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Quantifying Risk for Determining Optimal Joint Fires in Defence Planning

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***Abstract*—As the first step for a NATO System Analysis Study task on *Methods to Support Decision Making in Joint Fires*, this paper identifies the critical element of this task and develops a method for quantifying the risk of Collateral Damage. As a supplement to the current NATO Collateral Damage Estimation, this quantification methodology recognizes that the risk of Collateral Damage may vary with usage of different weapon and ammunition combinations even though the target is the same. Therefore, the weapon and ammunition characteristic properties were considered for this Collateral Damage quantification. This risk quantification methodology will help inform decision making on selecting optimal Joint Fires in Defence Planning.**

Keywords—risk; collateral damage; quantification; defence.

I. BACKGROUND

A. NATO task

At the NATO System Analysis and Studies (SAS) Panel Business Meeting (PBM) in February 2013, the SAS panel approved the formation of an Exploratory Team to examine issues related to *Methods to Support Decision Making in Joint Fires*[1].

First, during operations, there is a strong need for system support to select the most effective joint combination of platform-weapon-ammunition available in the theatre to achieve a given objective [1].

Second, because military operations are aimed at contributing to safety, the use of Joint Fires not only has to be effective but also proportionate [1]. This is asking for a trade-off between maximizing the effectiveness and minimizing the operational risks. The urge of minimizing operational risks is stressed by the uncertainty in targets and changing objectives.

Besides the considerations of the two aspects above, there is an increasing interest of efficiency of Joint Fires, i.e., effectiveness at the lowest possible cost [1], especially under the world's current economic situation. This is asking for a trade-off between maximizing effectiveness and minimizing the cost.

Both trade-offs are not easy to make; moreover, an integral trade-off between effectiveness, operational risks and cost, is truly a challenge [2].

B. Current situation from participating nations

Representatives from participating nations attended the first Exploratory Team meeting in September 2013 in NATO. Each of them presented their national work and some of them also presented NATO work done in the area. The conclusion was the same: there was no method for determining optimal Joint Fires by considering effectiveness, cost and risk all three factors.

II. CHALLENGE AND SOLUTION

A. Step 1- Find out the critical element

The desired output of the task group is a methodology which can evaluate various platform-weapon-ammunition combinations to support decision making on selecting the optimal combinations in a joint and/or coalition framework to obtain the desired results against a given threat taking into account operational risks and costs. First, it is a complicated question to begin with.

Furthermore, except for the complexcity introduced by the varieties of platforms, weapons and ammunition natures involved, how to consider cost, effectiveness and risk into selecting optimal Joint Fires is a challenge.

In order to take these three factors into consideration for determining the optimal Joint Fires, there is a need to measure these three factors. Measuring these factors is not straight forward, especially for quantifying the risk in advance.

Moreover, according to the findings from relevant work done in participating nations, as well as NATO, cost and effectiveness were better studied in this area. NATO even has an existing tool, i.e., Allied Command Resource Optimization Software System (ACROSS), which can select weapons and munitions for a given target based on optimizing both cost and effectiveness. However risk was less studied, especially the trade-off involving the risk for selecting optimal Joint Fires.

Above all, the author believes among all the three factors, risk is the critical element for this specific task. .

[1] Fires produced during the employment of forces from two or more components in coordinated action toward a common objective (http://www.thefreedictionary.com/joint+fires.)

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B. Step 2 - Simplify the question by focusing on the most important aspect of risk

"Make things as simple as possible, but not simpler."

– Albert Einstein

Simplifying the question is often the key to success.

There are many aspects of risk under this content. Here only major ones are listed, e.g., risk of affordability, risk of running out of ammunition, risk of collateral damage, and risk of operational success. In order to clear this bottleneck for this specific task, the author believes it is necessary to simplify the question by focusing on the most important aspect of risk.

For the direction of the task group in the next step, the author would suggest simplifying the question through focusing on the risk of Collateral Damage (CD). The reason is twofold:

- First, CD becomes more and more a concern to military operations, especially in the modern wars. The International Law, which includes the Law of Armed Conflict (LOAC), requires the pre-planned attacks, whether in offence or in defence, be subjected to an assessment (including checks and balances) to ensure that the expected CD is not excessive in relation to the concrete and direct military advantage anticipated [3].
- Furthermore, both the risk of affordability and risk of running out of ammunition are related to the financial aspects, therefore these aspects can be integrated into the consideration of the cost. And risk of operational success can be integrated into the consideration of the effectiveness. The only major aspect of risk left is CD; therefore it has to be considered.

In the following paper, the focus will be the CD. The US military provided a simple definition of CD: "the Collateral Damage is used in regards to unintentional or incidental damage to civilian property and non-combatant casualties.[2]"

Once the aspect of the risk is determined, the next question is, how to quantify the risk, i.e., how to quantify the CD?

C. Step 3 - Determine the method to quantify the risk

The current CD estimation methodologies used in NATO is dependent on the target only. NATO Collateral Damage Estimate (CDE) methodology is based on five progressive and ascending CDE levels expressing the risk estimation of CD based on the distance of civilians and civilian property to the selected Target Installation Boundary (TIB) [3]. The closer the target to the civilian and civilian property, the higher level of the CD estimated. The current Canadian CDE [4] used the similar methodology as NATO's, the slight difference is the Canadian CDE is based on four progressive and ascending CDE levels [4].

There are three shortcomings of this methodology:

- The CDE is only dependent on the distance of civilians and civilian property; the number of civilians and the value of the civilian property are not reflected into the CDE;
- The usage of different weapons-munitions is not considered in the CDE; and
- The CDE uses a five-level rank classification. It is a broad categorization, which does not recognize the difference within the same level. The detailed information is missing.

The purpose of this work is to develop a new risk quantification methodology to address the above shortcomings and provide a supplement to the current NATO CDE.

III. Concept and Statistics of Ballistic and Ammunition

Since we will discuss the risk quantification related to firing, let's first start with introducing some relevant concepts and statistics around Ballistic and Ammunition. The following is referenced mostly from [5] and [6].

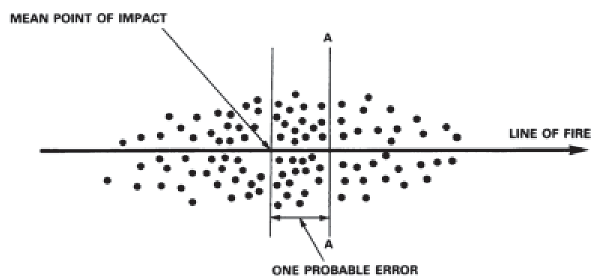

Figure 1: Dispersion and Probable Error (Figure 7-3-3 in [5])

Dispersion

It is found that if a number of rounds of the same caliber and same lot of ammunition are fired from the same weapon with the same settings in quadrant elevation and bearing, the round will not all fall at a single point but will be scattered in a pattern of bursts. This natural phenomenon of change is called Dispersion[3].

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[2] Some definitions of CD include the damage to the environment aspect, which is not in the scope of this paper.

[3] It is noted that dispersion is the results of minor variations of many elements from round to round and must not confused with variations in point of impact caused by mistakes or constant errors.

Mean Point of Impact (MPI)

MPI is the point whose coordinates are the arithmetic means of the coordinates of the separate points of impact/burst of a finite number of projectiles fired or released at the same aiming point under a given set of conditions (see Figure 1).

Probable error (*PE*)

If the distance from MPI to line A (see Figure 1) is a measure of error, it is clear that half of the rounds have a greater error and half of the rounds have a lesser error. The distance from MPI to line A is the PE. It is a mathematical fact that for any normal distribution, a distance of four *PEs* on either side of the MPI will include virtually all the rounds in the pattern[4].

Range Probable Error (PE_r)

The approximate value of the probable error (see Figure 1) in range is PE_r. It can be taken as an index of the precision of the weapon and ammunition. According to the mathematic approximation, the PE_r can be calculated as one-eighth the length of the dispersion pattern at its greatest length. The value of the respective PE_r for the weapon, charge and range being used can be found in the Firing Tables [7]. The PE_r can also be calculated based on the data obtained from firing of the specific weapon and ammunition.

Deflection Probable Error (PE_d)

The directional error, caused by dispersion, will be exceeded, as often as not, in an infinite number of rounds fired at a single deflection. Similar as PE_r, PE_d can be taken as an index of the precision of the weapon and ammunition as well. It is one-eighth the width of the dispersion pattern at its greatest width. The value of the respective PE_d for the weapon, charge and range being used can be found in the Firing Tables [7]. The PE_d can also be calculated based on the data obtained from firing of the specific weapon and ammunition.

Single Shot Hit Probability (P_{SSH})

The Single Shot Hit Probability is the probability of hitting a target or area of finite dimensions with any one round. The probability of a round hitting in any one of the areas bounded by one PE_r and one PE_d is the product of the probability of not exceeding that deflection error. This basic principle is applied in computing the P_{SSH}. The value of P_{SSH} (calculated from PE_r and PE_d) can be taken as an index of the precision of the weapon and ammunition as well. The higher the P_{SSH}, the more precise the weapon-ammunition is.

Assurance (P_A)

Assurance is a broad term associated with the probability of hitting a target with any given number of rounds, assuming a constant P_{SSH}.

[4] This is not precisely true, since a very small fraction of the rounds (approximately 7 out of 1000) will fall outside four *PEs* on either side of the MPI but it is true for all practical purposes.

IV. Risk Quantification

As defined earlier, the CD is used in regards to unintentional or incidental damage to civilian property and non-combatant casualties (i.e., civilian casualties).

Therefore, the author determined to investigate the risk quantification of CD in threefold, i.e. quantification of risk for civilian casualty, civilian property damage, and total CD.

In order to obtain certain desired assurance in missions, multiple shots are often planned. Therefore, this section provides not only the quantification of risk caused by a single shot hit but also the estimation of risk quantification caused by a number of shots to achieve a desired assurance. The following shows the structure of section IV:

- Risk quantification of civilian casualty;
  - Risk quantification of civilian casualty caused by a single shot
  - Risk quantification of civilian casualty caused by a number of shots to achieve a desired assurance
- Risk quantification of civilian property damage; and
  - Risk quantification of civilian property caused by a single shot
  - Risk quantification of civilian property caused by a number of shots to achieve a desired assurance
- Risk quantification of the total CD.

A. Risk quantification of civilian casualty

1) Risk quantification of civilian casualty caused by a single shot

Let P_{SSH} denote the probability of hitting a target with any one round shot and R_{CC} denote risk of Civilian Casualty. In general, the higher the P_{SSH}, the lower the R_{CC} [5].

Let A_{WER} denote the area within the Weapon Effective Radius. The smaller the A_{WER}, the lower the R_{CC}.

Let N_{In} denote the number of civilians in the target and D_{Out} denote the density of civilian population outside the target area. The lower the N_{In} and D_{Out}, the lower the R_{CC}.

And lastly, let CR_{Ammo} denote the civilian Casualty Rate caused by the burst of a single shot of specific ammunition.

As a weapon system delivers rounds on a specific target, it would not be possible to know in advance the exact location where the round would bust, e.g., whether the point of impact (note: not the MPI) is on the target or away from the target. It is a random event. So how can the risk of CD be quantified / estimated in advance when planning to use a

[5] The unknown civilians in the target are not accounted in this case.

specific weapon and ammunition system to tackle a specific target?

The author believes the solution to this is to use the information of probability distribution of hit (either known or calculated) to work out the expected value of the risk. Another decision made is to use counts of civilian lives in risk as the measurement for risk quantification in this aspect.

Since P_{SSH} is the probability of a single shot hit, the probability of a single shot not-hit is then $1- P_{SSH}$. Two events may occur once a single shot is delivered: one is this single shot hits the target; another one is the single shot misses the target. Now let's discuss the risk of civilian casualty under two opposite events.

It is assumed when the target is hit, all the civilians within the target will be at risk. It is also assumed when the target is missed, the civilians outside the target will be in risk; more specifically, the civilians within the Weapon Effective Radius are at risk.

Therefore the expected value of risk for civilian casualty caused by a single shot can be calculated as follows (An additional assumption here is the civilian population density outside the target is uniform.):

$$R_{CC}= P_{SSH} \times N_{in} \times CR_{Ammo} + (1 - P_{SSH}) \times D_{out} \times A_{WER} \times CR_{Ammo} \quad (1)$$

When $CR_{Ammo} = 1$, the R_{CC} will reach its maximum value[6] under this circumstance, i.e.,

$$R_{CC}= P_{SSH} \times N_{in} + (1 - P_{SSH}) \times D_{out} \times A_{WER} \quad (2)$$

Similarly as assumed in the NATO document [1], the unknown civilians or civilian property in the target area are not accounted for, therefore, $N_{in}=0$. Then formula (1) and (2) can be simplified as:

$$R_{CC}= (1 - P_{SSH}) \times D_{out} \times A_{WER} \times CR_{Ammo} \quad (3)$$

$$R_{CC}= (1 - P_{SSH}) \times D_{out} \times A_{WER} \quad (4)$$

When the target is known and the weapon and ammunition are chosen, D_{Out}, A_{WER} and CR_{Ammo} can be obtained. Then, the next step is to work out the P_{SSH} for the given weapon and ammunition against the specific target. In this paper, a surface and rectangular shaped target is considered. Shown as an example in Figure 2, the target is represented by a *L* by *W* rectangle, where *L* and *W* denote the length and width of the target with long axis parallel to the bearing of the fire.

For quantifying the risk in advance, it is necessary to assume that there is no human error when firing the system and therefore, the MPI of rounds delivered is on the center of the target. For the rectangular target, the center of the target is the intersection of the two diagonal lines.

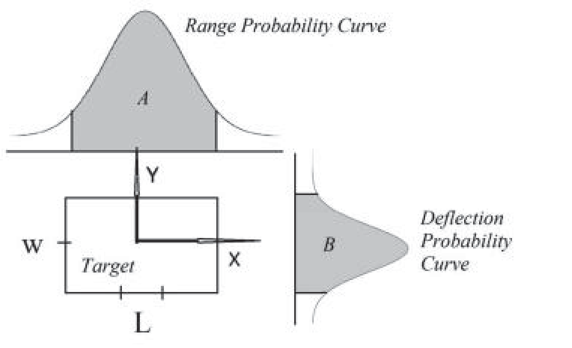

Figure 2: Range and deflection probability curve and an example of a rectangular target

As re-occurring events will obey the Law of Random Distribution (LRD), it is well observed that pattern of burst on the ground can be represented by a normal probability distribution at both range and cross range (deflection) direction (See the range probability curve and deflection probability curve in Figure 2).

The area under the range/deflection normal probability curve represents the probability of x/y occurring in certain range/deflection.

As defined earlier, P_{SSH} is the probability of single shot hit. For the example in Figure 2, P_{SSH} is the probability of hitting the target with any one round, i.e., probability of shingle shot hit of a *L* by *W* rectangular area. Assuming independence between the range and deflection errors, the P_{SSH}, the probability of single shot hit of the target can simply be calculated as the product of the range and deflection probabilities [6] (The computation of P_{SSH} can be found in [5] and [6]), i.e.,

$$p(x, y) = p(x)p(y) \quad (5)$$

Where

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left[-\frac{x^2}{2\sigma_x{}^2}\right] \quad (6)$$

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left[-\frac{y^2}{2\sigma_y{}^2}\right] \quad (7)$$

The basic principal is applied in computing the P_{SSH} for the target bounded by *L* and *W*. Therefore,

[6] In this paper, only the primary effect of the attack is considered.

$$P_{SSH} = \int_{-L/2}^{L/2} p(x)dx \int_{-W/2}^{W/2} p(y)dy \quad (8)$$

$$P_{SSH} = A \times B \quad (9)$$

Where A is the range probability and B is the deflection probability (see Figure 2). Since both range and deflection errors are normally distributed, the normal probability table can be used to determine the range probability and the deflection probability. Figure 7-3-8 in [5] listed a normal probability table, in which areas of the normal probability curve can be determined by entering the quotient, where the quotient is the limits of error (*L/2* and *W/2* for this specific target) divided by the respective *PEs* (i.e., PE_r and PE_d) for the weapon, charge and range being used. The approximate values of the *PEs* can be found in the corresponding reference, e.g., Fire Tables [6]. Instead of searching in the Fire Tables [6], the *PEs* can also be calculated directly based on the data obtained from firing of the specific weapon and ammunition.

Substitution of Formula (8) into Formula (3) results in an expression for the expected value of risk of civilian casualty caused by a single shot,

$$R_{CC} = (1 - \int_{-L/2}^{L/2} p(x)dx \int_{-W/2}^{W/2} p(y)dy) \times D_{out} \times A_{WER} \times CR_{Ammo} \quad (10)$$

This risk quantification methodology takes into consideration not only the information around the target, e.g., the measurers of the target, the civilian population around the target, but also weapon-ammunition characteristic properties, e.g., precision of the weapon-ammunition, i.e., P_{SSH} (as well PE_r and PE_d in the determination of P_{SSH}) and ammunition effectiveness, i.e. A_{WER} and CR_{Ammo}.

According to Formula (10), the higher the P_{SSH}, i.e., the higher the probability of single shot hit on the target, the lower the risk of civilian casualty. The lower the D_{Out}, i.e., the lower the civilian population density around the target, the lower the risk of civilian casualty; The smaller the A_{WER}, i.e., the smaller the Weapon Effective Radius, the lower the risk of civilian casualty; lastly, the lower the CR_{Ammo}, i.e., the lower the Casualty Rate of the specific ammunition, the lower the risk of civilian casualty.

2) Risk quantification of civilian casualty caused by a number of shots to achieve a desired assurance

Let n denote the number of shots delivered. It is logical to think of that before all the civilian get killed, the more the shots, the higher the risk of civilian casualty.

As we have already worked out the risk of civilian casualty caused by a single shot, as in Formula (10), let's calculate the total risk if a second shot is fired.

In addition to the assumption of a constant P_{SSH}, it is assumed that the point of impact of the second shot is not on the point of impact of the first shot. Furthermore, there is no overlap between the Weapon Effective Area of the second shot and the Weapon Effective Area of the first shot.

Under these assumptions, the expected risk of the civilian casualty caused by the second shot can be determined using the same calculation, i.e. Formula (10).

Therefore, the total risk of the civilian casualty for two shots will be:

$$R_{CC} = 2 \times (1 - \int_{-L/2}^{L/2} p(x)dx \int_{-W/2}^{W/2} p(y)dy) \times D_{out} \times A_{WER} \times CR_{Ammo} \quad (11)$$

Therefore, before all civilians get killed, the risk of civilian casualty will be cumulated if more shots are delivered. The risk of civilian casualty caused by multiple shots (denoted by n), can be simply calculated as:

$$R_{CC} = n \times (1 - \int_{-L/2}^{L/2} p(x)dx \int_{-W/2}^{W/2} p(y)dy) \times D_{out} \times A_{WER} \times CR_{Ammo} \quad (12)$$

As introduced in Section II, Assurance is a broad term associated with the probability of hitting a target with any given number of rounds (denoted by P_A), assuming a constant P_{SSH} [5].

In order to achieve certain desired assurance, a number of shots are planned to be delivered. As derived in [5] and [6], the Assurance can be calculated as Formula (13).

$$P_A = 1 - (1 - P_{SSH})^n \quad (13)$$

For the risk quantification purpose, n, i.e., number of shots required to achieve the desired Assurance needs to be calculated. Using the inverse function, n can be calculated as,

$$n = \log_{(1-P_{SSH})}(1 - P_A) \quad (14)$$

Substitution of Formula (14) into Formula (12), the risk of civilian casualty caused by a number of shots to achieve a desired assurance leads to

$$R_{CC} = (\log_{(1-P_{SSH})}(1 - P_A)) \times (1 - \int_{-L/2}^{L/2} p(x)dx \int_{-W/2}^{W/2} p(y)dy) \times D_{out} \times A_{WER} \times CR_{Ammo} \quad (15)$$

According to Formula (15), the higher the P_{SSH}, the fewer rounds required to achieve a desired assurance[7], therefore, higher P_{SSH} results in a less risk through less round required.

In reality, since human being will react after the first shot, the casualty rate can be lower than that for the first shot.

When $CR_{Ammo}=1$, the maximum risk of civilian casualty under this circumstance is:

[7] The higher the P_{SSH}, the smaller ($1-P_{SSH}$). However, since $0<(1-P_{SSH}) < 1$, for the log function as in Formula (14), a higher P_{SSH} will result in a smaller n.

$$R_{CC}= (\log_{(1-P_{SSH})}(1-P_A))\times(1-\int_{-L/2}^{L/2}p(x)dx\int_{-W/2}^{W/2}p(y)dy)\times D_{out}\times A_{WER} \quad (16)$$

B. Risk quantification of civilian property

1) Risk quantification of civilian property caused by a single shot

As assumed earlier, the unknown civilians or civilian property in the target area are not accounted for, therefore, similar to the calculation of risk for civilian casualty, only the civilian properties outside a target is considered.

It is decided to use the value of the civilian properties in risk as the measurement of the risk of this aspect.

Let R_{CP} denote the risk of civilian property damage. Let V_{OutSS} denote the value of the civilian pproperty, which is outside the target hit by a single shot. Therefore, the expected risk of civilian property damage can be calculated as:

$$R_{cp}= (1-P_{SSH})\times V_{OuttSS} \quad (17)$$

However, due to the random process, it is not possible to know in advance which civilian property (if more than one civilian properties surround the target area) will be hit by a single shot. To conquer this uncertainty, the author uses the average value of the civilian property per unit of area.

Let V_{ttlCP} denote the total value of civilian property around the target, which is at risk.

Let A_{ttl} denote the total area around the target, which is at risk. Hence, the average value of the civilian property per unit of area can be expressed by:

$$\overline{V}_{CP}=\frac{V_{ttlCP}}{A_{ttl}} \quad (18)$$

Let D_{Ammo} denote the Damage Rate of the property by specific ammunition. Then, the R_{CP} is quantified by

$$R_{cp}= (1-P_{SSH})\times\overline{V}_{CP}\times A_{WER}\times DR_{Ammo} \quad (19)$$

Where P_{SSH} can be obtained from Formulas (8) and (9).

When $D_{Ammo}=1$, that means the civilian property will be completely damaged.

$$R_{cp}= (1-P_{SSH})\times\overline{V}_{CP}\times A_{WER} \quad (20)$$

2) Risk quantification of civilian property caused by a number of shots to achieve a required assurance

Let *n* denote the number of shots delivered. It is logical to think of that before all civilian properties get destroyed, the more the shots, the higher the risk of civilian property damage.

As we have already worked out the risk of civilian property damage caused by a single shot, as in Formula (19), let's calculate the total risk if number of shot are fired.

In addition to the assumption of a constant P_{SSH}, it is assumed that there is no overlap among all the Weapon Effective Areas generated by all the shots. Then, the risk of civilian property damage caused by multiple shots (*n*) can be calculated as

$$R_{cp}= (1-P_{SSH})\times\overline{V}_{CP}\times A_{WER}\times n\times DR_{Ammo} \quad (21)$$

Substitution of Formula (14) into Formula (21), the expected risk of ccivilian pproperty caused by a number of shots to achieve a required assurance can be computed as following:

$$R_{cp}= (1-P_{SSH})\times\overline{V}_{CP}\times A_{WER}\times\log_{1-SSHP}(1-P_A) \quad (22)$$

In summary, Formulas (19), (21) and (22) provide a quantification of risk of the civilian property damage caused by a single shot, multiple shots and a number of shots to achieve a required assurance. Identical as the risk quantification for the civilian casualty, this risk quantification methodology takes into consideration not only the information of the target, e.g., the measurers of the target, the civilian property around the target, but also the weapon-ammunition characteristic properties, e.g., precision of the weapon-ammunition, i.e., P_{SSH} (as well PE_r and PE_d in the determination of P_{SSH}) and ammunition effectiveness, i.e., A_{WER} and DR_{Ammo}.

According to the formula, the higher the probability of single shot hit on the target, the lower the risk of civilian property. The less number and lower the average value of civilian properties around the target, the lower the risk of civilian property damage. The smaller the Weapon Effective Radius, the lower the risk of civilian property damage. Lastly, the lower the Damage Rate caused by specific ammunition, the lower the risk of civilian property damage.

C. Total Risk of Collateral Damage

How to get a holistic view of the risk of CD for a specific target if a specific weapon and ammunition combination is chosen.

Apparently, the total risk of the CD combines the risk of civilian casualty and the risk of civilian property damage. However, one is measured by number of civilians at risk; another is measured by value of the civilian property at risk. But can we go further?

The potency of life (or cost of life) is an economic value assigned to life in general, or to specific living organisms. In social and political sciences, it is the marginal cost of death prevention in a certain class of circumstances [8]. As such, it is a statistical term, the cost of reducing the average number of deaths by one [8]. This cost of life can be a surrogate solution to our question here. Since there is a cost value associated with a human life, we will be able to combine two components of CD together (both in cost), to get a total risk estimation for the CD.

According to [9], the cost value of a human life is about 4 to 10 million dollars per person, with an average value of life in the vicinity of $7 million[8].

This section provides risk quantifications of civilian casualty and civilian property damage separately. If there is a need for a single number estimation of the total risk of CD, the risk of civilian casualty can be multiplied by the value of life cost and then combine with the risk of civilian property damage.

V. Summary and Future Direction

As the first step for a NATO System Analysis Study task on Methods to Support Decision Making in Joint Fires, this paper

- identifies the critical element of this task;
- suggests a way to simplify the question;
- develops a method to quantify the risk of the civilian casualty and civilian property damage, which can be used in the planning phase (i.e., in advance);
- This paper also suggests a possibility if an overall CD estimation is needed when considering all factors into optimizing Joint Fires by providing a meaningful way to integrate both risk in life and risk in civilian property;
- As a supplement to the current NATO CDE (a five level category), this quantification method recognizes that the risk of CD may vary with usage of different weapon and ammunition combinations even though the target is the same. Therefore, the weapon and ammunition characteristic properties were considered into this new CD quantification. Hence, this risk quantification method is able to not only calculate the risk based on the information related to the target but also differentiate the risk according to the choice of the weapon and ammunition. This risk quantification certainly can provide more information to the defence planner than the current five-level NATO CDE.

During the Defence Planning phases, it is not avoidable that we will face lots of uncertainties. This risk quantification method uses the statistic property to address these unknowns. Hence, the risk can be quantified in advance based on the information about the target and the weapon-ammunition planned to be used. Furthermore, the risk quantification will enable comparisons between choices of different weapon-ammunition combinations when determining optimal Joint Fires for Defence Planning. This new risk quantification method will enable selecting the optimal Joint Fires in Defence Planning based on the risk consideration required for the task.

[8] The figures are generated based on the U.S. population.

In the recent review of Stockpile Planning User of Requirements (UOR) for the NATO Defence Planning Process (a review for the NATO Stockpile Planning Committee), the author suggested the risk, especially the aspect of CD, should be taken into consideration in the Stockpile Planning. For example, the requirements of different ammunition natures may significantly change due to the consideration of risk of CD for the future Defence Planning. This recommendation has been accepted and implemented into the latest Stockpile Planning UOR of NATO. The risk quantification which can differentiate the risk by different weapons and ammunition can make this proposal possible; and should be a way to go.

This paper provides a direction of risk quantification. The method developed in this paper can be generalized to a point target instead of the rectangular target, as well on a space target instead of the surface target.

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