	0.0247	0.0082
NLW 5: Kinetic (Blinis)	0.9992	0.5949	0.5949	0.5072	0.4669	0.5072	0.3424	0.4815
NLW 6: Kinetic (12 gauge)	0.9844	0.4614	0.4614	0.3857	0.3506	0.3857	0.2496	0.3656

The SAS-035 formula results show the saturation issue. If any $P_i = 1$ (and all P_i are non-negative), then the aggregated $P^* = 1$, as seen with the Optical Disrupter.

The RMS does not have a saturation issue. However, it does not take into account the priority among BRs, and this priority is important while analysing a particular sequence of events. This method is adequate when BR criteria are not needed. When all the weights are equal, the results obtained by the WED are the same as the RMS.

As with the WED, the SM also takes into account the priority of the BRs. As explained before, as all the weights are equal, the aggregated values are the arithmetic mean of the effectiveness values of the BRs.

The results of the SM and the PCW are the same because the maximum pairwise comparison in the PCW is made with the vehicle stopper (70 mph), and its inputs are 0 for all the effectiveness values of the BRs.

In this case, as all the weights are equal, the RWG gives aggregated results similar to the PCW (the higher the number of simulations for the RWG, the more similar the results would be).

In the AHP, the sum of the aggregated values for all the NLWs considered is equal to 1. This is why the aggregated values are lower than in the other methods and depends on the number and types of NLWs selected. For this reason, an accurate comparison of AHP results with the other methods could only be made by scaling other methods with the number of NLW available.

Finally, the ANN method is a combination among "weighted methods" (WED, SM, and AHP) results. Once the training is completed, the aggregated values provided are the average of these three methods.

3.5.2.2 Task-Target Combination Aggregation

Here is an example using Table 3-1 (Linkages from Tasks to Basis Responses). The aggregation methods will be applied to the "incapacitate individuals" case (consequently, the NLWs used need to be anti-personnel).

[3] The Vehicle stopper (70 mph) result is null because the P_1 inputs are 0 (see inputs in Table 2-2).

Table 3-6: Linkages from Tasks to BRs: Incapacitate Individuals

	Mobility	Communi-cations	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identi-fication
Incapacitate Individuals	S	S	P		S	S	

The aggregation example applied the following considerations (resulting in the weights' vector shown in Table 3-7):

- All the primary BRs are equally weighted.
- All the secondary BRs are equally weighted.
- The primary BRs are considered twice as important as the secondary BRs.

Table 3-7: Weights' Vector for Incapacitate Individuals

	Mobility	Communi-cations	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identi-fication
Incapacitate Individuals	1/6	1/6	1/3	0	1/6	1/6	0

In the AHP case, if $w_p = 2\ w_s$, then the relative importance of the BRs to build up the criteria comparison matrix is:

Table 3-8: Importance of BRs for Incapacitate Individuals

	Mobility	Communi-cations	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identi-fication
Incapacitate Individuals	4	4	8	1	4	4	1

Finally, the criteria comparison matrix is:

Table 3-9: Criteria Comparison Matrix for Incapacitate Individuals

	Mobility	Communi-cations	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identi-fication
Mobility	1	1	½	4	1	1	4
Communications	1	1	½	4	1	1	4
Physical Function	2	2	1	8	2	2	8
Group Cohesion	1/4	1/4	1/8	1	1/4	1/4	1
Sense & Interpret	1	1	½	4	1	1	4
Motivation	1	1	½	4	1	1	4
Identification	1/4	1/4	1/8	1	1/4	1/4	1

Table 3-10: Methods' Results for Incapacitate Individuals

	Non User Weighted Methods			User Weighted Methods				
P^*_1	**SAS-035**	**RMS**	**RWG (N = 25)**	**PCW**	**WED**	**SM**	**AHP**	**ANN**
NLW 1: Optical Disrupter	1.0000	0.6372	0.0868	0.0750	0.6432	0.5250	0.3035	0.4906
NLW 5: Kinetic (Blinis)	0.9992	0.5949	0.1389	0	0.5268	0.4500	0.3756	0.4508
NLW 6: Kinetic (12 gauge)	0.9844	0.4614	0.0192	0	0.5492	0.4500	0.3209	0.4400

If we applied the aggregation methods to the "Stop/Interdict Vehicles, Vessels, and Aircraft" case the NLWs used need to be anti-materiel.

Table 3-11: Linkages from Tasks to BRs: Stop/Interdict Vehicles, Vessels, and Aircraft

	Mobility	Communi-cations	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identi-fication
Task – Stop/Interdict Vehicles, Vessels, and Aircraft	P		P		S		
Weights	2/5	0	2/5	0	1/5	0	0
Importance (for AHP)	8	1	8	1	4	1	1

And the criteria comparison matrix:

Table 3-12: Criteria Comparison Matrix for Stop/Interdict Vehicles, Vessels, and Aircraft

	Mobility	Communi-cations	Physical Function	Group Cohesion	Sense & Interpret	Motivation	Identi-fication
Mobility	1	8	1	8	2	8	8
Communications	1/8	1	1/8	1	1/4	1	1
Physical Function	1	8	1	8	2	8	8
Group Cohesion	1/8	1	1/8	1	1/4	1	1
Sense & Interpret	1/2	4	1/2	4	1	4	4
Motivation	1/8	1	1/8	1	1/4	1	1
Identification	1/8	1	1/8	1	1/4	1	1

The results are presented in Table 3-13.

Table 3-13: Methods' Results for Stop/Interdict Vehicles, Vessels, and Aircraft

	Non User Weighted Methods			User Weighted Methods				
P^*_1	**SAS-035**	**RMS**	**RWG (N = 25)**	**PCW**	**WED**	**SM**	**AHP**	**ANN**
NLW 2: Vehicle Stopper (30 mph)	1.0000	0.5323	0.3108	0.7967	0.8908	0.7967	0.4478	0.7118
NLW 3: Vehicle Stopper (49 mph)	0.9994	0.5211	0.3042	0.7798	0.8719	0.7798	0.4407	0.6975
NLW 4: Vehicle Stopper (70 mph)	0	0	0	0	0	0	0.1114	0.0371

The most appropriate methods to take into account linkages from tasks to BRs (priorities among BRs) are user weighted ones (PCW, WED, SM, AHP, ANN).

3.5.2.3 Comparison of Methodologies

Table 3-14 shows a comparison of the various aggregation methodologies.

Table 3-14: Comparison of Methodologies

METHOD	Analytical formula	User criteria	Pairwise dominance	Expert input required?	Comments
SAS-035	Yes	No	No	No	Saturation: If any $P_i = 1$, then the aggregated **P* = 1**.
RMS	Yes	No	No	No	An appropriate method when priority among BRs is not needed.
WED	Yes	Yes	No	Yes	Assign relative importance to the BRs.
SM	No	Yes	No	Yes	Assign relative importance to the BRs.
RWG	No	No	Yes	No	Weights determined by uniformly random generation. Results are averaged.
PCW	No	Yes	Yes	Yes	Assign relative importance to the BRs by pairwise.
AHP	No	Yes	Yes	Yes	Rank the BRs in comparison to each other. Adequate method when there are few NLW selected. ***Accurate and realistic results.***
ANN	No	Supervised nets are trained using results from the other methods	It compares every NLW to the others (one at a time, not pair by pair)	Supervised nets Yes Unsupervised No	Results depend on the methods used to train the net. ***Good choice when database is incomplete. The best method when there are a large number of alternatives.***

A software script was used to compare the different methods' results across a range of randomly generated MoSE values. In the comparative analysis, the inputs (1000 NLW) are randomized (effectiveness values of the 7 BRs uniformly distributed between 0 and 1, with BRs weighted equally) and the variability of effectiveness values is simulated by means of a Gaussian random generator (100 simulations for each NLW). The Monte Carlo method is then applied running 100,000 simulations for each aggregation method[4]. Conclusions about certain limits of use of the methods are presented. However, experimental data is absolutely required to decide which one of the methods is the most appropriate to use in MoSE aggregation.

The resulting matrix of correlations between the scores obtained from the different methods is as follows:

Table 3-15: Correlation Matrix (r)

	SAS-035	RMS	WED	SM	RWG	PCW	AHP	ANN
SAS-035	1	0.6634	0.6634	0.6007	0.2869	0.2358	0.3908	0.6118
RMS	0.6634	1	1	0.9665	0.6390	0.5958	0.5860	0.9457
WED	0.6634	1	1	0.9665	0.6390	0.5958	0.5860	0.9457
SM	0.6007	0.9665	0.9665	1	0.6583	0.6245	0.6612	0.9714
RWG	0.2869	0.6390	0.6390	0.6583	1	0.9722	0.8326	0.7704
PCW	0.2358	0.5958	0.5958	0.6245	0.9722	1	0.7917	0.7276
AHP	0.3908	0.5860	0.5860	0.6612	0.8326	0.7917	1	0.8069
ANN	0.6118	0.9457	0.9457	0.9714	0.7704	0.7276	0.8069	1

If a high correlation between methods is obtained (r greater than 0.7), then the methods follow the same "tendency". However, high correlation between methods does not prove the two methods agree and the obtained values cannot be considered accurate or adequate for our interests. Nevertheless, this would be a good starting point to begin the comparison of methods.

The proposed SAS-035 method has lower correlations with all the other methods. Moreover, the saturation issue previously identified may limit the method's usefulness.

Since all the weights of the BRs are equal (for this example case), the aggregation formulas are the same and there is a perfect correlation between the RMS and WED methods (r = 1).

The SM shows a high correlation with the RMS, the WED and the ANN, but the correlation presented with the RWG and the PCW is poor. The last two methods have good correlations between one another and poor with the rest of the methods.

The AHP and the ANN have high correlation between them. However, the ANN presents higher correlations with the other methods.

Figure 3-4 shows the correlation averages for the different methods:

[4] Examples of 10 inputs generated are presented in Annex A.3. User criteria give the same relative importance to all BRs when it is needed.

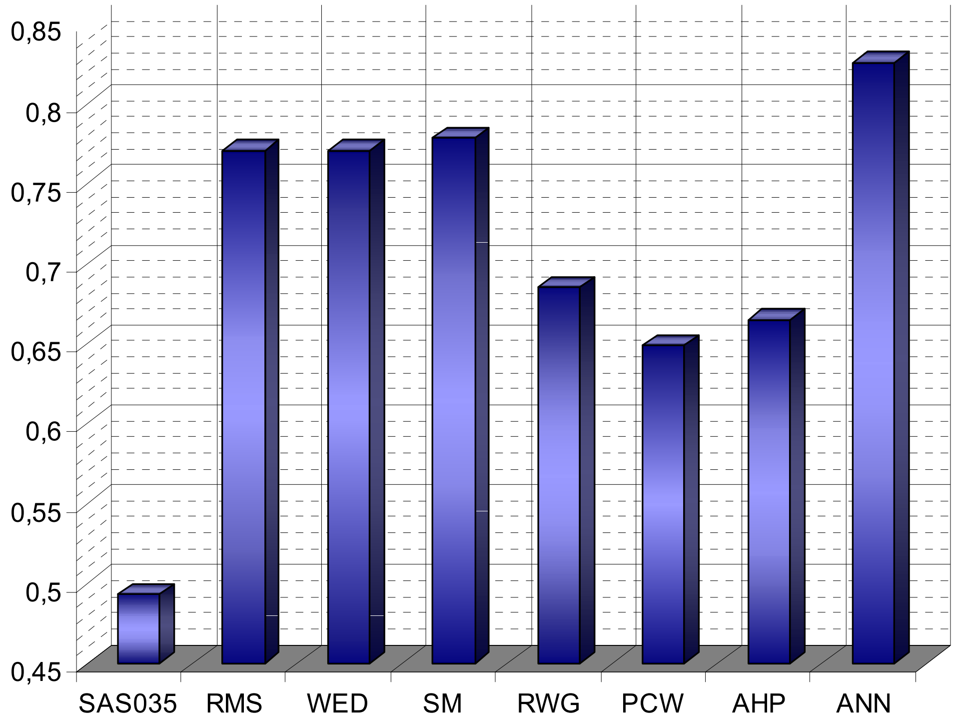


Figure 3-4: Average Correlations for Each Method.

ANN has the highest correlations, with the SM, RMS and WED also having high correlations, whereas the SAS-035 has the lowest as mentioned. Even if the highest correlations do not mean the best methods, it is recommended to get a high one.

Next, a comparison of methods is made plotting the scatter diagrams of the data obtained by the Monte Carlo method (Figure 3-5). Scatter diagram give a valuable insight into the way the different methods are related. In Figure 3-5, the values of a method are plotted against the corresponding values of the other methods.

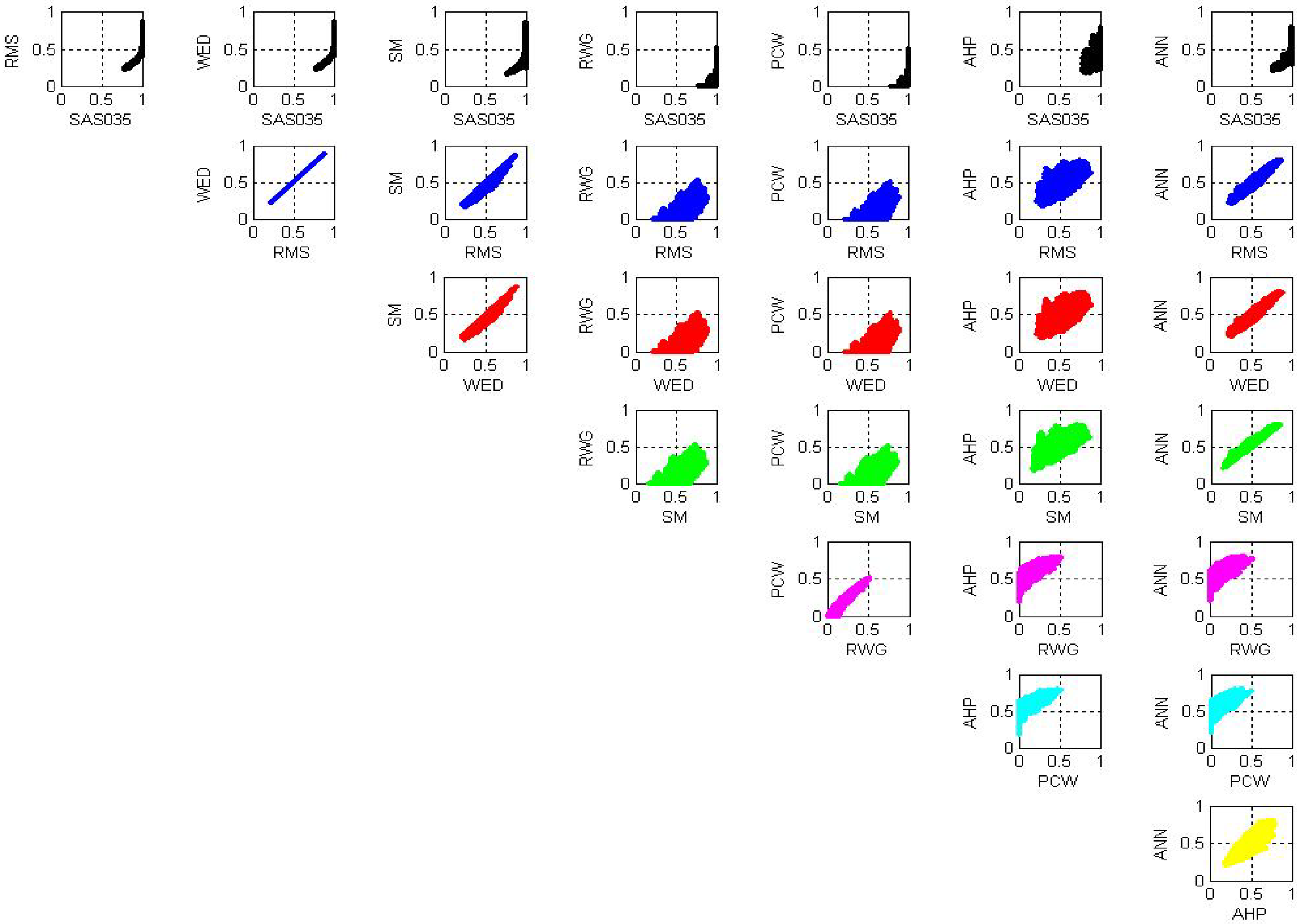


Figure 3-5: Scatter Diagrams of the Methods.

All the methods studied present a positive slope, which means that the aggregation values of the methods are broadly in concordance. If the correlation is perfect, the scatter diagram becomes a straight line.

As seen in the scatter diagrams, certain methods reach the axis, which are the bounds of the values. This happens with the SAS-035, RWG, and PCW methods. These methods, which have values on the limits, could be considered inappropriate for aggregation.

Of the other methods, four (WED, SM, AHP and ANN) take into account user criteria, and one (RMS) does not. When aggregating effectiveness values, user criteria are desirable. Therefore, the RMS could be eliminated from the list of methods. Moreover, if relative importance is equal for all the BRs, the RMS and WED formulations are identical.

The four remaining methods are: WED, SM, AHP and ANN. Figure 3-5 graphs with AHP show a wider and less clear cloud of points. However, this method includes a process for determining weights.

The mathematical relation between methods may be estimated by a regression line. The disagreement between methods is measured by the departure of the regression line from the bisecting line of the plot (unitary slope) and the offset (the intersection with the y-axis).

Regression lines have been calculated for the methods and two indexes of merit are obtained (see Annex D): absolute values of deviation from unitary slope and offset. These indices are averaged for each method and represented in Figure 3-6. If the values of the indexes averaged are lower, then the agreement between one method and the remaining three is higher. Consequently, ANN, WED and SM show higher concordance than the AHP.

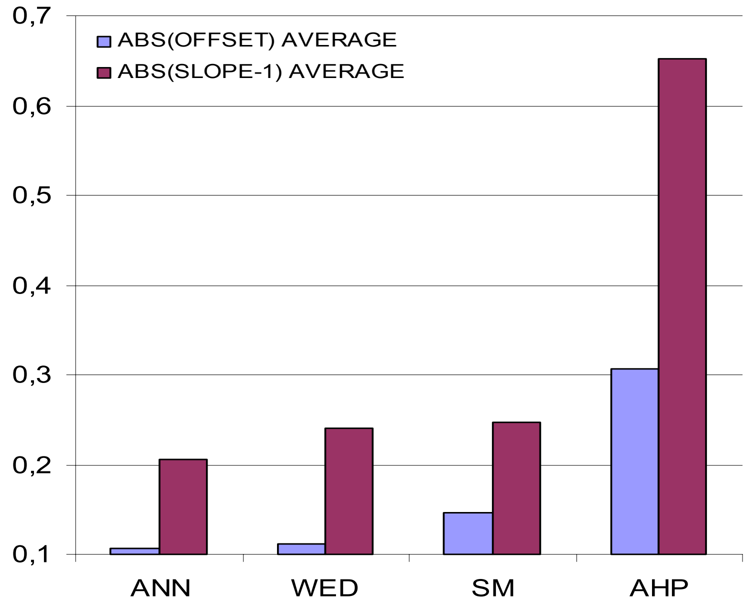


Figure 3-6: Regression Lines Indexes of Merit.

3.6 VARIABILITY ANALYSIS AND UNCERTAINTY TREATMENT

3.6.1 Definitions

The definitions of uncertainty and variability are included below:

- **Uncertainty**: Lack of knowledge about specific factors, parameters, or models[5].
- **Variability**: Refers to observed differences attributable to true heterogeneity or diversity in a population or exposure parameter (natural random processes). Taken into account as population distribution model (univariate normal distribution for each BR)[6].

3.6.2 Variability Analysis: Monte Carlo (MC) Simulations

The aggregation methods (except RWG) are deterministic; this means that if the inputs are defined, then the aggregation value obtained is the same every time the method is calculated (results are independent of how many times aggregation is recalculated – i.e., number of simulations or iterations).

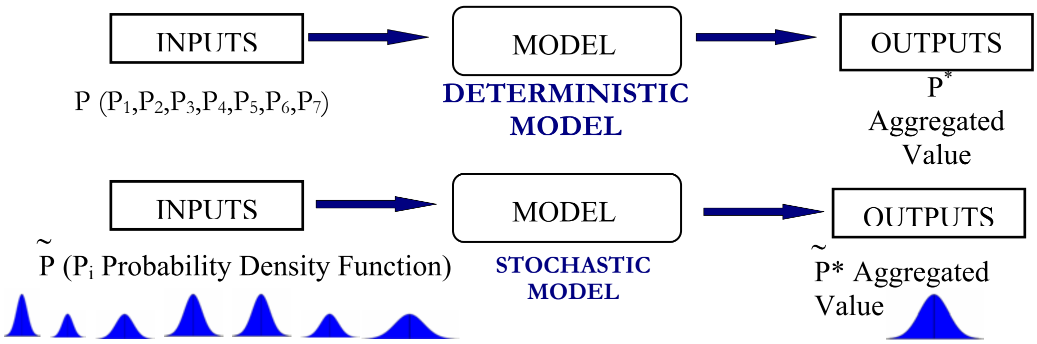


Figure 3-7: Monte Carlo Simulations Method.

The Monte Carlo Method was applied in order to estimate the impact of MoSE on aggregated results for the different aggregation methods. The Monte Carlo process steps are as follows:

1) Define the Problem/System definition.
2) Generate pseudo-random numbers.
3) Generate pseudo-random variables.
4) Simulate N-times applying a model or method (i.e., aggregation method).
5) Statistical Analysis of the N simulations results.

The pseudo-random number generation used produces Gaussian random values by using the Ziggurat method. The pseudo-random numbers and variables generation are shown in Annex D.

Given an input of 7 effectiveness values, the initial model proposed, is based on 7 normal distribution functions with the following hypothesis:

- Mean value of the effectiveness based on each BR: $\mu_i = P_i$ ($i = 1, \ldots 7$)
- Standard deviation: σi proportional to P_i ($i = 1, \ldots 7$)

That is to say, the standard deviation σ_i proportional to the effectiveness value for each BR and the mean μ_i is the corresponding value. An input of a semi-empirical parameter **e** must be given by the user, so σ_i can be calculated:

5 More advanced models may include: Measurement and systematic errors; Due to the simplification of the real world.

6 More advanced models may include: Effects; Physiological variability.

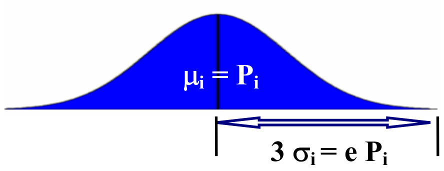


Figure 3-8: Normal Distribution of Each P_i.

Using the proposed model, Figure 3-9 shows one example of the generation of the pseudo-random variables is represented given the semi-empirical parameter e = 0.1 (10%) and the following vector P (0.1, 0.15, 0.2, 0.3, 0.5, 0.6, 0.8)[7]. The number of simulations for the example is N = 1000.

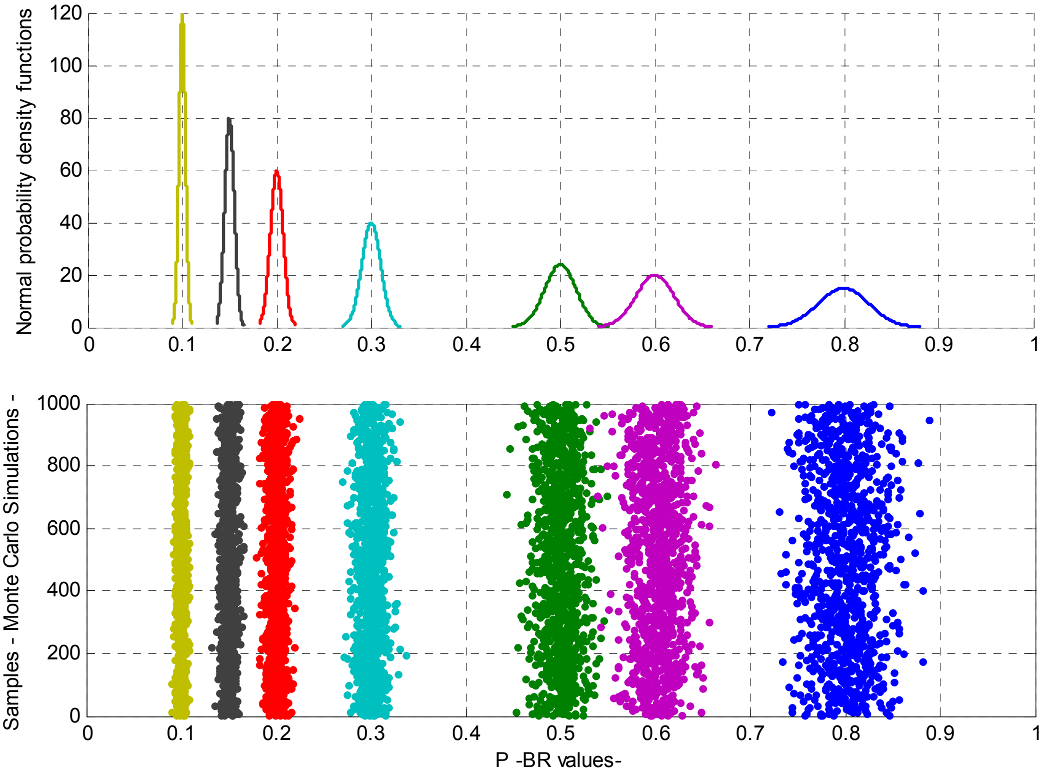


Figure 3-9: Normal Probability Density Functions and Monte Carlo Simulations to Cope with Variability.

This Monte Carlo model ensures P_i lies between 0 and 1 as follows[8]:

- if Pi < 0, then run new simulation until $P_i > 0$
- if $P_i > 1$, then run new simulation until $P_i < 1$

As a result of these boundary conditions, the probability density functions of the P_i cease to be normal. Statistical Analysis of the results has been carried out, obtaining the mean (which is a new aggregated value) and the standard deviation.

[7] Not based on real data.

[8] Boundaries might be between -1 and 1.

The pairwise comparison methods (AHP and PCW) cannot be applied directly to cope with variability. Next, an approach of the Analytic Hierarchy Process combined with Monte Carlo is presented.

The AHP attaches weights to criteria and determines how well each alternative scores. If variability is ignored, the scores are unique (single-valued). The AHP aggregation method can be extended with information about variability by combining it with the Monte Carlo method, which takes the range of possible values of the variables and their probability into account. This combination derives in a probabilistic score for each NLW option on the various criteria. It allowed us to evaluate differences in scores but also a possible overlap between them. Figure 3-10 illustrates how the AHP and Monte Carlo approaches are combined (Annex D provides additional detail).

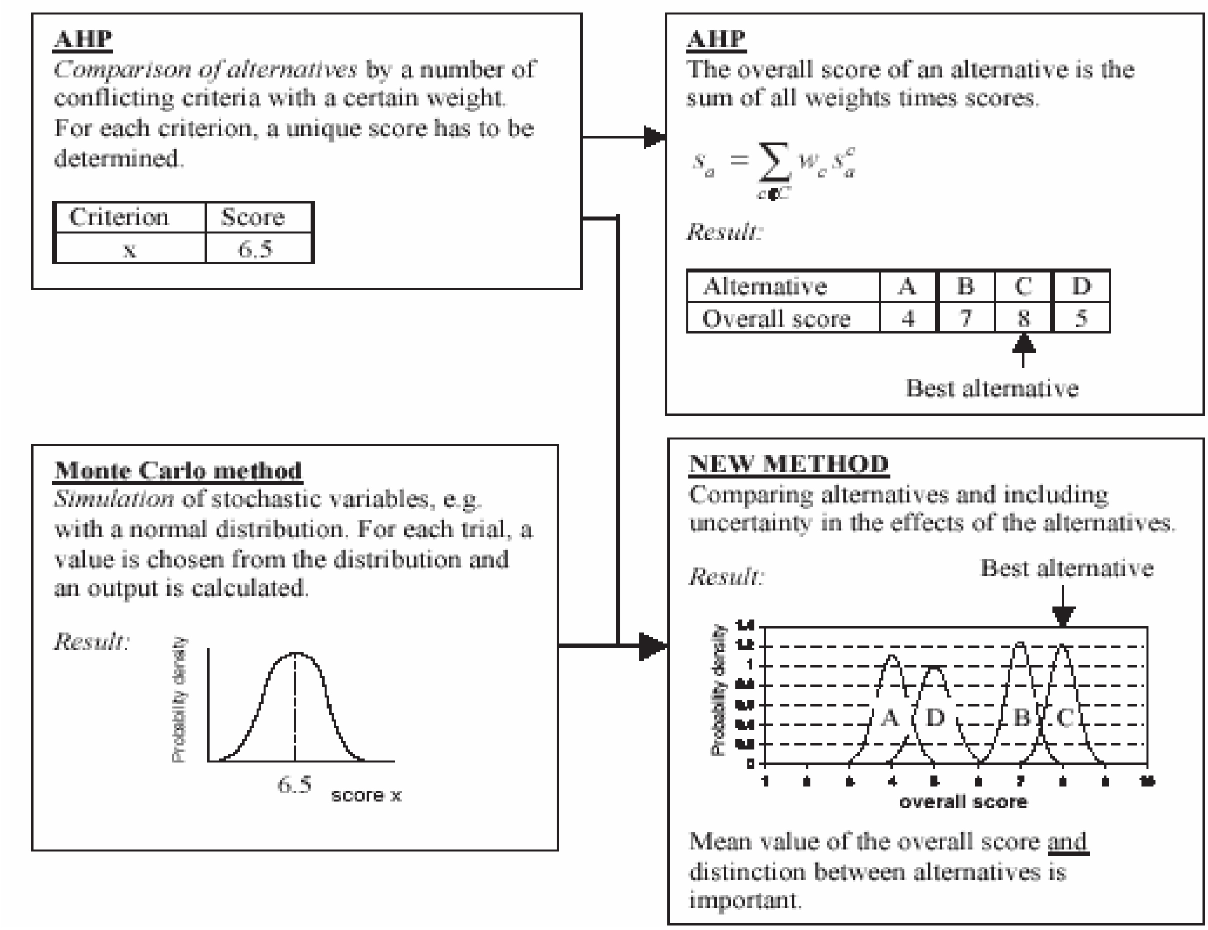


Figure 3-10: Combination of AHP and Monte Carlo Approaches in a New Method[9].

The next step is to apply the aggregation methods[10]. Table 3-16 shows results obtained by the WED, SM and AHP methods, with e = 0.1 and N = 1000 simulations.

[9] "Comparing uncertain alternatives for a possible airport island location in the North Sea Ocean & Coastal Management". Caroline S. van der Kleij, Suzanne J.M.H. Hulscher, Teunis Louters, 2003.

[10] The inputs (P_1) from Table 1-1 are considered.

Table 3-16: Results Obtained by WED, SM and AHP and its MC Combinations

NLW	WED	WED & MC		SM	SM & MC		AHP	AHP & MC	
		Mean (μ)	Dev (σ)		Mean (μ)	Dev (σ)		Mean (μ)	Dev (σ)
Optical Disrupter	0.6372	0.6345	0.0088	0.4786	0.4771	0.0071	0.1933	0.1934	0.0031
Vehicle Stopper (30 mph)	0.5323	0.5261	0.0078	0.2846	0.2812	0.0043	0.0958	0.0959	0.0019
Vehicle Stopper (49 mph)	0.5211	0.5197	0.0097	0.2786	0.2775	0.0055	0.0943	0.0944	0.0018
Vehicle Stopper (70 mph)	0	0	0	0	0	0	0.0247	0.0247	0.0008
Kinetic (Blinis)	0.5949	0.5945	0.0096	0.5072	0.5071	0.0072	0.3424	0.3423	0.0051
Kinetic (12 gauge)	0.4614	0.4615	0.0079	0.3857	0.3859	0.0058	0.2496	0.2496	0.0036

The mean from combining the two methods is approximately equal to the results obtained by the simple methods. However, the combination provides a standard deviation that quantifies the variability of the effectiveness measures. Finally, an example of the representation of the Optical Disrupter (WED-MC) is presented:

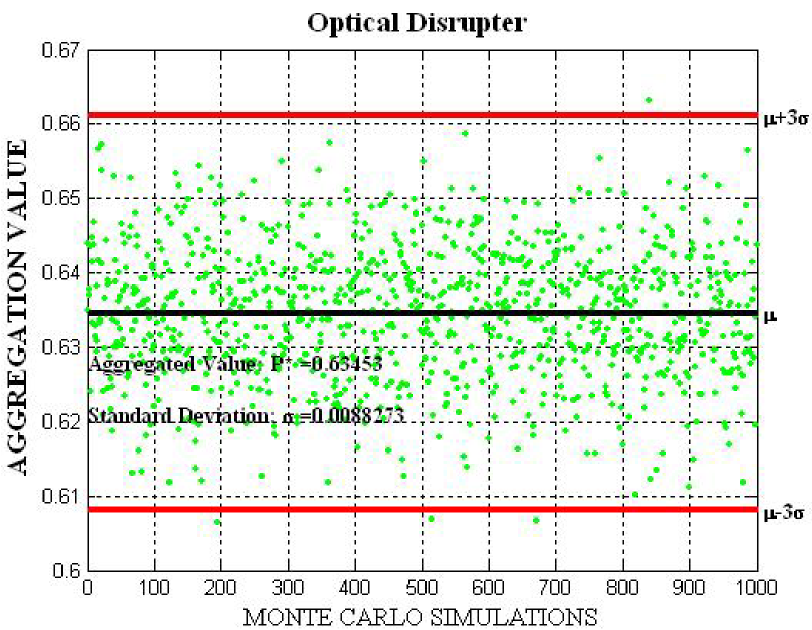


Figure 3-11: WED-MC Variability Representation for the Optical Disrupter.

3.6.3 Uncertainty Treatment: Fuzzy Logic (FL)

Traditional MCDMs require precise input data to determine the preferred alternative based on the performance characteristics of each alternative. Unfortunately, only a limited amount of operational data exists for NLW Effectiveness assessment. Moreover, the limited available data is dependent on the operational conditions, and is characterized by uncertainty, subjectivity, imprecision and ambiguity. Fuzzy sets theory provides a mathematical means to order alternatives according to preference using imprecise, subjective, and uncertain performance characteristics and subjective and ambiguous stakeholder opinions and preferences.

The block diagram of the fuzzy logic application is the following:

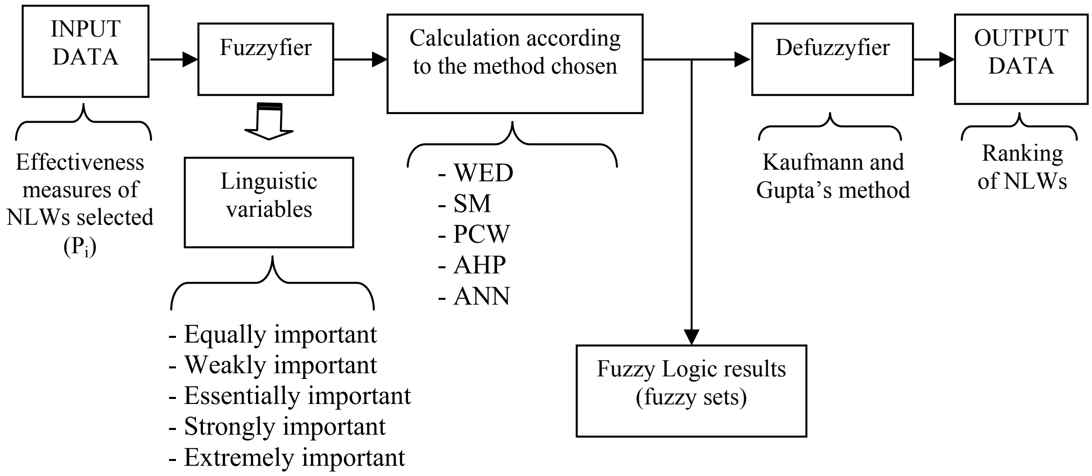


Figure 3-12: Fuzzy Logic Application.

A statement of the Fuzzy Logic Theory is provided in Annex D. The following illustrative example demonstrates the application of fuzzy set concepts. Six alternatives will be evaluated using the seven criteria (BRs). User preferences will also be considered. The objective is to rank alternatives.

The analytical procedure follows the following six steps:

1) Determine the alternatives and relevant criteria to be evaluated. In this case, the alternatives are the NLW from Table 3-4, and the criteria are the BRs.
2) Convert alternative performance measures (P_i) to fuzzy numbers. The uncertainty in the measures is 10% of each MoSE. (The new input matrices – each NLW's P_1 for Red – are shown in Annex D.)
3) Generate stakeholder preference-based criteria weights. The criteria become triangular fuzzy numbers predefined linguistically by the fuzzy logic theory. In this case, all BRs are of equal importance.
4) Apply the corresponding method for the three different matrices (lower, mean and upper) independently.
5) Rank the alternatives using multi-attribute decision making methods.
6) Finally, use the Kaufmann and Gupta's method to rank the fuzzy sets.

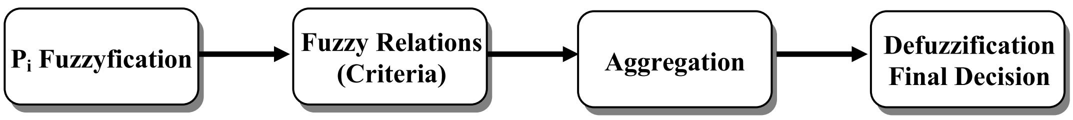


Figure 3-13: Stages of the Fuzzy Application.

Experience has shown that fuzzy logic allows decision making with estimated values in spite of incomplete information. However it should be noted that a decision may not be correct and can be improved later when additional information is available. Of course, a complete lack of information will not support any decision making using any form of logic.

Fuzzy logic may be applied to Neural Networks becoming a Fuzzy-Neural hybrid system that is an efficient method. The work essentially consists of two stages: a Fuzzy system and an Artificial Neural Network system. The initial stage accounts for the uncertainty due to imprecise effectiveness data. The final stage is comprised of classification of the BRs based on the outputs obtained from the trained neural network. Radial Basis Function (RBF) neural networks were applied to fuzzy systems.

The rankings obtained for the different methods are presented in Table 3-17.

Table 3-17: Ranking of Fuzzy Combined with WED, SM, AHP and ANN

NLW	Ranking			
	Fuzzy WED	Fuzzy SM	Fuzzy AHP	Fuzzy ANN
Optical Disrupter	1	2	3	2
Vehicle Stopper (30 mph)	3	4	4	4
Vehicle Stopper (49 mph)	4	5	5	5
Vehicle Stopper (70 mph)	6	6	6	6
Kinetic (Blinis)	2	1	1	1
Kinetic (12 gauge)	5	3	2	3

3.7 AGGREGATION THROUGH PHASES (OPTIMIZING THE USE OF AVAILABLE TYPES OF NLWs THROUGH THE DIFFERENT PHASES OF A MISSION)

In this section, an optimization example of the use of available types of NLWs through the different phases of a mission is presented. It is assumed that one type of NLW is used in each phase (see Annex D). Certain definitions and/or the user criteria are needed to specify the phases' characteristics. These are:

- *Operational Evaluation*: This is important to quantify the relative importance of phases.

  The proposal is to parameterize this input according to the following criteria:

Table 3-18: Operational Evaluation Parameterization

Importance of the Phase	Operational Evaluation	Importance of the Phase	Operational Evaluation
Null/Unnecessary	1 – 10	Essential	51 – 60
Insignificant	11 – 20	Big	61 – 70
Very Small	21 – 30	Enormous	71 – 80
Small	31 – 40	Extreme	81 – 90
Near Essential	41 – 50	Super Extreme	91 – 100

- *Duration*: It is imperative to know the time duration of each phase. Without this information, it is not possible to calculate accurate results.
- *Relative importance*: At times it is useful to weight the importance of accomplishing the task (P_1) relative to associated constraints (P_2). This is only meaningful for Red. Blue and white colours only have P_2.
- *Consumption of ammunition per time unit* per each NLW selected.
- *Maximum availability of ammunition* per each NLW for all the phases.

After defining all the characteristics for the different phases, the aggregation through phases can be undertaken.

Example: USE OF THE ALGORITHM TO OPTIMIZE THE USE OF NLWS THROUGH PHASES (NLWEESS APPLICATION)

This example shows produced by applying the NLWEESS software. This example involves the protection of a military compound. The details of the scenario are in Annex D.

3.7.1 Inputs

Several types of NLW are used to defend the compound, which are distributed among the 10 personnel appointed to the compound protection (control force) as shown in Table 3-19.

Table 3-19: Available NLW

NLW	Technology	Distribution (Soldiers Carrying The NLW)	Unit Consumption (Per Min.)	Total Consumption (Per Min.)	Number Maximum (Available Ammunition)
Optical Disrupter	Optic-Electronic (Laser)	5	1	5	**
Kinetic	Kinetic (Impact)	5	8*	40	450
Malodorant (hand thrown)	Chemical (Irritant)	5	1	5	20
Flash-Bang (hand thrown)	Acoustic-Optic	5	1	5	20
HPM	Electromagnetic	1	1	1	**
Vehicle Stopper	Confinement (Nets)	3	1	3	15

* Time of charge included.

** A near-infinite supply was assumed when evaluating directed energy (optical disrupter and HPM).

The duration and total NLW consumption per phase (if allowed by NLW availability) is shown in Table 3-20. Obviously, NLW availability may constrain total consumption.

Table 3-20: Duration and Total NLW Consumption Per Phase

	Phase 0	Phase 1	Phase 2	Phase 3
Duration of the Phase (min)	10	15	15	10
Optical Disrupter	–	75	75	50
Kinetic	–	600	600	400
Malodorant	–	75	75	50
Flash-Bang	–	75	75	50
HPM	–	15	15	10
Vehicle Stopper	–	45	45	30

The operational evaluation (weighting the relative importance of phases) is shown in the following table:

Table 3-21: Operational Evaluation Per Phase

	Phase 0	Phase 1	Phase 2	Phase 3
Operational Evaluation[11]	–	100	50	100

In the above table, please note that the phases considered more important are:

- Phase 1, because eliminating the threat before it becomes a larger problem is preferred.
- Phase 3, because the threat must be eliminated completely before using lethal weapons, anticipating an increase of violence.

The relative importance of task accomplishment (P_1) versus constraint satisfaction (P_2) is given as the parameter λ. For this example, the values by phase are:

Table 3-22: Relative Importance of P_1 and P_2 Per Phase

	Phase 0	Phase 1	Phase 2	Phase 3
λ (P_1 vs. 1-P_2)	3	0.0	0.5	1

Reversibility is more important (see constraints of the Phase 1) when λ is 0. As the sequence of phases proceeds, reversibility is less significant. Finally in Phase 3, the effects produced on the target are essential and reversibility is not deemed important (see constraints of the Phase 3), so λ is 1.

3.7.2 Results

The aggregation method chosen for this example is AHP. In this case, the most important BRs are Mobility and Motivation (both with a rating of 7), and the other BRs have an importance rating of 1, yielding the following matrix:

[11] The Operational Evaluation is estimated from 0 to 100, following the relationship quali-quantitative presented on page 3-26.

Table 3-23: Matrix of Relative Importance for the AHP

	Mobil.	Commun-ication	Physical Function	Sense & Interpret	Group Cohesion	Identif-ication	Motiv-ation
Mobility	1	7	7	7	7	7	1
Communication	0.1429	1	1	1	1	1	0.1429
Physical Function	0.1429	1	1	1	1	1	0.1429
Sense & Interpret	0.1429	1	1	1	1	1	0.1429
Group Cohesion	0.1429	1	1	1	1	1	0.1429
Identification	0.1429	1	1	1	1	1	0.1429
Motivation	1	7	7	7	7	7	1

The results are as follows:

Table 3-24: Results for One Phase (Red)

	P_1	P_2
NLW 1: Kinetic (Blinis)	0.2268	0.3494
NLW 2: Optical Disrupter	0.1273	0.2077
NLW 3: Vehicle Stopper (30 mph)	0.1178	0.0827
NLW 4: Malodorant	0.0328	0.0079
NLW 5: Flash-Bang	0.2088	0.11
NLW 6: HPM	0.2865	0.2422

According to the aggregated P_1 and P_2 values, the NLW that produces the highest effect on the target is the HPM (highest P_1), whereas the NLW with the best reversibility is the Malodorant (smallest P_2).

The results cover $6^3 = 216$ (number NLW $^{\text{number phases}}$) different combinations. The output file obtained from the simulation with the final results and the specifications used is presented in Annex D. A few combinations are shown to extract some essential conclusions in the table below.

As observed in the previous table, the best combinations use NLW number 1 (Kinetic) in Phase 1 and the Optical Disrupter (NLW 2) in Phase 2. Table 3-25 shows results for all the possible NLW combinations in Phase 3.

Table 3-25: Results of Combinations

Nº comb.	NLW Ph. 1	% of use	Time of use (min)	NLW Ph. 2	% of use	Time of use (min)	NLW Ph. 3	% of use	Time of use (min)	Max.
1	**1**	75	11.25	**2**	100	15	**2**	100	10	125.66
2	**1**	75	11.25	**2**	100	15	**5**	40	4	124.79
3	**1**	75	11.25	**2**	100	15	**6**	100	10	124.26
4	**1**	75	11.25	**2**	100	15	**3**	50	5	123.82
5	**1**	75	11.25	**2**	100	15	**4**	40	4	123.38
6	**1**	75	11.25	**2**	100	15	**1**	0	0	123.12
7	**1**	75	11.25	**4**	26.67	4	**2**	100	10	121.63
…	**…**	…	…	**…**	…	…	**…**	…	…	…
37	**1**	75	11.25	**1**	0	0	**1**	0	0	117.10
38	**2**	100	15	**2**	100	15	**1**	100	10	66.07
39	**2**	100	15	**1**	8.33	1.25	**1**	100	10	63.49
…	**…**	…	…	**…**	…	…	**…**	…	…	…

Combination number 6 raises an issue. The use of kinetic weapons in Phase 3 shows a time of use of 0 minutes (because all kinetic rounds have already been expended). As this also happens in other combinations (see results in Annex D), the results require some filtering. Introducing conditional probability of occurrence through the phases could be a solution to eliminate combinations that aren't possible.

Combinations with the highest rankings (normalized between 0 and 100) are shown in the following graph. All of these highest ranking combinations begin with the use of Kinetic devices (NLW 1). A comparison between the best option "122" and the others can be made easily. For example, the final option shown "111" has a difference of relative value (100 – 92.87 = 7.13%). So, while there are 35 options with higher rankings than "111", there is not a large difference in relative value from the best option ("122").

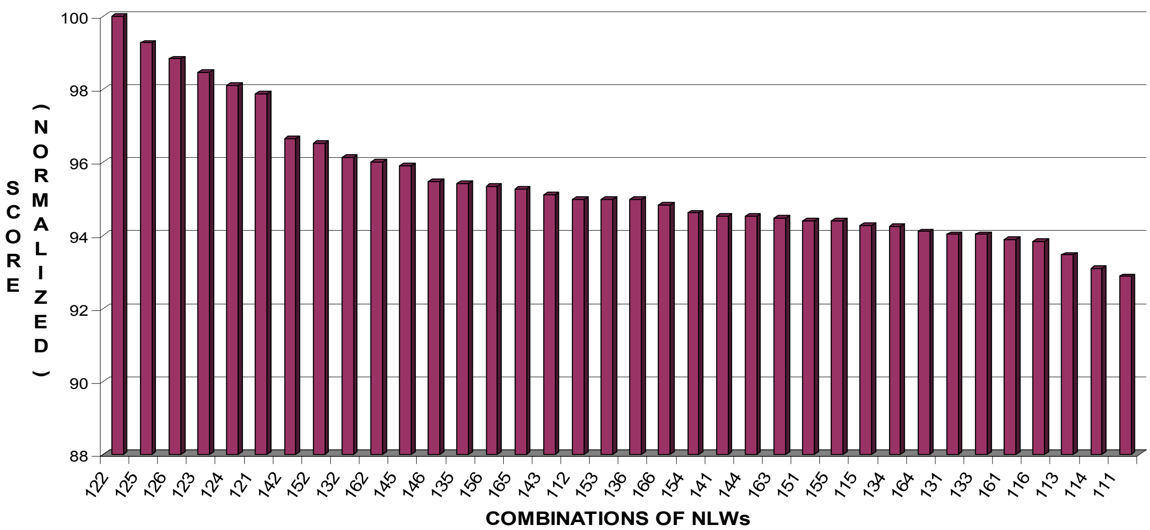


Figure 3-14: Relative Ranking of Combinations.

3.8 TASK 2 CONCLUSIONS AND RECOMMENDATIONS

The main goal of this task was the analysis and development of different aggregation methods for the system effectiveness methodology developed by SAS-035 and refined by SAS-060 (through the efforts of the Task 1 working group).

3.8.1 Conclusions

An algorithm to optimize the use of available types of NLWs through the different phases of a mission has been developed. The results give the best combinations across phases for different available NLW. Thus, the methodology can assist in addressing how a force with different NLW might best achieve its aims and objectives in a particular scenario.

The aggregation methods and algorithms to analyze the best NLW combination have been implemented in a software tool called NLWEESS. Multiple simulations with available and simulated data have been carried out using the NLWEESS tool, with selected results presented this report.

Each phase is related to a probability. This probability is based on the sequence of phases, and the likelihood associated with the scenario ending in a particular phase or continuing on to the next phase, a tree branch of probabilities. The probability of going from one phase to the next is not a strict function of the data but must also be informed by scenario and mission analysis (to include simulation).

One important point to emphasize is that more real data would be useful to validate the aggregation process. Much more data would be needed to support statistically significant test samples and stronger conclusions. The analysis presented in this report has been done mostly with pseudorandom figures – so the results aren’t well suited for direct application, but they have been effective for testing the methods.

3.8.2 Recommendations

Environmental factors could be included in the calculation of aggregated values to get more realistic results according to the specific situation. There has been some discussion about how environmental conditions may influence results. For instance, a flash effect is much greater at night than in the day (and much greater if the optics/eyes are unprotected). Some proposals for addressing environmental factors are in Annex D, but further research will be needed to solve this problem.

The NLWWEES software can support testing of aggregation methods, and continued efforts should be pursued to the extent that data will support.

Finally, a NLW wargame might have significant value, with objectives to:

- Agree on appropriate scenarios and missions;
- Identify the key mission tasks to be undertaken within each scenario;
- Identify the requirements derived from these tasks;
- Identify current NLW capabilities and capability gaps;
- Identify the concepts that were most usefully employed;
- Identify procedural changes that were more appropriate in light of the deployment of these concepts; and
- Provide input for NATO and national defence planning processes.

Wargame issues and opportunities could include:

- Doctrinal considerations;
- Organizational options;
- Training; and
- Analytical support to the assessment of new NLW, new technologies, systems and concepts.

The intended outputs would be a better understanding of:

- How a force using different NLW might best achieve its aims and objectives;
- The strengths and weaknesses of different NLW; and
- Doctrinal strengths and weaknesses.

Chapter 4 – ENHANCING AWARENESS AND COORDINATING WITH OTHER NATO NLW EFFORTS

4.1 INTRODUCTION

The Task 3 working group had two main objectives:

1) Enhance NLW awareness; and

2) Co-ordinate with other NATO NLW efforts.

Associated with the first objective, the working group identified supporting items such as developing and disseminating relevant NLW information materials (information sheets, briefings, etc.) to interested parties. SAS-060 provided this information to other NATO organisations. Individual members provided appropriate information to their respective nations, with some multinational efforts also undertaken, to include the use of existing NLW Information/Data Exchange Agreements (IEAs/DEAs) and the development of new agreements.

The second objective involved:

- The actual conduct of briefings; and
- Interactions with other NATO organisations (with most activity being with Allied Command Transformation, NAAG Quick Reaction Team, and NATO Defence College).

4.2 ACTIONS TO ENHANCE NLW AWARENESS

During the course of SAS-060, the Task 3 working group prepared:

- Briefings:
  - ***NATO and NLW, NLW Effectiveness, and SAS-060 Overviews*** (based on the SAS-035 Final Report and ongoing work of SAS-060) presented on multiple occasions, including to Allied Command Transformation and as a stage setting presentation at the NAAG Quick Reaction Team's kickoff meeting.
  - ***CNAD NLW Exhibition Presentation*** offered in continuous display mode throughout the exhibition.
  - ***National NLW Capabilities Briefings*** presented to Allied Command Transformation.
- Information materials:
  - ***Trifold Brochures*** (prepared by the working group, with graphics and printing support provided by the Norwegian Defence Research Establishment) that have been distributed widely among NATO organisations and member nations.
  - ***Summary Papers*** prepared and disseminated in conjunction with the CNAD NLW Exhibition (most of these related to NLW, and in particular to SAS-060's ongoing work; the Task 3 working group also disseminated, however, an RTO summary at the request of, and provided by, the SAS Panel Executive).
  - ***Posters*** displayed during the CNAD NLW Exhibition.
  - ***NLW Survey***, soliciting inputs for use by SAS-060.

- ***Proposed Workshop Outline*** for NATO Defence College, discussed in greater detail in the next section.
- ***NLW White Paper*** prepared for NATO Defence College and Allied Command Transformation, discussed in greater detail in the next section.

4.3 ACTIONS TO CO-ORDINATE WITH OTHER NATO NLW EFFORTS

Task 3 working group actions to co-ordinate with other NATO NLW efforts obviously and intentionally had overlaps with the actions to enhance NLW awareness. The identified briefings were given in person to Allied Command Transformation, NAAG Quick Reaction Team, NATO Modelling and Simulation Group, SAS Panel, CNAD NLW Exhibition, and multiple Ministries of Defence.

The greatest level of interaction and co-ordination was with ACT, NAAG QRT, and NATO Defence College.

ACT hosted one of the SAS-060 Study Team meetings, and one day of this meeting was devoted to an exchange of briefings. SAS-060 presented background information on NATO and NLW, NLW technologies and capabilities (including detailed presentations and videos offered by several SAS-060 member nations), the work of SAS-035 and SAS-060, and issues and challenges (including the near total gap, outside of RTO studies, in implementing the initial NATO NLW Roadmap). ACT briefed SAS-060 on the command and its reorganisation, transformation initiatives, education and training (including ACT's interest in forwarding the SAS-060 provided NLW information to the Joint Force Training Centre and Joint Warfare Centre), experimentation process, and concept development (where ACT would like to initiate work on a NATO NLW Concept, which is one of the reasons underlying development of the NLW White Paper).

The Task 3 working group not only provided a stage setting brief during the NAAG Quick Reaction Team's kickoff meeting but also provided a great deal of supporting information on NLW technology types, weapon characteristics, performance and effectiveness measures (and some available data), operational requirements and identified capability gaps. One of the NAAG QRT's recommendations is initiation of a SAS-060 follow-on study. The Task 3 working group discussed this with the full SAS-060 Study Team, and this is discussed further in the Conclusions and Recommendations section (Chapter 5).

Finally, the Task 3 working group interacted extensively with the NATO Defence College (NDC) on a NLW Seminar. This seminar, to be hosted in 2008 by NDC, has a proposed outline that is included in Annex E. In addition to the workshop outline, the Task 3 working group also prepared a White Paper to convey NLW issues and opportunities. This NLW White Paper is also included in Annex E.

Chapter 5 – CONCLUSIONS AND RECOMMENDATIONS

5.1 TASK 1

The principal aim of Task 1 was to verify the MoSE methodology. Five non-lethal technologies were assessed and as a result, the MoSE methodology was agreed as being verifiable. Due to a lack of data, the methodology was not fully verified.

The study team identified a number of issues that require further consideration but were satisfied that none were so serious as to pose a threat to the viability of the process. These constraints were:

- **Lack of Orthogonality of the Basis Response Variables**. This relates to the risk of overlap between different variables, leading to double-counting some of the benefits of a given weapon. This issue arose in the cases of the vehicle stopper – where the estimated effects on Mobility and Physical Function measure exactly the same thing – and the Optical Disrupter.

- **Choice of Appropriate Basis Response**. A related issue is the difficulty of selecting the right Basis Response variable to measure the effect of a weapon. This arose in the case of the High Power Microwave weapon, where the effect could equally well be defined in terms of the Communication or Sense and Interpret responses. A more orthogonal and explicit definition of the Basis Responses is a partial solution.

- **Provision of Required Response**. The RR specifies the commander's requirement for the weapon, and should ideally come from military sources. It was felt that commanders would state the target RR in military terms (defeat, seize, secure, deny) whereas the methodology requires the response in terms of a combination of the Basic Responses. This process of translation was not examined in SAS-060.

- **Coupled Effects**. The possibility was identified that, where more than one weapon was used in achieving the same task, the overall effect might be more than the sum of the individual effects. This issue was not assessed during the process of verification.

- **Derivation of MoR from MoP**. MoP were available for all the weapons examined but it was noted that the only ones for which complete MoR were available were those – vehicle stopper and HPM – whose effect is on equipment rather than people. Deriving MoRs for human subjects requires either a validated theory (not known to exist) or experiments, which raise ethical and practical issues. The study had doubts regarding the availability of MoR data.

- **Issues Related to MoSE**. These issues include:
  - MoSE normalisation: in order to calculate the MoSE measures and normalise them to lie within [-1,1] the methodology requires specification of a total time period for the scenario, and upper limits to the effects achieved by the weapon. If the weapon effect does not return to zero in some reasonable time then (as demonstrated by the case of the vehicle stopper) the values of P_2 and P_3 will depend on the time period selected as the length of the scenario, and an agreed method of defining the scenario cut off point is needed.
  - Setting the upper limit did not in practice cause problems in the exercise, but there are at least three issues:
    - In the case of P_1, how to account for cases where the weapon has a greater effect than the specified upper limit.

- In the case of P_2, where the aim is to eliminate the effect as quickly as possible when it is no longer needed, a strong argument can be made that excess effects should be included; but this could lead to a $P_2 < -1$.
- In the case of P_3, there is no obvious way of setting the upper threshold, and hence measure collateral effects. A better approach would be to repeat an analysis of P_1 and P_2 for Red, Blue and White. In this way a series of acceptable effect magnitudes, durations and recovery times could be specified for all actors. This removes the arbitrariness of the "upper magnitude comparison limit" and makes all calculations more logical and defensible.

- **Sensitivity Analysis**. While analysis of the Vehicle stopper data demonstrated the feasibility of sensitivity analysis, the generic use of sensitivity analysis remained an issue as it depended on estimates being available of the relative uncertainty in the various data – RR, MoR and the thresholds used in calculating P_1, P_2 and P_3. The availability of estimates was not examined.

- **Software Implementation**. The SAS-035 report envisioned the implementation of the methodology as a computer tool or model. However the experience of Task 1 would suggest that no single computer tool could meet the needs of all weapon types. Given the ability to specify the MoP, MoR and RR in agreed formats, then a calculation engine could be created which would perform the various calculations for P_1 and P_2. However, uncertainty over the format of data sets and fields would make the creation of such a tool a challenge.

- **Use of Combat Modelling**. The possibility was identified that aggregation methods of deriving MoOE from MoSE would not adequately capture the impact of effects on individual targets during the course of a scenario. In this case, the MoSE measures could only be integrated adequately into a meaningful high level measure of operational success by formal modelling or wargaming of the overall sequence of events.

5.2 TASK 2

The aim of Task 2 was to extend the MoSE methodology by examining methods of aggregation and to assess the feasibility of developing MoOE. Multiple aggregation methods were identified and implemented (but no best one identified). In addition, the team examined data variability and uncertainty using Monte Carlo analysis and Fuzzy Logic, respectively. Finally, a software tool (NLWEESS) was developed by Spain that assessed the algorithm from each method of aggregation in order to determine P_1 and P_2 across phases of a single scenario.

A method of aggregation across phases of a scenario was also developed. This method identifies the best NLW combinations for use in the scenario and offers insight into how a force with different NLWs might best achieve its aims and objectives.

Two challenges for the future are:

- Estimating the probability of a scenario entering each phase. This probability is based on the sequence of phases, and the likelihood associated with the scenario ending in a particular phase or continuing on to the next phase, a tree branch of probabilities. The probability of going from one phase to the next is not just a function of the data but must also be informed by scenario and mission analysis (which may need to include simulation).
- Validation of the aggregation process. Not enough real data was available to conduct such a validation, and the analysis has been done mostly with pseudorandom figures so the results achieved are not appropriate for direct application.

5.3 TASK 3

The aim of Task 3 was to enhance the awareness of NLW and integrate with other NATO efforts. This has been achieved through increased visibility and action, up to CNAD level, with major efforts including support for the CNAD NLW Exhibition, NAAG Quick Reaction Team/Topical Group 3 and the NLW Seminar planned for 2008 at the NATO Defence College in Rome.

5.4 SUMMARY

The overarching conclusion of this study is that the methodology developed during SAS-035 to measure the effectiveness of NLW is a sound basis for further development and has significant potential for analytical and operational use. The study has highlighted a number of issues regarding the methodology that require further investigation, none deemed insurmountable. There remains a fundamental issue regarding the availability of suitable data which can only be met through experimentation, trials and exercises.

Annex A – TERMS OF REFERENCE

Non-Lethal Weapons Effectiveness Assessment Development and Verification Study (SAS-060)

I. ORIGIN

A. Background

NATO has identified non-lethal weapons (NLWs) as a critical additional capability needed in order to meet the demands of future operations. This need has been reinforced in recent peace support operations (as highlighted in conclusions from SAS-041/SAS-048) and in anti-terrorism/counter-terrorism efforts (as discussed in MC472). Although the need for NLWs has been formally recognized, NATO and its member nations still must determine which non-lethal capabilities to develop and field and how best to employ them. NATO has begun to address these issues.

In April 1994, CNAD tasked the NATO research organisation to establish a Specialist Team on Non-Lethal Weapons. The Team examined the feasibility and utility of NLWs in peacekeeping and peace support operations, and identified possibilities for international co-operation in research and development on promising technologies. In 1997 the Council identified the need for a common NATO NLW policy, and in 1999 the draft policy document drafted by the Non-Lethal Weapons Policy Team and the Council approved this as the official NATO NLW policy. In 2000 an Exploratory Team developed a NATO NLW Roadmap in support of Defence Capabilities Initiative Item 2 EE(i). This NATO NLW Roadmap led to the initiation of three studies:

- **NATO NLW Effectiveness Assessment** (SAS-035), which developed Measures of Effectiveness (MoEs) appropriate for assessing system effectiveness.
- **Non-Lethal Technologies and Future Peace Enforcement Operations** (SAS-040), which investigated future requirements for NLWs and the types of technologies that may meet these requirements.
- **The Human Effects of Non-Lethal Technologies** (HFM-073), which is gathering existing information on human effects to support future research.

The Roadmap also called for a follow-on study to continue addressing NLW effectiveness, with the follow-on to begin soon after SAS-035 completed its efforts. SAS-035 confirmed the need for the follow-on study, and the SAS Panel directed an Exploratory Team (ET.AM) to develop plans for the follow-on study.

The importance of NLWs has been noted by SAS-041/048, MC472, the Bi-SC Long-Term Capability Requirements Study, AC/225, Land Group Three on Close Combat Infantry Team of Experts on NLW/ MOUT, Anti-Personnel Land Mine Alternatives (SAS-023), and Land Group Two on Close Combat Armour. Moreover, the SAS-035 follow-on study has received written endorsement from senior operational commanders at the flag officer level.

B. Justification (Relevance for NATO)

The challenges confronting NATO are very different from those that prevailed throughout the Cold War. As seen in ongoing peace support operations in the Balkans and in anti-terrorism/counter-terrorism efforts, NATO is facing new types of threats, undertaking new kinds of missions, performing a broad range of military tasks within difficult operating environments, and conducting these tasks subject to a variety of policy and operational constraints.

As it pursues operational capabilities and concepts consistent with 21st Century demands, NATO needs to:

- Expand the set of tools available to commanders and their forces, so they can match the right tool to the opportunity at hand.
- Exploit the precision offered by NLWs in terms of type and magnitude of effect, onset time, duration, and recovery/reversibility.
- Create asymmetries on the battlefield by developing and employing capabilities that our adversaries lack.
- Be able to assess the effects of NLWs that may be used against NATO forces in the future.

NLWs offer new capabilities across the spectrum of operations (including high-intensity conflict), and NLWs can help meet future operational demands. Before commanders will be comfortable employing NLWs, however, they must understand their effectiveness. SAS-035 developed a methodology for assessing NLW effectiveness, and that methodology now needs to be tested, verified, and extended.

II. OBJECTIVES

A. Scope

Verify and extend the methodology developed by SAS-035.

B. Objectives

The specific objectives of the study are to:

1) Verify the Measures of System Effectiveness (MoSE) Methodology:
   - Identify necessary data types and experiments or experimental guidelines for generating them.
   - Make explicit the process for describing required responses.
   - Verify the methodology, with realistic data for actual system(s) in an operational context, and provide worked example(s).
2) Extend the MoSE Methodology:
   - Address potential uses and associated methods of aggregation.
   - Address confidence levels, including an examination of potential sources of variation and how variations propagate through the methodology’s calculations.
3) Explore development of Measures of Operational Effectiveness (MoOEs):
   - Assess the feasibility of extending the methodology to account for operational effectiveness (i.e., the simultaneous and/or sequential use of one or more systems – non-lethal and/or lethal – to achieve a desired outcome).
   - Develop and explore concepts for assessing operational effectiveness.
4) Enhance awareness of NLW work and integrate with other NATO efforts:
   - Engage with organisations identified in the NATO NLW Roadmap.
   - Conduct briefings for Allied Command-Operations and Allied Command-Transformation and others as appropriate and develop and conduct a seminar/workshop if warranted.

C. Deliverables

Deliverables will be an extended and verified methodology, worked example(s), experimentation guidelines, seminar(s)/workshop(s), interim briefings on key findings, and a Final Report with results and recommendations. Conclusions and recommendations will be briefed through the NATO chain of command. Members are responsible for briefing their respective nations as appropriate.

D. Duration

This will be a 3-year study beginning after formal approval.

III. RESOURCES

A. Membership

Participants are likely to include SAS-035 and Exploratory Team participants – Canada, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Turkey, the United Kingdom, the United States, Allied Command Operations, and Allied Command Transformation – and others who have an interest in NLWs. NC3A participation is desired.

B. National and/or NATO Resources Needed

Each nation is responsible for funding the participation of its own team members. Wherever possible, the team will draw on national programmes and studies. It is the intention to conduct a series of focused working sessions wherever appropriate. There will also be significant work undertaken by small groups or individual nations in between working sessions in order to complete study efforts and required deliverables. Individual nations will be invited to host one or more working sessions. In addition each nation will be asked to identify particular resources that could support the study to include data and funding.

C. RTA Resources

None.

IV. SECURITY CLASSIFICATION LEVEL

The Study Team will determine whether efforts will be classified.

V. PARTICIPATION BY PARTNER NATIONS

Openness to Partner Nations may be precluded by study classification.

VI. LIAISON

The study will draw from previous efforts such as SAS-035, SAS-040 and SAS-041/048 and will co-ordinate its activities with related, ongoing NATO and national study efforts, including HFM-073 and the Land Group Three on Close Combat Infantry Team of Experts on NLW/MOUT.

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14. Abstract

Whether you're in the operating forces making decisions about weapon selection and employment, a planner addressing capability requirements, a modeller analyzing systems or tactics, a system developer working on new weapons, or an acquisition official making program funding decisions, being able to assess weapon effectiveness is of great importance. As a result of SAS-060, there is now a developed and tested methodology for assessing NLW effectiveness.

SAS-060 received the 2008 NATO Scientific Achievement Award for its path breaking contributions. This study and its predecessor (SAS-035) developed an understanding of non-lethal effects, target responses (physical, physiological, and psychological), and effectiveness (comparing actual responses to required responses within an operational context).

The methodology explicitly addresses two components of task requirements: 1) Task accomplishment (what must be done to the target); and 2) Constraint satisfaction (what must not be done, with respect to the target or to others (own force, non-combatants, infrastructure, etc.)). The methodology applies graphical comparison techniques to quantify the degree to which a NLW addresses task accomplishment and constraint satisfaction. And, it does so with respect to seven target factors: mobility, communications, physical function, ability to sense and interpret, group cohesion, motivation, and identification.

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