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COMMON RELEVANT OPERATIONAL PICTURE: AN ANALYSIS OF EFFECTS ON THE PROSECUTION OF TIME-CRITICAL TARGETS

by

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March 2002

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COMMON RELEVANT OPERATIONAL PICTURE: AN ANALYSIS OF EFFECTS ON THE PROSECUTION OF TIME-CRITICAL TARGETS

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ABSTRACT

The conceptual template laid out in Joint Vision 2010 called for leveraging technological opportunities to achieve new and higher levels of effectiveness in a joint operating environment. Born out of this concept the U.S. Joint Forces Command developed a concept – the Common Relevant Operational Picture, or CROP. It is a presentation of timely, fused, accurate, assured and relevant information. The CROP concept addresses battlespace awareness, information transport and processing, combat identification and joint command and control – four of the six high priority challenges identified by the Joint Staff for the 21st century. This thesis investigates CROP, comparing and contrasting it to uncoordinated separate service systems in a time-critical targeting setting. The Measures of Effectiveness (MOEs) used are the time to kill a target and the number of weapons expended. Previous work on this problem used an analytical model with some simplifying assumptions concerning processing time latency following target detection. In this thesis, a simulation is used to investigate the validity of some of the analytical model assumptions. The simulation also extends the model for more general command and control time distributions and models Battle Damage Assessment. The results provide distributional information about the MOEs, showing how improvements in information sharing and optimal weapons assignment due to CROP can improve systems performance. However, this improvement is lost if processing time latency under CROP is too long.

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EXECUTIVE SUMMARY

The conceptual template laid out in Joint Vision 2010 called for leveraging technological opportunities to achieve new and higher levels of effectiveness in a joint operating environment. Born out of this concept the U.S. Joint Forces Command developed a concept – the Common Relevant Operational Picture, or CROP. It is a presentation of timely, fused, accurate, assured and relevant information. The CROP concept addresses battlespace awareness, information transport and processing, combat identification and joint command and control – four of the six high priority challenges identified by the Joint Staff for the 21st century. This thesis investigates CROP, comparing and contrasting it to an uncoordinated separate services system in a time-critical targeting setting.

Previous work on this problem used an analytical model with some simplifying assumptions concerning processing time latency following target detection. In this thesis, a simulation is used to investigate the validity of some of the analytical model assumptions. The simulation also extends the model for more general command and control time distributions and models Battle Damage Assessment (BDA). The simulation is written in Visual Basic for Applications (VBA) and uses Microsoft Excel for input and output of data.

The models include several services, with their respective sensor systems and weapons systems, and several target types. Model inputs include random times to detection for each sensor system, probabilities of kill for each weapon system against each target type, probabilities that sensors classify target types either correctly, or misclassify targets as other target types, probabilities of accurate BDA, random times until targets are lost or hide (representing the time criticality of engagement before loss), and random times for processing target information and engaging.

The Measures of Effectiveness (MOEs) used here are the time to kill a target and the number of weapons expended. The results provide distributional information about the MOEs, showing how improvements in information sharing and optimal weapons

assignments due to CROP can improve system performance. The distributional information also allows risks of unfavorable events to be assessed.

The verification part of this thesis shows excellent agreement between the analytical model and the simulation. A simplifying assumption of the analytical model is that the relative duration of the random time to process targets compared to the random time until a target is lost probabilistically determined whether or not a target is engaged or lost, but that otherwise, the actual time to process the target could be disregarded because it was negligibly short compared to the random time to detect a target. The simulation results show that the simplifying assumption does not significantly change the MOE results.

CROP fuses information from the participating services, gaining knowledge of the battlespace and exploiting this gained knowledge. CROP's ability to disseminate the information to the entire joint force, and its ability to use a weapon from any participating service to attack the target, is CROP's pay-off. The decision criterion used in this thesis for weapons selection is to use the weapon with the highest perceived single shot probability of kill.

The BDA Parameter determines the effects of accurate BDA information on the number of weapons mistakenly expended against dead targets. The measure is important because these weapons could have been used against live targets. The results show that accurate information plays a key role in limiting the number of weapons wrongly expended against dead targets. As the probability of accurate BDA increases the number of weapons so expended decreases. The mean number of weapons expended when BDA is 50% accurate is 1 extra weapon. This mean number of weapons expended decreases to 0 when BDA is perfect.

The results also show that CROP decreases the time to kill a target, when the classification time rate is similar to those of the separate services. As the classification time rate slows down (i.e., the mean time to classify increases), the effects of the higher probability of correct classification and the benefit of selecting the "best" weapon for the perceived target type are negated. In an example, CROP initially begins with a classification time rate equal to the second-slowest service's classification time rate.

CROP's rate is then decreased to less than the slowest service's classification rate; this is to incorporate CROP's command and control overhead into the process. This overhead includes, but is not limited to, CROP's ability to fuse the data from the participating services, pairing the "best" weapon to the perceived target type and disseminating the information to the relevant entities in the battlespace.

The data collected show that increased knowledge gained by CROP is beneficial when the information is timely. As the delay in fusion of the information from the services becomes too large, or equivalently if any processing time latency under CROP is too long, the benefits of CROP are lost, and the uncoordinated services work as efficiently or more efficiently than CROP.

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I. INTRODUCTION

A. TECHNOLOGY, A REQUIRED TOOL FOR FUTURE WARFARE

> "The nature of modern warfare demands that we fight as a joint team. This was important yesterday, it is essential today, and it will be even more imperative tomorrow. Joint Vision 2010 provides an operationally based template for the evolution of the Armed Forces for a challenging and uncertain future. It must become a benchmark for service and Unified Command visions."
>
> General Shalikashvili
> Chairman Joint Chiefs of Staff
> JV 2010, Introductory Statement

In Joint Vision 2010 [reference 1] General Shalikashvili set into motion his vision for the U.S. military in 2010. The goal is to leverage the vast information technology industry burgeoning within the U.S. and achieve new and higher levels of effectiveness. This increase is required since, as force numbers decrease, the U.S. will need to rely on joint forces fighting with information superiority.

The improvements in information technology and systems integration will have a significant impact on future military operations. Successfully adapting new and improved technologies may provide greater increases in military capabilities, allowing for economy of force and a higher tempo of operations. Decision makers will be provided with more timely and accurate information. Technology will improve the ability to display the information, prioritize targets and intelligence, assign tasks to subordinates and assess all this information at the command level as well as the tactical unit level. The relevant data necessary for all the levels in the chain of command will be accessible at thousands of locations, while thousands of other locations are inputting data into the system. The fusion of the data and the fluid integration of sensors, weapons platforms, command organizations and logistic support centers will allow more tasks to be accomplished in a shorter period of time. Smaller units with autonomous equipment will have much greater ability to detect, communicate and target. Technology will allow these smaller units to complete more missions, reducing the number of U.S. personnel in harms way, while also allowing these small units the opportunity to disperse and remain covert. This increases

force protection overall, by reducing the number of personnel and increasing the self-defense capabilities of the small units.

The improved communications and information flow capability will allow these small units to call upon and coordinate numerous actions simultaneously. These capabilities, coupled with the agility and rapid maneuver of the units, will tend to minimize risk while maximizing the ability to mass forces and their effects when necessary and on U.S. terms.

> "We must have information superiority: the capability to collect, process and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same." [reference 1 page 16]

Information Superiority in a Joint environment is the impetus behind U.S. Joint Forces Command concept of a Common Relevant Operational Picture (CROP). The Information System developed as the foundation for CROP will be the enabler for many of the goals mentioned above and in Joint Vision 2010. Secretary of Defense Cohen stated in his 1999 Annual Report to the President and the Congress,

> "Information superiority is the critical enabler of the transformation of the Department currently in progress. The results of research, analysis, and experiments designed to create and leverage information superiority, reinforced by recent experiences in Kosovo, are very encouraging. They demonstrate that the availability of information and the ability to share it results in enhanced mission effectiveness and improved efficiencies. This evidence points to increased speed of command, a higher tempo of operations, greater lethality, less fratricide and collateral damage, increased survivability, streamlined combat support, and more effective force synchronization." [reference 2 page ii].

Joint Vision 2020 [reference 3] continues the theme of using technology and the potential of the information revolution to improve on current capabilities for maneuver, strike, logistics and protection. Integrating the unique core competencies of the individual services is essential for successful joint operations. This integration will continue to evolve as technologies improve and more data can be transferred at faster rates. This information and the processing of it and distribution of the information to other entities in the battlespace through communication networks are the foundation upon which success is achieved. The information alone does not make an operation or exercise

a success, but using the information to make quicker decisions than the opposition determines the success of the operation. The information transferred must be processed and turned into knowledge for the decision maker and staff, allowing them to make well-informed decisions, at a rapid rate.

Information is the enabler, but cannot be the only innovation to bring Joint Vision 2010 goals to reality. Organizations must adapt the command and control mechanisms that gather the information and display it. This will allow commanders to make the right decisions early, and can enable the high operational tempo desired in future joint operations. The information will not be perfect; however all the commands operating together in a theatre will be seeing, and acting on, the same tactical and strategic picture. This should reduce the fog of war [reference 4, chapter 7]. However, the fog of war can never be completely eliminated. Decisions will still be required of decision makers without perfect information. A goal of information technology and information superiority is to give the decision maker greater the ability to "know what is known and what is not known".

The Common Relevant Operational Picture (CROP) concept is targeted at getting the right information to the decision maker, and allowing the decision maker to gain knowledge and make decisions in a timely manner.

The timeliness of information is a key foundation for CROP. The closer the information is to real-time, the better it may be for the tactical advantage, assuming the information is correct. As information becomes older it may not be possible to respond to it, or a situation. An example of a situation where the timeliness of information is drastically important is "Time-Critical Targeting". Time-critical targets present themselves for only a short period of time. If strikes are not immediately initiated upon detection, targets could disappear before weapons arrive. A specific example from Desert Storm is the Iraqi SCUD launchers; the launchers would come out of hiding for only enough time to launch a missile and then return to a hiding place. Certain space-based sensors were able to sense the launch. However, if the information were not available to the warfighter in position to engage the launcher quickly, the SCUD launcher could be re-stowed and out of the area before a weapons platform could respond. There

are at least two key factors for a positive strike on a Time Critical Target. The first is information about the location of the target; the second is having a weapons delivery platform, with a capable weapon to destroy the target, within striking distance before the target disappears. CROP deals with the first requirement: to get relevant information from a sensor to commander and weapons platform quickly and accurately.

II. CROPDUSTER MODEL

A. INTRODUCTION: CROPDUSTER MODEL

The CROPDUSTER model is a high level, low resolution, stochastic model developed and used to evaluate the CROP concept [reference 5]. CROP is built on the foundation of current practices in the U.S. Armed Services. A characteristic of the Services is of stove-piped systems that are not necessarily inter-operable with other systems. The lack of smooth timely information flow can slow the rate of operations in a theater.

B. CROPDUSTER MODEL AND MEASURES OF EFFECTIVENESS

For purposes of comparison and computation CROPDUSTER considers three services and three target types. CROP capability is compared to the Uncoordinated Services capability for the detect-to-engage process with different target types. The Uncoordinated Services do not share information between the services; however information is shared within a service. This is in contrast to CROP, where it is assumed that the services share all information relatively quickly.

The ability to share information within a single service is represented by the detection rate of that service's sensor system(s). The detection rates for the services are represented by x_{rs}, where r stands for the target type, r $\in$ {1, 2, 3, …, R}. The subscript s stands for the services, s$\in$ {1, 2, 3, …, S}. The mean time to detect one target is $1/\xi_{rs}$. The time until target detection is an exponential random variable, $\mathbf{T}_{rs}$. The distribution is exponential for ease of calculation, however the model can accommodate the distribution of any non-negative random variable.

The probability that service s detects a target of type r that is available for detection at time t by time T ($t \le T$), is modeled as

$$P\{t \le \mathrm{T}_{rs} \le \mathrm{T}\} = \begin{cases} F_{T_{rs}}(T) - F_{T_{rs}}(t) & , \mathrm{t} \le \mathrm{T} \\ 0 & , \text{otherwise} \end{cases} \qquad (1)$$

In the above equation t represents the time that a target becomes available for detection. This can occur by the target entering the area under surveillance, or by the sensors

entering the area. Assuming, as mentioned above, that the detection time distribution is exponential, then.

$$F_{T_{rs}}(T) - F_{T_{rs}}(t) = \begin{cases} 1 - e^{-x_{rs}(T-t)} & ,t \le T \\ 0, & ,\text{otherwise} \end{cases} \tag{2}$$

The probability that a target will remain undetected until time T, (t < T) is the complement.

$$1 - (1 - e^{-x_{rs}(T-t)}) = e^{-x_{rs}(T-t)} \tag{3}$$

The probability that no service will detect the target prior to time T, assuming that the target becomes available for detection at time t for all services and there is no coordination between the services is.

$$\text{P}\{\mathbf{T}>\text{T}\} = \prod_{s=1}^{S} e^{-\xi_{rs}(T-t)} \tag{4}$$

$$= e^{-\left(\sum_{s=1}^{S} \xi_{rs}(T-t)\right)} \tag{5}$$

T is the time for the first service to detect the target. This is also the detection time for CROP following the assumption that all information is shared among the services instantly.

The probability that the target will not be detected by a subset of the services given that the detection rates for the services are equal (i.e. $x_{r1} = x_{r2} = x_{r3} = x_r$), is referred to as the *Homogenous Sensor Case*. The number of Services that have not detected the target by time T is determined with the binomial.

$$\text{Binomial}\left(e^{-x_r(T-t)}, S\right) \tag{6}$$

Where $e^{-x_r(T-t)}$ is the probability that the target remains undetected until time T, and S is the number of services operating within the battlespace. The mean number of services in time interval T-t to not detect the target is

$$Se^{-x_r(T-t)} \tag{7}$$

The general case when the detection rates for the services are not the same, the Heterogeneous Case is

$$\sum_{s} e^{-x_{rs}(T-t)} \tag{8}$$

1. Shots, Losses, Target Survival

Once a target is detected it must be classified, weaponeered, and a shot or salvo fired if the target is classified as an enemy target. The general flow of a Detect-to-Engage cycle follows the following sequence. Once detection occurs, the target is classified, a weapon selected to be fired (if appropriate), and the target will either be killed or it will survive the engagement. If for any reason during this cycle the target is lost, the entire process must start over, with detection of the target.

2. Shot or Loss, Uncoordinated Services

The model follows this cycle: detection occurs, then the target is classified and a weapon or a salvo of weapons fired at the target. If the target is killed, it is deleted; if the weapon(s) miss, the target returns to the environment and is placed in position to be detected again. The cycle is repeated until the target is killed or survives past time T.

$\boldsymbol{K_{rs}}$ is the time it takes service *s* to kill a target of type *r*. There may be several shots taken before the target is killed due to misses; the target may also evade for some time prior to the fatal shot being fired. There are two competing events at the time of detection, time to target loss and time to getting a shot off at the target. The rate of target loss is ν_{rs} and the rate of target mensuration is η_{rs}. Mensuration is here assumed to include the time to classify, weaponeer (choose the appropriate weapon), shoot the weapon and the time for the weapon to arrive at the target and detonate. It is assumed in the analytical model that the time until target loss and the mensuration time are independent exponential random variables. Since these two events are mutually exclusive, the rate that the first occurs is $\nu_{rs} + \eta_{rs}$. The probability that the detection ends in a target loss is

$$q_{rs} = \nu_{rs} / (\nu_{rs} + \eta_{rs}) \tag{9}$$

The probability that the target is shot at is

$$p_{rs} = 1 - q_{rs} \tag{10}$$

$$p_{rs} = \eta_{rs} / (\nu_{rs} + \eta_{rs}) \tag{11}$$

In the analytical model the time from detection until either target loss or target kill is neglected. Hence the time-to-kill random variable has the following structure

$$? \;_{rs} = \begin{cases} \text{[illegible]}_{rs} & prob.k^{*}_{rs} \\ \text{[illegible]}_{rs} \text{[illegible]}'_{rs} & prob.(1-k^{*}_{rs}) \end{cases} \tag{12}$$

where $?'_{rs}$ is an independent random variable with the same distribution as $?_{rs}$. The probability of kill through each Detect-to-Engage cycle is assumed to be the same each time a true target type is shot at.

$$k^{*}_{rs} = p_{rs} \sum_{j} c_{rj}(s) \sum_{k} d_{jk}(s) k_{kr}(s) \tag{13}$$

$$\bar{k}_{rs} = x_{rs} k^{*}_{rs} \tag{14}$$

The probability of kill, k^{*}_{rs} involves the probability the service gets a shot off, p_{rs}. The classification matrix, $[c_{rj}(s)]$, gives the probability that a true target type r will be classified as target type j by service s. The weaponeering matrix $[d_{jk}(s)]$, determines the weapon type fired at the classified target type. The single shot probability of kill, κ_{jr}, is the probability that a weapon appropriate for target type j kills a target of type r. The kill rate $\bar{k}_{rs}$ involves the detection rate, ξ_{rs} and the probability of kill k^{*}_{rs}. The EXCEL Spreadsheet Model "CROPDUSTER.xls" [reference 8] computes these kill rates.

3. Target Survival, Uncoordinated Services

The r true target type individual survival probability is

$$\bar{G}_r(T-t) = e^{-\bar{k}_r (T-t)} \tag{15}$$

where $\bar{k}_r = \sum_{S} \bar{k}_{rs}$, neatly placing into one parameter all the Service's classification, weapons decisions and weapons effectiveness.

4. Target Survival, CROP

For CROP the detection rate $x_r = \sum_{S} x_{rs}$. Once it is detected, the classification takes place. Once classification is complete the weapon with the highest perceived

probability of kill for the classified target type is selected and fired at the target. The CROPDUSTER.xls spreadsheet model [reference 8] also calculates the kill rates for CROP as well.

The probability of kill for CROP is.

$$k_r^* = p_r(C)\sum_{l=1}^{S}\bar{c}_{rl}(S)k_{lr}(s(l)) \qquad (16)$$

where $p_r(C)$ is the probability an attack will occur before the target is lost, and $\bar{c}_{rl}(S)$ is the probability that a target of type r is classified as target type l and assigned to service $s(l)$. The service assigned to the target, by CROP, will be the service with the highest perceived probability of kill against the classified target type, designated here as $s(l)$.

The Excel Spreadsheet model [reference 8] is used extensively throughout this thesis to calculate the kill rates for CROP and the Uncoordinated Services. These rates are used to verify the simulation with the CROPDUSTER model in Chapter IV.

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III. SIMULATION METHODOLOGY

A. INTRODUCTION TO SIMULATION

The simulation discussed below was developed to increase the variety of experimentation possibilities with the CROP concept. As in the analytical model there is no saturation of resources or queueing of targets. The simulation considers one target at a time. The output of a single replication of the simulation is the time to kill a target, the time to declare a target dead, and the number of weapons expended to kill the target, as well as the number of weapons expended on the target after it is already dead. The simulation has been used to verify its results with those of the analytic calculations from the CROPDUSTER model [reference 5]. This comparison is discussed in Chapter IV. After verification, the simulation is used to study the capability and effectiveness of CROP in conditions other than those examined with the analytical model.

The simulation is written in Visual Basic, and is run by hitting the appropriate button on the "Data" page in the EXCEL worksheet shown in Figures 1 thru 3 below. Exponentially distributed random times are generated by the inverse distribution function method using the following equation:

$$\text{Time (randomly generated)} = -\ln(\text{uniform (0,1)random number}) / \text{rate} \qquad (17)$$

Where the random variate is a uniform random number (0,1), and the rate is taken from the appropriate cell shown in Figures 1, 2, or 3.

Section D describes the simulation for the CROP model. Much of this simulation is also used for the uncoordinated services simulation as well. Section E describes the additional features needed to simulate the uncoordinated services.

B. RANDOM NUMBER GENERATION

The random number generator is a Visual Basic for Applications (VBA) implementation of the well-tested, well-known prime modulus multiplicative linear congruential generator (PMMLCG):

$$Z_i = aZ_{i-1} \pmod{m} \qquad (18)$$

where a = 630,360,016, and m = 2^{31}-1. This generator is known to produce a full cycle stream of 2^{31}-1 = 2,147,483,647 pseudo-random numbers before repeating, and produces an output stream of numbers that do not differ significantly in behavior from numbers that are truly independent and identically distributed Uniform(0,1) [reference 9].

C. INPUT PARAMETERS

The following figures show the three pages of parameters used in the simulation. The screens shown are the three different sections of a single EXCEL worksheet. The values shown are those used for verification, which is discussed in chapter IV.

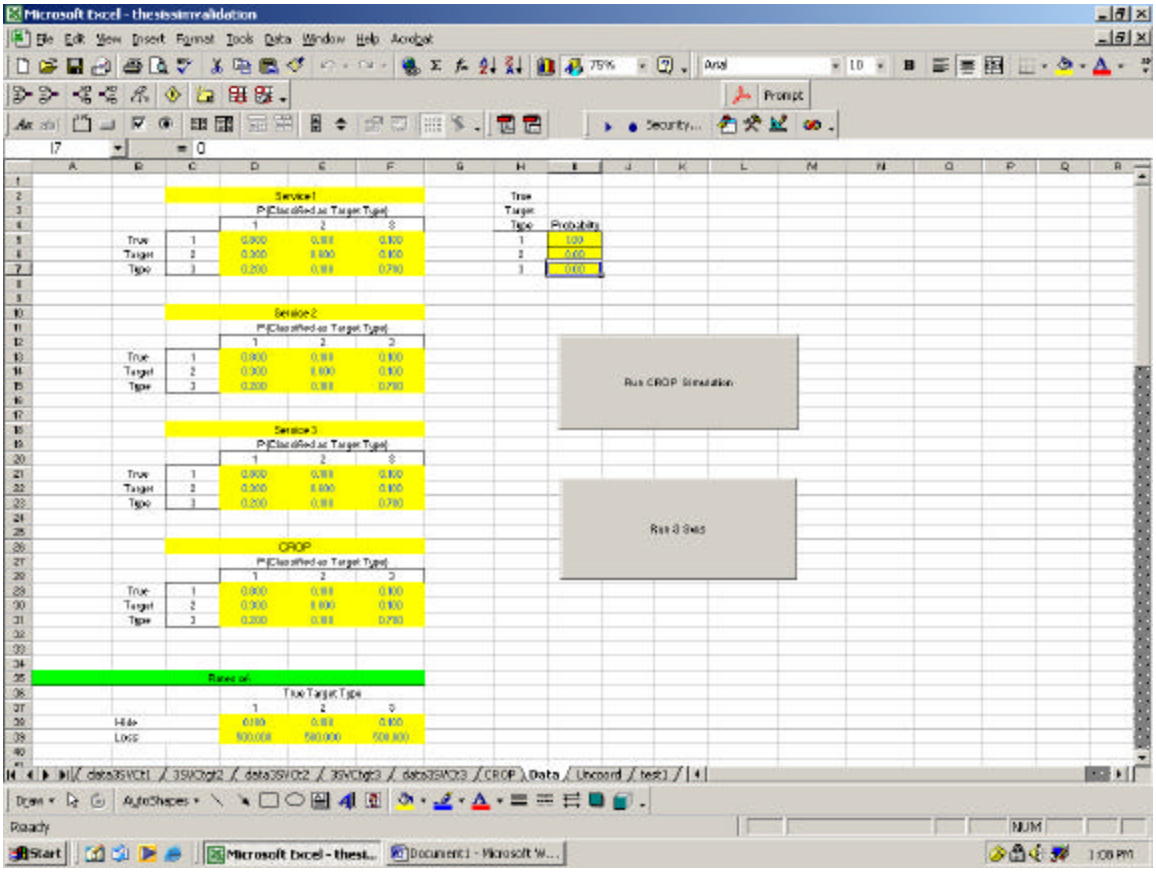

Figure 1. Page 1 of the Simulation Parameter Input Worksheet

Figure 1 shows input parameters. The parameters include classification probabilities for each of the respective services that a target will be classified a certain target type, given its true target type. The rates for hiding and loss for each true target type are also given on this page.

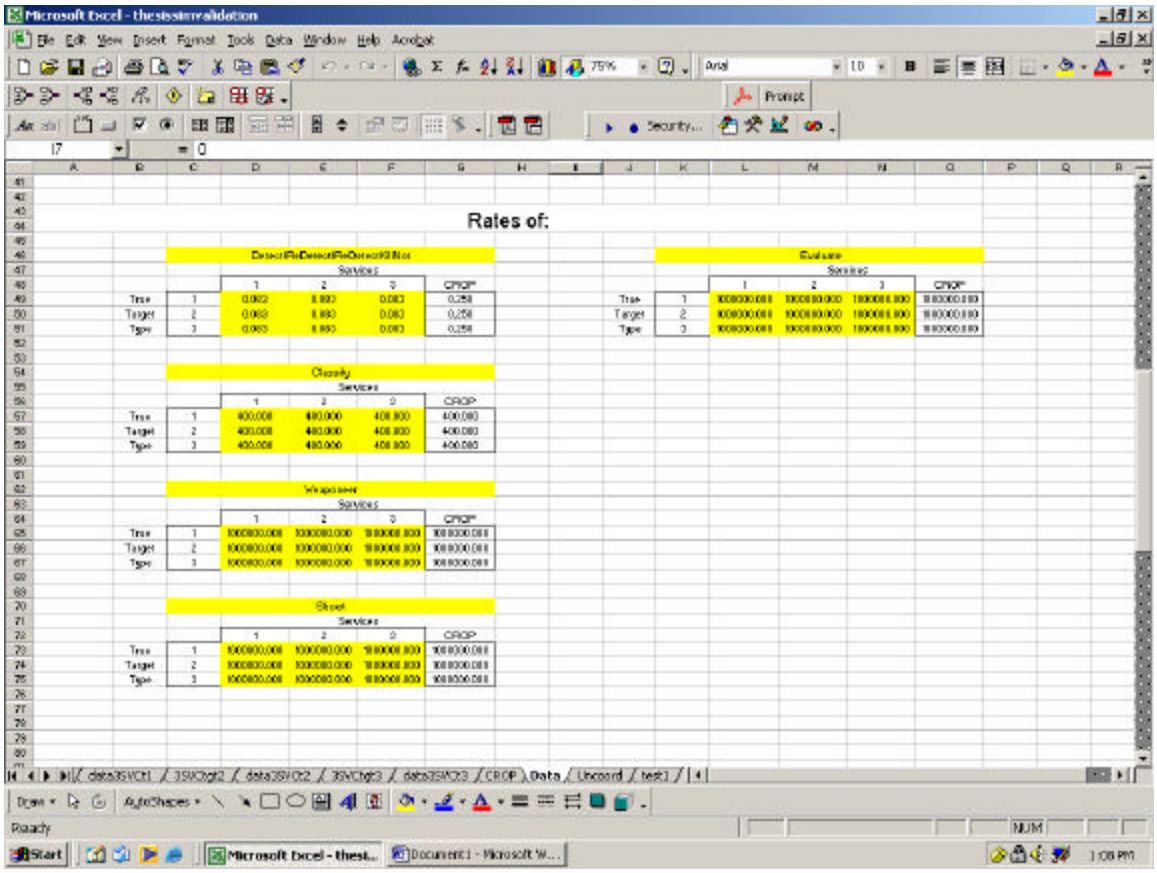

Figure 2. Page 2 of the Simulation Parameter Input Worksheet

Figure 2 has rates to Detect/ReDetect/ReDetectKillNot, these specific names and where they are used in the simulation are explained below. The other matrices found on page 2 are the rates to classify, weaponeer, shoot and evaluate.

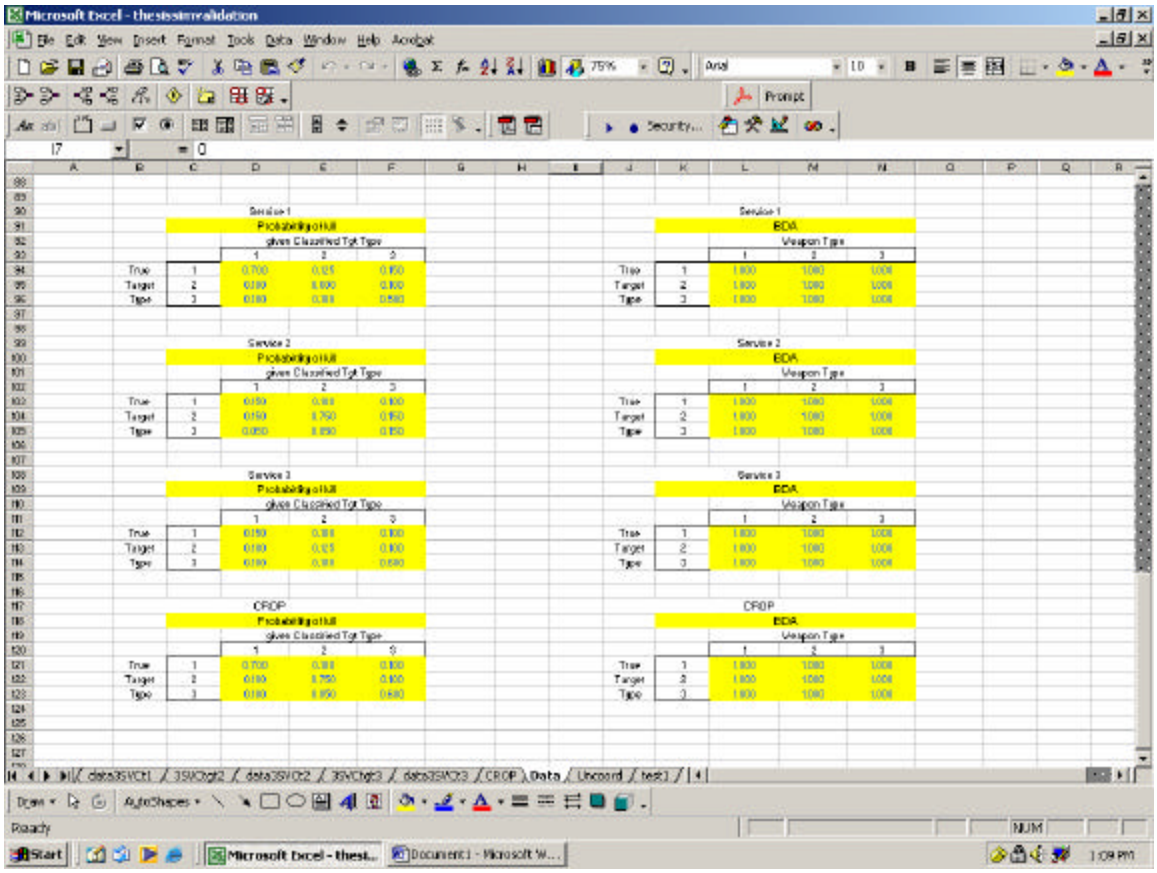

Figure 3. Page 3 of the Simulation Parameter Input Worksheet

Figure 3 shows the single shot probability of kill for each service and each weapon type given the true target type. The other matrices are the Battle Damage Assessment (BDA) probabilities for each service against the classified target type, given the true target type.

D. THE SIMULATION

1. CROP Initial Detection and Lose or Shoot the Target

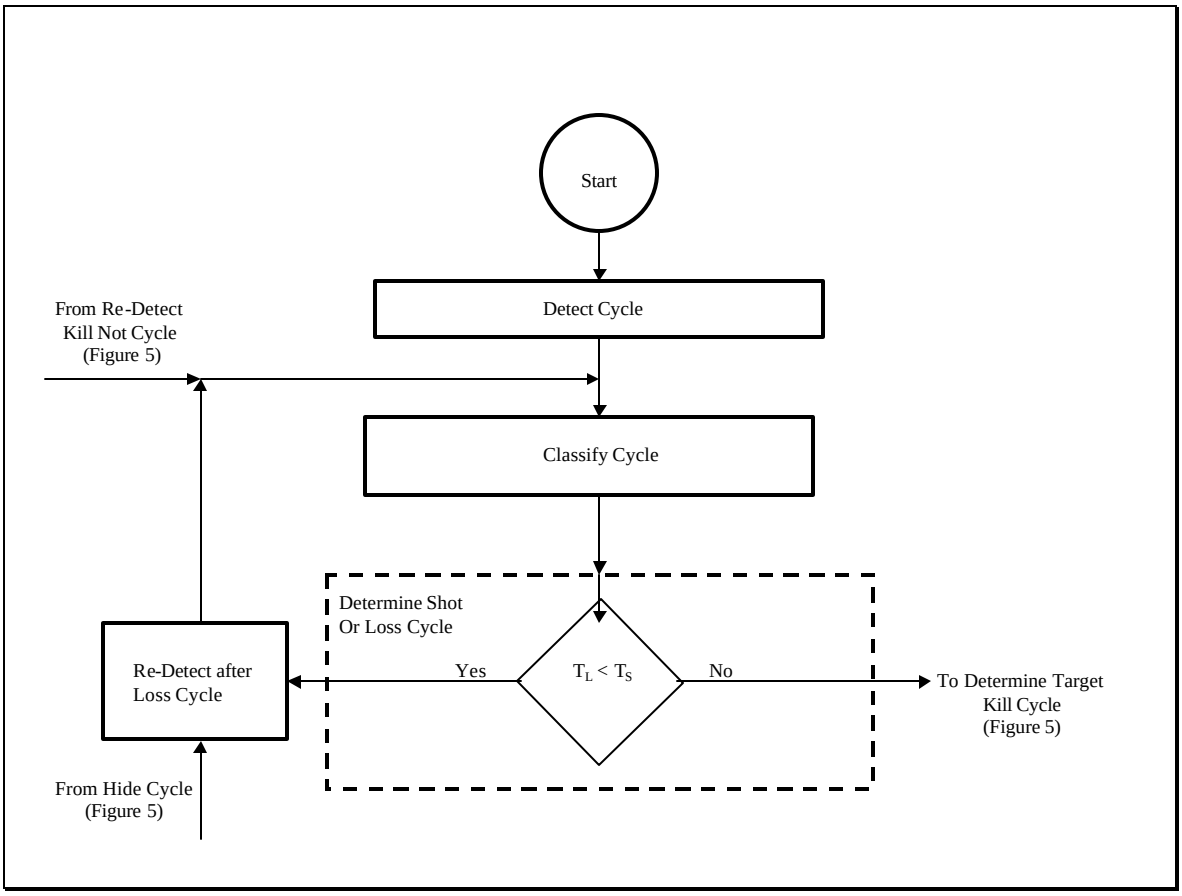

Figure 4. CROP: Detection and Determine Loss or Shot Event Graph

The CROP simulation starts with the arrival of the target to the region. Each replication of the simulation is for one target. The output of this simulation can be used in models for the arrival of targets to the battlespace. For example, n replications of the simulation will simulate a scenario in which there are n targets in the region at time 0 and no other targets arrive, as in the CROPDUSTER numerical examples. .

The target is assigned a True Target Type 1, 2 or 3. Each target is identified and tracked throughout the simulation by its True Target Type and its target number. Once a True Target Type is assigned, the target's next event occurs in the Detect Cycle. Here, the "Time to Detect" is calculated using equation 19, applying the rate of detection from the parameter input page shown in Figure 1. The "Time to Detect" is added to the "Time

to Kill Actual" (TTKA) and the "Time to Kill Perceived" (TTKP). These times are continuously updated until the target is killed, and eventually declared dead. Once the target type is assigned, in the CROP portion of the simulation the classification of the target is calculated. The Classify Cycle determines the classification of the True Target Type. A uniform random number is generated and compared to the cumulative distribution function (cdf) of the probability the target is classified as each of the target types. The cdf is the obtained by summing across the row corresponding to the appropriate True Target Type in the matrix. For example, from Figure 1, using Service 2 and True Target Type 1, the classification probability values are 0.8, 0.1, and 0.1. To determine what the classification of the target is, the simulation compares the generated random number to 0.8, 0.9 and 1. If the random number is below 0.8 it is classified as Target Type 1, if it is above 0.8 but below 0.9 it is classified as Target Type 2, and all others are classified as Target Type 3; note that this classification can be in error.

After the target has been classified, the target is either lost or an attack initiated. To determine which of these occurs, four random times are calculated: "Time to Loss", "Time to Classify", "Time to Weaponeer", and "Time to Shoot". The variable "Time For Shot" is the sum of the last three variables. The "Time For Shot" is compared to the "Time to Loss", and the minimum of the two determines the next event to occur. The next two possible cycles the target proceeds to are the Determine Target Kill Cycle and ReDetect Loss Cycle. The Determine Target Kill Cycle is the first cycle encountered in the branch of the simulation if an attack is initiated. This branch is discussed below. If the target is lost, the "Time to Loss" is added to the TTKA and TTKP, and the target is redetected, again applying the parameters from Figure 1. The target is redetected and another set of random times generated to determine if the target is lost or shot. This cycle continues until the "Time for Shot" value is smaller than the "Time to Loss" and an attack is conducted. When this occurs the target is sent to the portion of the simulation depicted below.

2. CROP Cycle Ending in Shot and BDA

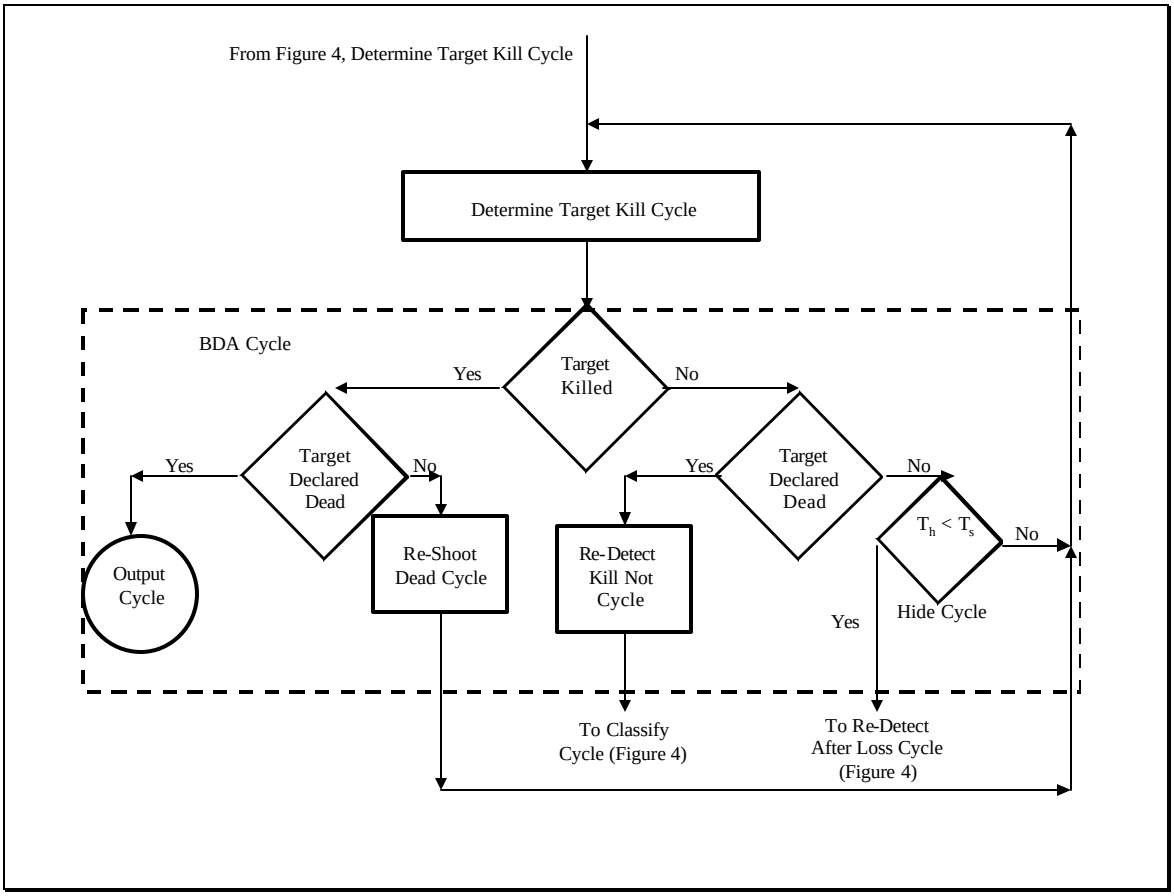

Figure 5. CROP: BDA Event Graph

Figure 5 above shows the events that occur when a target is attacked. The cycles determine the classification of the target, the outcome of the shot or salvo, and what the result of Battle Damage Assessment (BDA) is, kill or no kill.

The Determine Target Kill Cycle determines if the target is killed, what service conducts the attack, and determines the BDA. To determine if the target is killed by a shot, a uniform random number is compared to the respective single shot probability of kill, shown in Figure 3. If the random number is less than the probability of kill, the target is killed, and the TTKA is sent to the worksheet as the output of the time the target is killed. This is where the weapons expended on a target are calculated. For CROP each service only has one weapon type. This assumption is made for CROP because each service has a weapon with a higher single shot probability of kill against a certain target type than the other two services. Due to the nature of CROP in this case, choosing the

"best" weapon for the target reduces the weapons choices within a service to the one weapon type. For purposes here the best weapon is the one with the highest probability of kill against the perceived target type. This weapons selection principle could be changed in future work. The changes would necessarily need to occur in the simulation, they could be completed in a spreadsheet and the parameters entered into the appropriate cells in Figure 3.

The outcome of BDA is dependent on whether or not the target is killed. If the target is killed, the BDA random number is compared to the appropriate BDA parameter, from Figure 3. This determines if the target is declared dead or not after it has been killed. If, however, the target is not killed, the BDA random number is compared to, 1-BDA parameter. For example: If the BDA parameter equals 0.9, meaning BDA is 90% accurate, and the target is killed, there is a 90% chance the target is declared dead. If the target is not killed, there is a 10% chance (1-0.9) the target is declared dead, and the random number is compared to this. Another possibility for future consideration would be to have two BDA parameters, one for a live target and one for a dead target. Likewise the time to evaluate the BDA takes only one rate during the simulation. This rate could also have more than one parameter.

If the target is killed and declared dead, the data collected for the target is sent to the appropriate worksheet and the next target is generated, and the process begins for that target. This cycle is the Output Cycle.

If the target is not killed but incorrectly declared dead, the target's next event is the Re-Detect Kill Not Cycle. The target is redetected, and a random time generated using the detection parameters from Figure 2. The target then goes to the cycle in Figure 4, determining whether it is lost or shot.

If the target is killed and declared not dead, the next event is the Re-Shoot Dead Cycle. Here the target is shot again. The true status of the target is dead; therefore it is unable to be lost or to hide (discussed below). The target waits until it is declared dead. The mensuration time is generated and the target is classified again and a shot taken. The Determine Target Kill Cycle is the next event the target goes to after the mensuration time computed and added to TTKA and TTKP.

The next cycle if the target is declared not dead, and the target is not dead is the Hide Cycle. The target can be shot at again or it can hide. The two times, "Time to Hide" and "Time to Mensurate" are generated and compared to determine what happens to the target. If the "Time to Hide" is smaller than the "Time to Mensurate" the target hides; the "Time to Detect" is then calculated in the Re-Detect Loss Cycle in Figure 4. If the "Time to Mensurate" is shorter the target is shot at again and the next event is the Classify Cycle.

Each replication consists of one target. The times for each event, as stated earlier are added to the two "Time to Kill" variables, "Time to Kill Actual" and "Time to Kill Perceived". These times are used to measure the effectiveness of CROP vs. the Uncoordinated Services.

E. UNCOORDINATED SERVICES SIMULATION

The Uncoordinated Services follow the same pattern through the Detect-to-Engage cycle simulated for CROP. However, there are some differences in the mechanics of the program. Since the services are uncoordinated they do not share the same information that is shared in CROP. There are two important pieces of information shared between the services in this portion of the simulation. The first is that, once a service detects the target and starts its attack, the other services are informed and do not prosecute the target. The second is that, once a target is declared dead the other services are given this knowledge. For example if Service 1 declares the target dead after conducting an attack on the target, all the services get this information. If the perceived dead target *is* dead then the simulation goes to the Output Cycle. However, if the target is not dead this information is only used to determine the next cycle; and in this case the target is considered lost and must be re-detected. The target may then be redetected by one of the services and prosecuted. The fact that it had already been attacked is not relevant. These assumptions limit services eligible to attack the target during a detection sequence to the first service to detect the target. The shared of the BDA information presents the services from attacking a dead target that has been declared dead by another service.

1. Uncoordinated Services Initial Detection and Lose or Shoot the Target

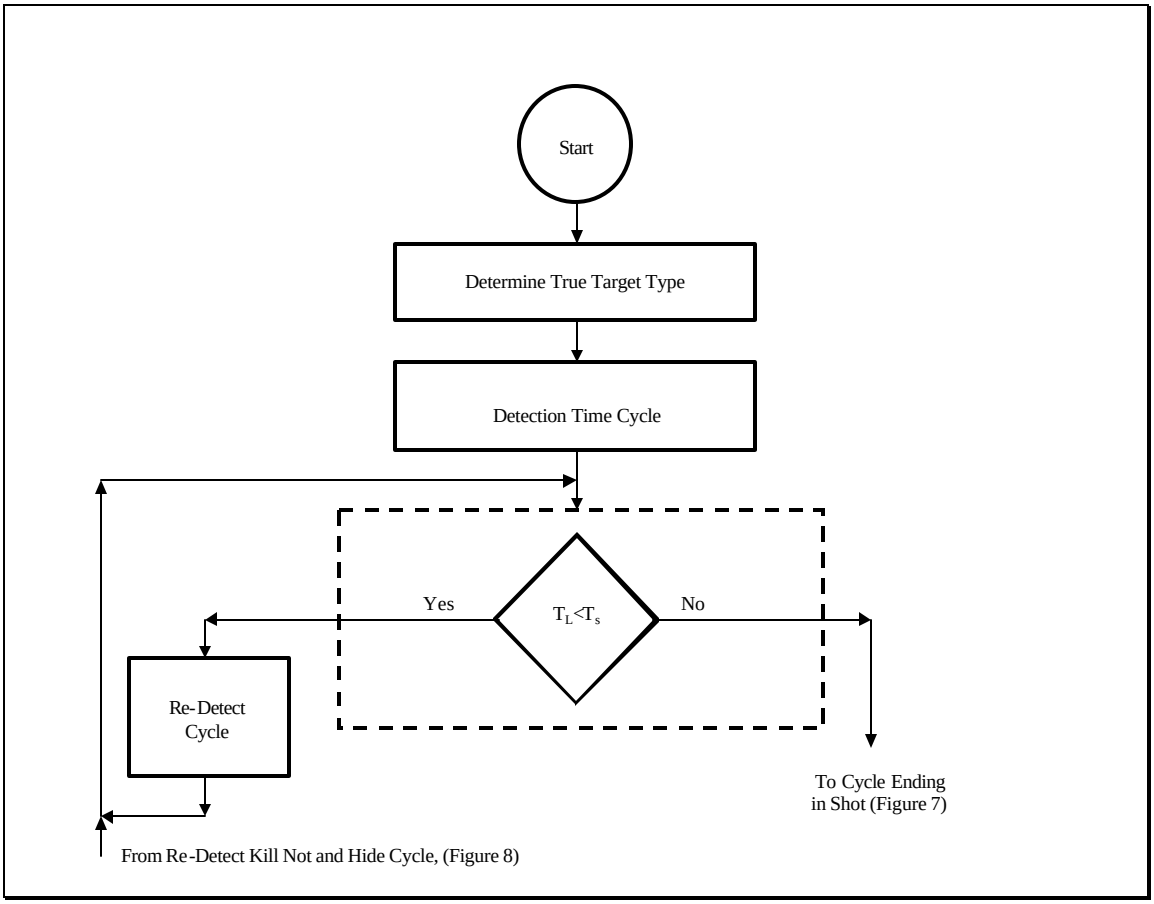

Figure 6. UNCOORD: Detection and Determine Loss or Shot Event Graph

The initial cycles for the Uncoordinated Services simulation are the same as for CROP. The differences are in how many random numbers are generated. Each service has a "Time to Detect" generated, as well as a "Time to Loss", "Time to Classify", "Time to Weaponeer", and "Time to Shoot". The service with the minimum "Time to Detect" conducts the attack during the detection sequence, and is the "lead" service. This detection sequence lasts until the target is killed and classified as dead, or, if the target is lost until be redetection. The "lead" service is re-calculated each time the target requires

re-detection. The service with the minimum "Time to Detect" becomes the "lead" service.

As in CROP, the two options after detection are for the target to be lost or shot. If the target is lost, the next cycle is the Re-Detect Cycle. As mentioned above, this cycle will simulate the new "lead" service, and sends the simulation result back to determine whether the target is lost or shot. Once the simulation calculates that a shot is taken, (the "Time for Shot" is less than the "Time to Loss"), the target is passed on the cycles shown in Figure 7 below.

2. Uncoordinated Services Cycle Ending in Shot

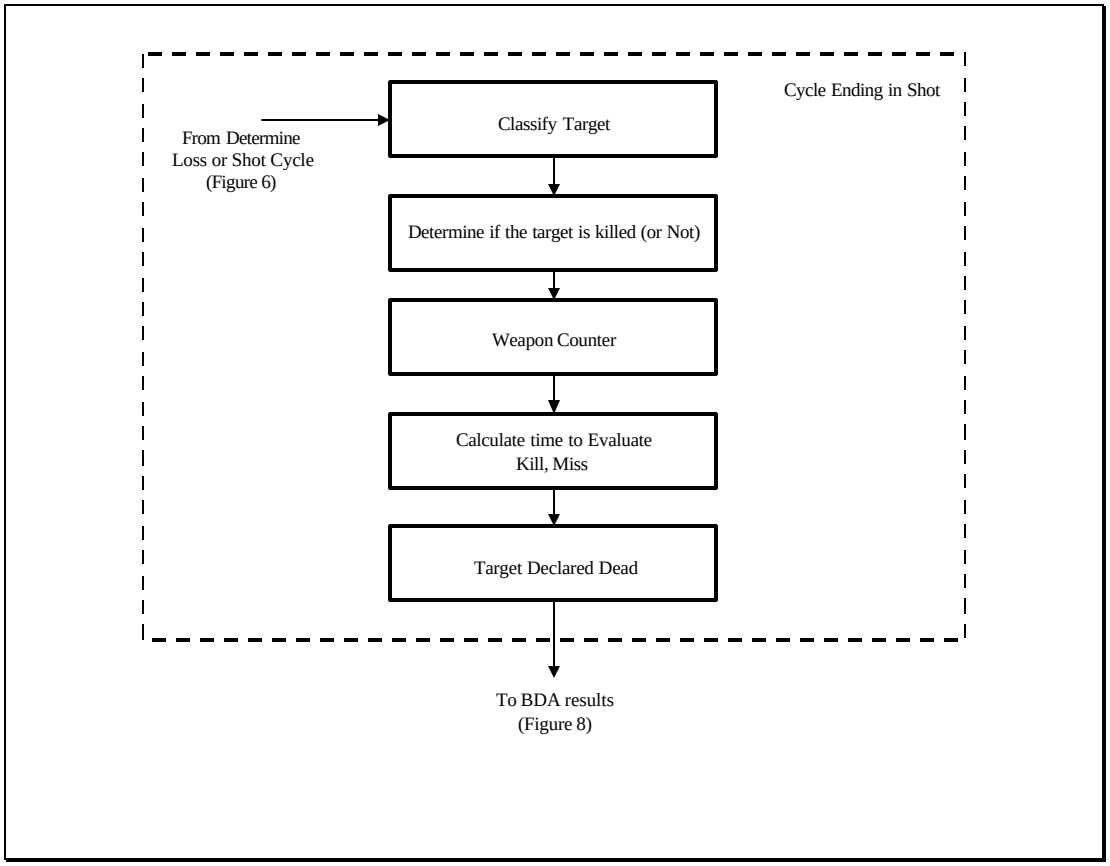

Figure 7. UNCOORD: Cycle Ending in Shot Event Graph

The Classify Cycle classifies the target, using the matrices found in Figure 1, for the respective services. A random number is compared to the (mis)classification matrix probabilities, given the "True Target Type". The "lead" service determines the matrix that is used to compare with the random number.

The classification, along with the "True Target Type" and the service conducting the attack are used to determine whether or not the target is killed within the Determine if Target is Killed Cycle. Each service has three weapon types, and the single shot probabilities of kill are in Figure 3. Each weapon is assumed to be most capable against a certain target type. For present purposes the weapon with the highest single shot probability of kill against the "Classified Target Type" is selected. Once a target is correctly perceived to be killed, the Weapon Counter Cycle tallies the number of weapons expended at that target. Weapon expenditure is tracked by service and weapon type.

The Calculate time to Evaluate Cycle simply computes a random time, using the rate parameter found in the appropriate cell in Figure 2. This time represents the time duration required to evaluate the BDA information and make a decision: the target is either perceived killed, or not killed.

The final cycle shown in Figure 7 above is the Target Declared Dead Cycle. It is the cycle that determines whether the target is declared killed or not. As in the CROP simulation there is a BDA parameter; it is invoked when the target is actually dead and, when it is actually alive. If the target is truly dead, a random number is compared to the BDA parameter to determine if the target is declared dead. If the target is truly alive, the random number is compared to 1 – BDA parameter to determine if the target is declared dead incorrectly. The simulation has the same BDA Parameter for all services, and for CROP.

The status of the target, killed or not killed, and whether the target has been declared dead or alive determines the outcome of the cycles shown in Figure 8 below.

3. Uncoordinated Services BDA Cycle

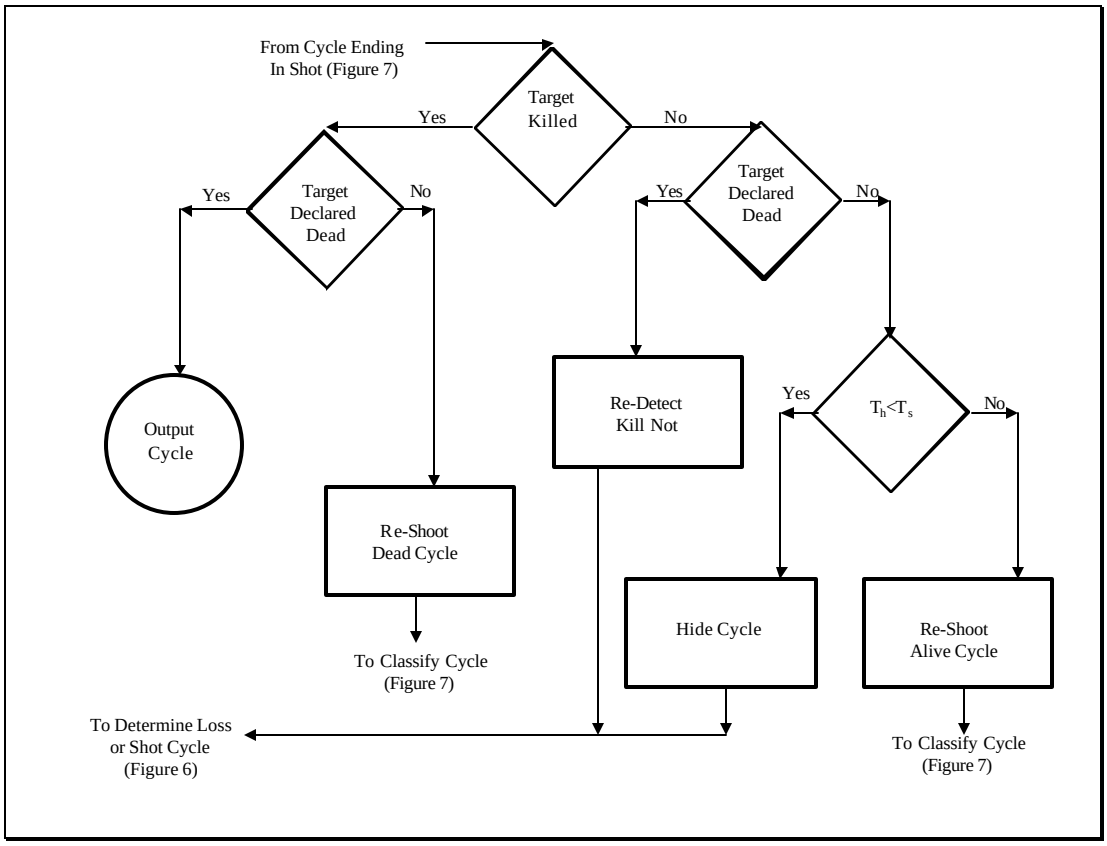

Figure 8. UNCOORD: BDA Event Graph

The BDA events above are the same logically as those for CROP. If the target is killed and declared dead the Output Cycle sends all the information for the current target to the worksheet and the replication is complete.

If the target is declared dead and it is not killed the target needs to be redetected and is sent to the cycles in Figure 6 to determine which service takes the "lead" and if there is a shot taken or if the target is lost.

If the target is declared not dead and it is dead, as before the target continues to be shot at until a service declares it dead.

The fourth option is for the target to be declared not dead and for it to be alive. In this case the "Time to Hide" and the "Time to Mensurate" is calculated and the minimum of the two is the next event. If the target hides, the detection time and the service that

takes the "lead" are determined within this cycle. The next cycle entered is the Determine Loss or Shot Cycle. If the target does not hide, and the service that previously shot and perceived a miss gets another shot at the target, that service retains its "lead" status and fires another weapon. The service has another opportunity to classify the target again in the Classify Cycle. There is no gained knowledge due the previous shot. It is simply another random number draw to determine the classification of the target. The target continues through the Cycle Ending in Shot as described above. The cycle continues until the target is killed, and possibly later, declared dead.

IV. INITIAL ANALYSIS OF THE SIMULATION FOR CROP AND THREE UNCOORDINATED SERVICES

A. INTRODUCTION

The purpose of this chapter is to compare the simulation with a numerical example using the analytical CROPDUSTER model [reference. 5]. The measures to be compared are the survival rates of three true target types, the mean number of times a target is lost and the mean number of weapons expended before time T. Each is computed for CROP and the three Uncoordinated Services.

B. INPUT PARAMETERS

The following tables show the parameters used for analysis in this chapter.

True Target Type	Classified Target Type		
	1	2	3
1	0.8	0.1	0.1
2	0.3	0.6	0.1
3	0.2	0.1	0.7

Table 1. CROP and the Uncoordinated Service's Conditional Probability of Classifying a Target, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.7	0.125	0.15
2	0.1	0.6	0.1
3	0.1	0.1	0.5

Table 2. Service 1, Probability of Kill for a Classified Target Type, given its True Target Type

	Classified Target Type		
	1	2	3
1	0.15	0.1	0.1
2	0.15	0.75	0.15
3	0.05	0.05	0.15

Table 3. Service 2, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.15	0.1	0.1
2	0.1	0.125	0.1
3	0.1	0.1	0.6

Table 4. Service 3, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.7	0.1	0.1
2	0.1	0.75	0.1
3	0.1	0.1	0.6

Table 5. CROP, Probability of Kill for a Classified Target Type, given its True Target Type

Since the analytical CROPDUSTER model does not yet include imperfect BDA, the BDA parameters are set to 1. This forced the simulation to consider the Target Dead each time it passed through the BDA Cycle for CROP and the three Uncoordinated Services, limiting the target's route through the simulation. That is, after detection, the targets can only be considered lost or killed. A target does not have the opportunity to be re-attacked after a perceived miss until it is re-detected by the Services or CROP.

The Loss rate is 5 per hour for the three True Target Types. The detection rate for the three Services is 1/12 per hour, giving CROP the detection rate of 3/12. This rate is used for the initial detection as well as re-detections when the target is lost, or is declared dead and is not actually killed.

Time to Classify, time to Weaponeer and time to Shoot, the three times which sum to equal the mensuration time have their rates set at 4, 1000, and 1000 respectively. These parameters result in a random time that closely approximates the exponential random time in CROPDUSTER with mensuration rate, 4 per hour. For CROP targets 1 and 2 the parameters were set to 400, 1,000,000 and 1,000,000 and the loss rate to 500. The parameters have the same ratio $\frac{400}{500} = \frac{4}{5}$. The current analytical CROPDUSTER model approximates the mensuration time to be 0 (it is small compared to the time to detect). The model thus only includes the probability that the events, loss and

mensuration, occur. The above simulation parameters should result in behavior similar to that of the CROPDUSTER model. The simulation time to classify rate is equal to 4 per hour, while the other two parameters are set artificially high so they add a small, inconsequential amount of time to the cycle. This same rationale is used for setting the Evaluation rate to 1000 again here for CROP targets 1 and 2 the rate was set to 1,000,000. These parameters add flexibility to the simulation for later trials.

C. SURVIVAL FUNCTION, MEAN TIME TO KILL RESULTS

The following plots show the simulated estimates of the probabilities that the respective True Target Types survive greater than time T for CROP and the Uncoordinated Services. The number of simulation replications (targets) is 10,000 for each target type.

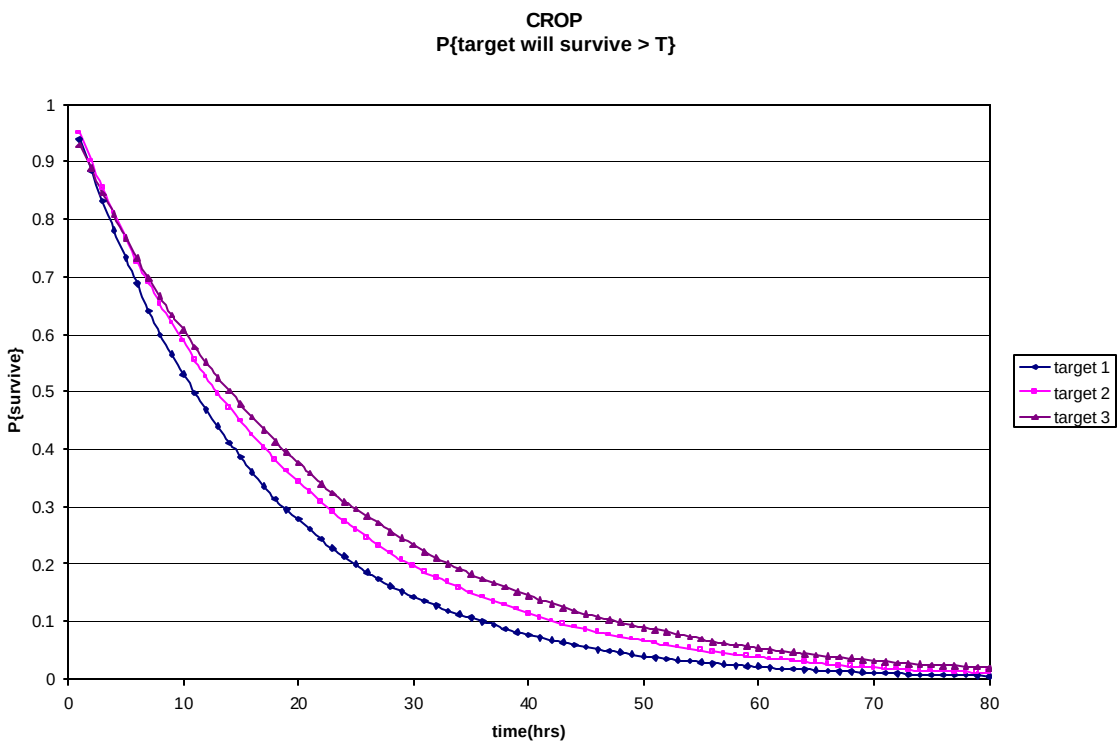

Figure 9. CROP Probability a Target Survives > T from Simulation

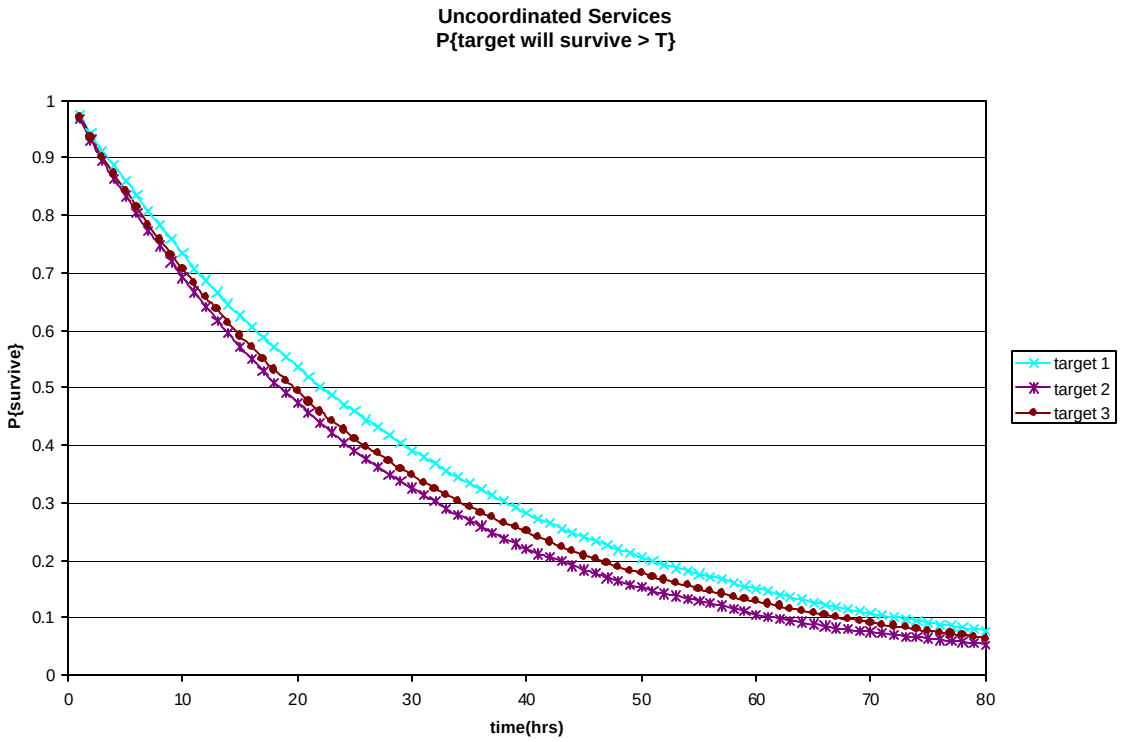

Figure 10. Uncoordinated Services Probability a Target Survives > T from Simulation

Observing the curves in the plot, the probability distributions seem to be exponential. This corresponds to the CROPDUSTER model. To verify that distribution is exponential a plot of -ln(P{survive >T}) against time can be used. If the empirical distributions of the survival time of the targets in Figures 9 and 10 are exponential the –ln plots will be approximately linear.

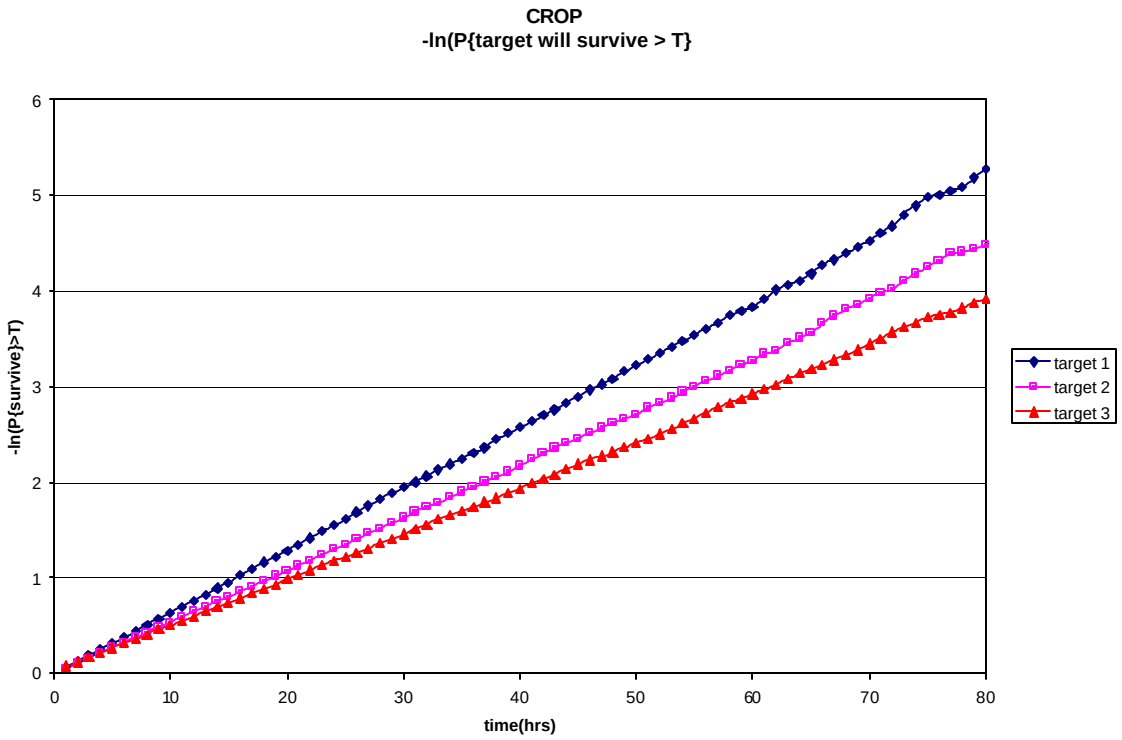

Figure 11. CROP: Plot of –ln(P{target survives > T})

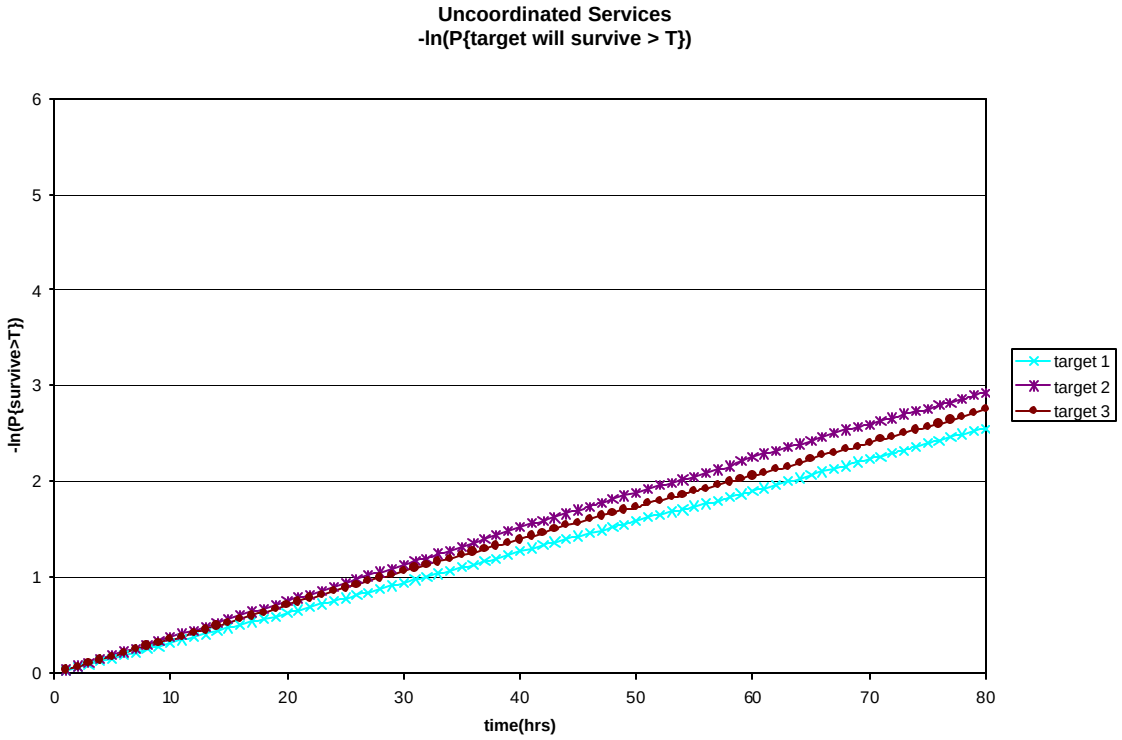

Figure 12. Uncoordinated Services: Plot of –ln(target survives > T})

Figures 11 and 12 above show the distribution of the time to kill the targets for both CROP and the Uncoordinated Services are very close to exponential.

Table 6 shows the average time to kill for each environment, (CROP and the Uncoordinated Services), the standard errors, and the analytical mean time to kill from CROPDUSTER is also displayed. The mean time to kill for CROPDUSTER was computed using an EXCEL Spreadsheet model [reference 8] that calculates the kill rates using the input parameters. Taking the reciprocals of the rates gives the mean time to kill.

Environment	True Target Type	Mean Time To Kill (Standard Error)	Standard Deviation	Mean Time To Kill, CROPDUSTER
CROP	tgt 1	15.6 (0.15)	15.4	15.53
	tgt 2	18.47 (0.18)	18.1	18.38
	tgt 3	20.3 (0.2)	20.4	20.24
Uncoordinated Services	tgt 1	31.58 (0.31)	31.3	31.25
	tgt 2	26.92 (0.27)	27.4	26.32
	tgt 3	28.84 (0.29)	29.3	28.57

Table 6. Mean and Standard Errors For Survival Functions of True Target Types In CROP and Uncoordinated Service Environments

For both environments and their respective target types the Mean Time To Kill in the simulation is within two standard errors of the CROPDUSTER analytic calculation.

D. MEAN NUMBER OF TIMES A TARGET IS LOST

Table 7 below shows the data from CROPDUSTER and the simulation regarding the number of times a target is lost. Lost within the simulation means the following: a lost target occurs when a target is lost after detection, prior to getting a weapon on the target. In the analytical model CROPDUSTER, a lost target occurs when the target is lost after detection but prior to getting a weapon on the target.

Environment	True Target Type	Mean Number of Times Lost (Standard Error)	Standard Deviation	Mean Number of Times Lost, CROPDUSTER
CROP	tgt 1	2.34 (0.39)	3.92	2.14
	tgt 2	2.15 (0.25)	2.46	2.51
	tgt 3	2.73 (0.30)	2.97	2.69
Uncoordinated Services	tgt 1	3.91 (0.37)	3.68	4.36
	tgt 2	3.44 (0.39)	3.91	3.72
	tgt 3	3.64 (0.39)	3.91	3.83

Table 7. Mean Number of Times a Target is Lost

The simulation means are within two standard errors of the CROPDUSTER analytical calculations.

E. MEAN NUMBER OF WEAPONS EXPENDED

The analytical CROPDUSTER model allows calculation of the mean and variance of the number of weapons each environment, (CROP and the Uncoordinated Services), expended against each target type [reference 5] in time T. Figures 13, 14 and 15 below are plots of the mean number of weapons expended in the simulation for CROP and the Uncoordinated Services against each target type respectively, prior to time T. The data was collected over 50 replications, each simulating 100 targets. Each of these simulation replications output the number of weapons fired against each individual target, for both CROP and the Uncoordinated Services. Each weapon fired also had the time it was fired associated with it in the data. These times were collected into their respective time intervals, (0, 100 hours], in 1 hour increments. The mean and standard error of the number of weapons expended were calculated for each hour in the interval (0,100 hours] for the 50 replications. Plotted below are the mean number of weapons expended over the 100 hours, and the 95% confidence interval (1.96 * standard error).

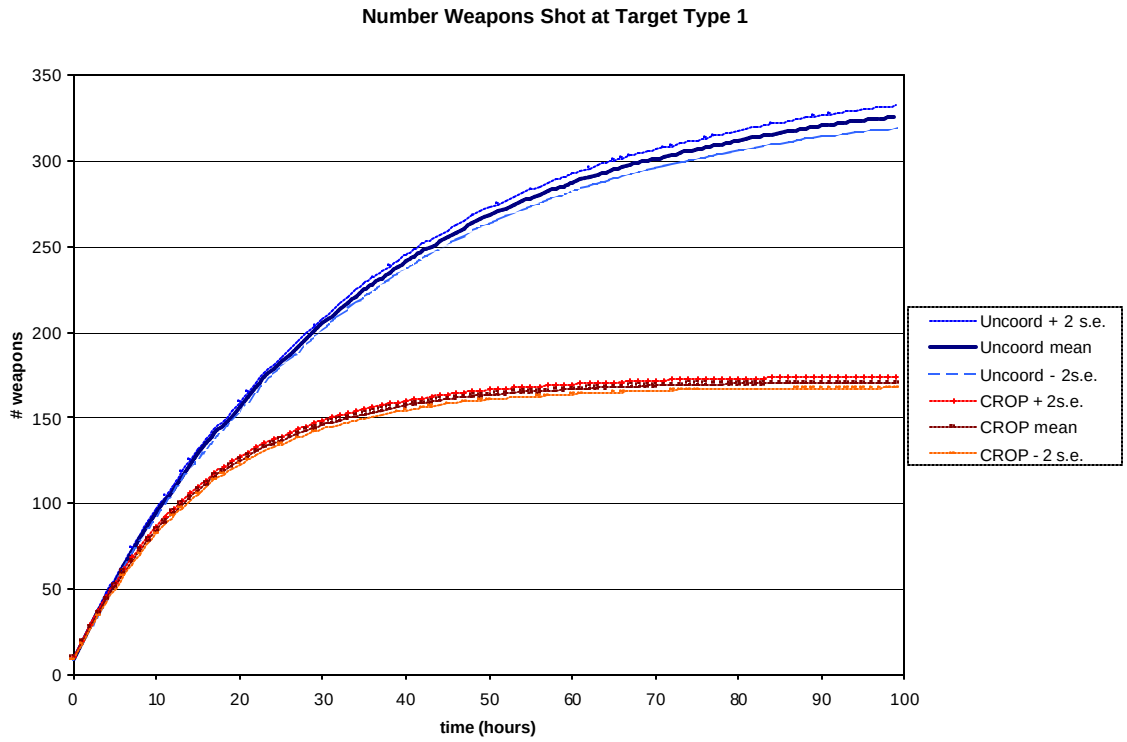

Figure 13. Mean Number of Weapons Expended and 95% CI on Target Type 1 in time T

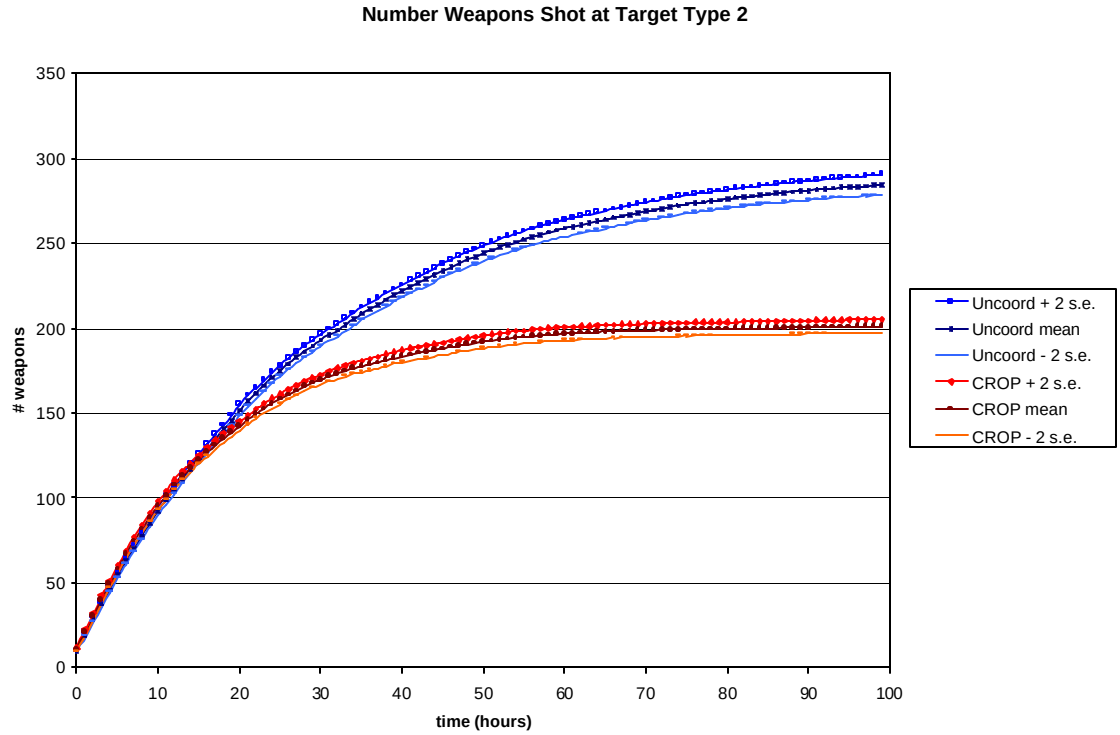

Figure 14. Mean Number of Weapons Expended and 95% CI on Target Type 2 in time T

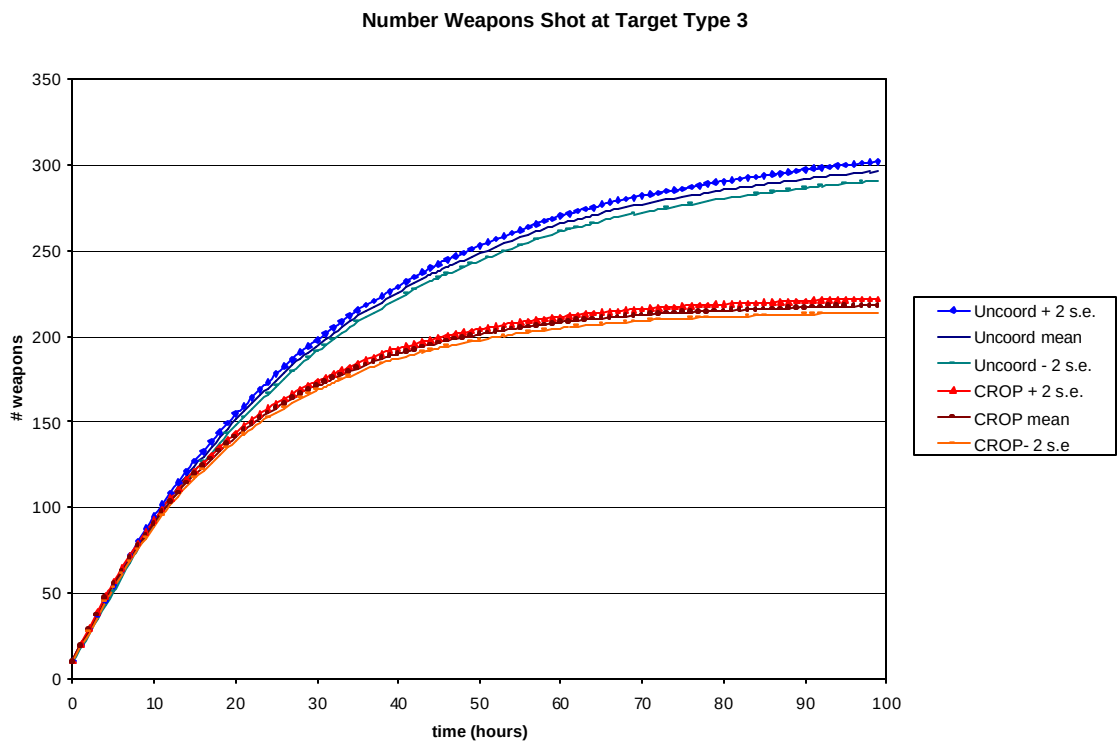

Figure 15. Mean Number of Weapons Expended and 95% CI on Target Type 3 in time T

Table 8 below displays the results from a simulation, starting with 100 targets present at time 0, and ending at time = 100 hours.

Environment	True Target Type	Mean Number of Weapons Expended T < 100 hours. For 100 targets	- 2 standard errors	+ 2 standard errors
CROP	1	170.56	167.5	173.7
	2	201.06	197.1	205.0
	3	217.9	213.8	222.0
Uncoordinated Services	1	325.9	319.3	332.5
	2	284.48	278.5	290.4
	3	296.46	290.9	302.0

Table 8. Mean Number of Weapons Expended in time interval (0, 100 hours], from the simulation

The mean number of weapons expended against target type 1 in the CROPDUSTER Model for CROP is 173.6. The interval from the analytical model with +/- two standard deviations is from 150.9 to 196.3 weapons. For the Uncoordinated services the analytical model's mean number of weapons against targets of type 1 is 306.4, with the interval of 259.4 to 352.8 weapons.

F. DISCUSSION

Using the mean of the target survival time, the mean number of targets lost and the mean number of weapons expended in time T = 100 hours as the Measures of Effectiveness, the simulation output compares well to the CROPDUSTER model. With the same input parameters and minimizing the impact of other parameters not used in the analytical model, notably the time to Classify, Weaponeer, Shoot and Evaluate, the simulation's output means are close to the 2 standard errors of the analytic calculations. This coupled with the exponential distribution of the time to kill a target suggested by the –ln empirical survivor function plots, suggests the simulation is consistent with the CROPDUSTER analytical model for these parameters.

V. EFFECTS OF THE BDA PARAMETER ON THE NUMBER OF WEAPONS EXPENDED AFTER THE TARGET IS KILLED

A. INTRODUCTION

The purpose of this chapter is to explore the effects of BDA on the number of weapons expended against a target after it has been killed. This is accomplished by varying the BDA Parameter for both CROP and the Uncoordinated Services. The BDA Parameter is equal to the probability that the BDA information is accurate. The values will range from 0.1 to 1.0 in increments of 0.1. The data are displayed by environment: CROP and Uncoordinated Services. The mean number of weapons expended after the target is killed is computed. The Measure of Effectiveness under investigation is the number of weapons expended after the target is killed, and if and how the BDA Parameter affects this number. A dead target of type r has the same classification probabilities shown in Table 9 below. The number of weapons expended after the target is killed is the number of weapons wasted on a dead target.

B. PARAMETERS

The following tables show the parameters used in the 1000 simulation runs.

True Target Type	Classified Target Type		
	1	2	3
1	0.8	0.1	0.1
2	0.3	0.6	0.1
3	0.2	0.1	0.7

Table 9. CROP and the Uncoordinated Service's Conditional Probability of Classifying a Target, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.7	0.125	0.15
2	0.1	0.6	0.1
3	0.1	0.1	0.5

Table 10. Service 1, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.15	0.1	0.1
2	0.15	0.75	0.15
3	0.05	0.05	0.15

Table 11. Service 2, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.15	0.1	0.1
2	0.1	0.125	0.1
3	0.1	0.1	0.6

Table 12. Service 3, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.7	0.1	0.1
2	0.1	0.75	0.1
3	0.1	0.1	0.6

Table 13. CROP, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Service			
	1	2	3	CROP
1	4	6	12	4
2	4	6	12	4
3	4	6	12	4

Table 14. The Classification Rates for each Service and CROP given the True Target Type

True Target Type	Service		
	1	2	3
1	12	12	6
2	12	12	6
3	12	12	6

Table 15. The Weaponeering Rates for each Service given the True Target Type

True Target Type	Service		
	1	2	3
1	12	3	4
2	12	3	4
3	12	3	4

Table 16. The Shooting Rates for each Service given the True Target Type

Rates	True Target Type		
	1	2	3
Hide	4.0	12.0	6.0
Loss	2.5	1.75	2.0

Table 17. Hide and Loss Rates for the Targets

The conditional classification probabilities are the same for CROP and the Uncoordinated Services. The services each have three weapons; however each service is specialized against one target type. In the CROP environment the "best" weapon is chosen against the classified target type. The "best" weapon for the simulation is the weapon with the highest single shot probability of kill against that target type. Unfortunately CROP does not make the weapon better, therefore the weapon brings along its inability to kill the other target types, if the target is classified incorrectly.

The times to classify, weaponeer, shoot, lose, and hide are independent, and all assumed to be random variables with a general distribution. For this study, the random times are taken to be a constant plus an exponential time. The constants represent a minimum time for each of the processes. The minimum times are: classify-5 minutes (0.0833 hours), weaponeer-1 minute (0.0167 hours), shoot-6 minutes (0.1 hours), lose-1 minute (0.0167 hours), and hide-0.5 minutes (30 seconds or 0.00833 hours).

The BDA parameters are varied for each of these parameter sets from 0.1 to 1.0 with increments of 0.1. The detection rates and re-detection rates remain the same, 1/12 (0.083) for each Uncoordinated Service and 3/12 (0.25) for CROP.

C. OUTPUTS

The simulation was run for each BDA Parameter for each target type and each environment with 1000 replications. The tables and plots below are generated from the

results of those simulation runs. Plotted are the mean number of weapons expended after the target was killed and the 95% confidence interval (1.96*standard error).

Finding a relationship between the numbers of weapons expended after the target is killed and the BDA Parameter is the goal of this chapter. The following tables show the statistics for both CROP and the Uncoordinated Services.

BDA Parameter	Target Type 1		Target Type 2		Target Type 3	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
0.1	9.65	10.1	9.27	9.7	9.22	9.5
0.2	3.98	4.6	3.76	4.4	4.07	4.8
0.3	2.26	2.7	2.29	2.74	2.29	2.8
0.4	1.44	1.9	1.51	1.96	1.52	1.9
0.5	0.97	1.42	0.96	1.4	1.02	1.38
0.6	0.63	1.05	0.68	1.09	0.66	1.04
0.7	0.41	0.75	0.41	0.77	0.47	0.86
0.8	0.25	0.54	0.25	0.56	0.26	0.58
0.9	0.1	0.31	0.1	0.32	0.099	0.34
1.0	0	0	0	0	0	0

Table 18. CROP Mean Number of Weapons Expended After Target is Killed

BDA Parameter	Target Type 1		Target Type 2		Target Type 3	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
0.1	8.76	9.39	9.3	9.3	8.93	9.7
0.2	3.85	4.4	4.02	4.4	4.07	435
0.3	2.17	2.6	2.32	2.8	2.14	2.6
0.4	1.42	1.9	1.5	2.04	1.38	1.9
0.5	0.92	1.39	0.97	1.47	0.94	1.4
0.6	0.68	1.17	0.63	1.07	0.64	1.01
0.7	0.4	0.79	0.39	0.76	0.43	0.82
0.8	0.26	0.59	0.21	0.5	0.24	0.53
0.9	0.12	0.39	0.1	0.34	0.11	0.35
1.0	0	0	0	0	0	0

Table 19. Uncoordinated Services Mean Number of Weapons Expended After Target is Killed

The numbers clearly show a pattern. The plots of the data below show without a doubt there is a relation between the number of weapons expended after the target is dead and the probability of accurate BDA information, the BDA Parameter.

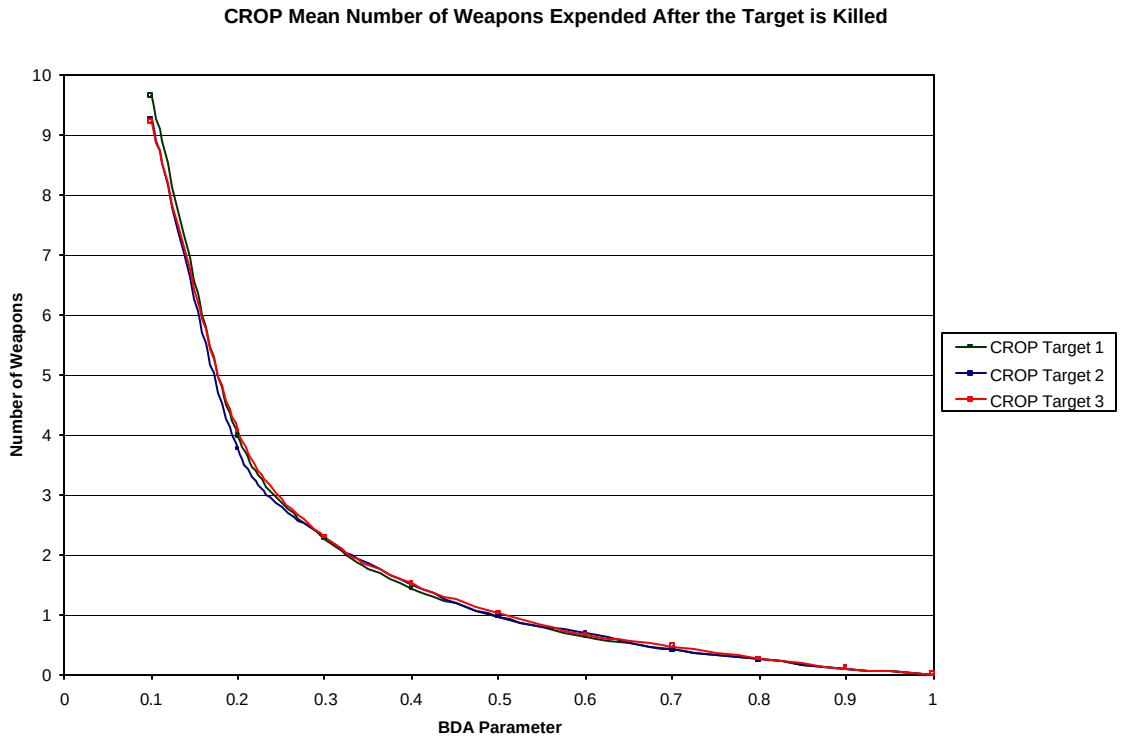

Figure 16. CROP Mean Numbers of Weapons Expended After the Target is Killed

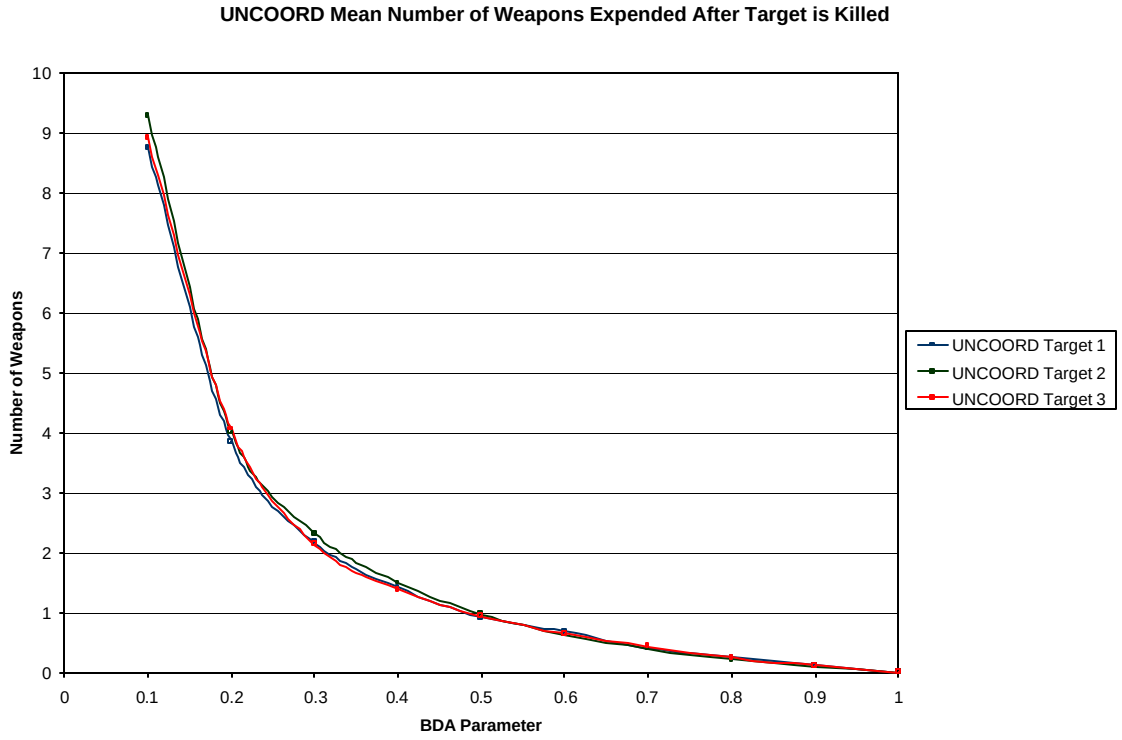

Figure 17. Uncoordinated Services Mean Numbers of Weapons Expended After the Target is Killed

D. DISCUSSION

Comparing the two environments (CROP and Uncoordinated services) and three target types in each environment, it appears that the number of weapons expended after the target is killed is highly dependent on the BDA Parameter. Looking at the plots and tables above, it is obvious there is a pattern.

Some investigation shows the number of weapons expended after a target is killed has a geometric distribution (the number of failures before the first success), or a negative binomial distribution with r = 1, as defined in reference 7. Where r is the number of successes desired before the experiment ends. In this case r =1, as there is only one success required, success in this case is to declare a dead target, to be dead.

Using the equations, in reference 7, page 132, for the expected value and the variance of the distribution.

$$\mathrm{E}[X] = \frac{r(1-p)}{p} \tag{19}$$

$$V[X] = \frac{r(1-p)}{p^2} \tag{20}$$

BDA Parameter P	1-p	E[X]	V[X]	Standard Deviation
0.1	0.9	9.0	90	9.49
0.2	0.8	4.0	20	4.47
0.3	0.7	2.33	7.78	2.79
0.4	0.6	1.5	3.75	1.94
0.5	0.5	1.0	2.0	1.41
0.6	0.4	0.67	1.11	1.05
0.7	0.3	0.43	0.61	0.78
0.8	0.2	0.25	0.31	0.56
0.9	0.1	0.11	0.12	0.35
1.0	0.0	0.0	0.0	0.0

Table 20. The Statistics of the Negative Binomial Distribution with Parameters shown, r = 1

The values in table 20 corresponding to the expected value (column 3) are comparable to the values in tables 18 and 19 above. This shows that the number of weapons fired at a dead target is directly related to the BDA Parameter and the number of weapons fired can

be predicted using the geometric distribution. The data shows that if the BDA accuracy is above 0.5 or 50% the mean number of weapons “wasted” on a target should be at most one.

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VI. EFFECTS OF CLASSIFICATION RATE ON THE TIME TO KILL A TIME-CRITICAL TARGET

A. INTRODUCTION

This chapter investigates the effect on CROP of the classification time rate. It is assumed that the Uncoordinated Services are specialized against a certain target type. The service's sensors and weapons both have increased capability against this target type. The weapons have a higher single shot probability of kill and the sensors have a higher probability of classifying it correctly.

CROP classification is fused using an algorithm described in CROPDUSTER [reference 5]. The parameters shown below for the conditional probabilities were calculated using reference 8, a spreadsheet model where the inputs are the individual service's conditional probabilities for correct classification, and the output is a fused conditional probability matrix for CROP.

To determine the effects of the classification time rate on the time to kill a target a baseline rate is selected and incrementally decreased. This decrease, or increase in the mean time to classify, roughly quantifies the entire Command and Control overhead latency associated with CROP. The goal is to determine how much of this overhead can exist for CROP to be more beneficial than the Uncoordinated Services.

B. PARAMETERS

The following tables show the parameters used in the simulation runs for this chapter. The first four tables show the conditional classification probabilities for the services and CROP. They show that the services are again highly specialized. The weapons for the services also remain specialized. The CROP conditional classification probabilities are calculated using a fusion algorithm from CROPDUSTER [reference 5]. The calculations were conducted in a spreadsheet model [reference 8].

True Target Type	Classified Target Type		
	1	2	3
1	1.0	0.0	0.0
2	0.25	0.5	0.25
3	0.25	0.25	0.5

Table 21. Service 1, Conditional Probability of Classifying a Target, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.5	0.25	0.25
2	0.0	1.0	0.0
3	0.25	0.25	0.5

Table 22. Service 2, Conditional Probability of Classifying a Target, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.5	0.25	0.25
2	0.25	0.5	0.25
3	0.0	0.0	1.0

Table 23. Service 3, Conditional Probability of Classifying a Target, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.8	0.1	0.1
2	0.1	0.8	0.1
3	0.1	0.1	0.8

Table 24. CROP, Conditional Probability of Classifying a Target, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.7	0.125	0.15
2	0.1	0.6	0.1
3	0.1	0.1	0.5

Table 25. Service 1, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.15	0.1	0.1
2	0.15	0.75	0.15
3	0.05	0.05	0.15

Table 26. Service 2, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.15	0.1	0.1
2	0.1	0.125	0.1
3	0.1	0.1	0.6

Table 27. Service 3, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Classified Target Type		
	1	2	3
1	0.7	0.1	0.1
2	0.1	0.75	0.1
3	0.1	0.1	0.6

Table 28. CROP, Probability of Kill for a Classified Target Type, given its True Target Type

True Target Type	Service			
	1	2	3	CROP
1	4	6	12	4
2	4	6	12	4
3	4	6	12	4

Table 29. The Classification Rates for each Service and CROP given the True Target Type

True Target Type	Service		
	1	2	3
1	12	12	6
2	12	12	6
3	12	12	6

Table 30. The Weaponeering Rates for each Service given the True Target Type

True Target Type	Service		
	1	2	3
1	12	3	4
2	12	3	4
3	12	3	4

Table 31. The Shooting Rates for each Service given the True Target Type

Rates	True Target Type		
	1	2	3
Hide	4.0	12.0	6.0
Loss	2.5	1.75	2.0

Table 32. Hide and Loss Rates for the Targets

The services in this investigation are specialized against certain target types. A close look at the conditional classification probability matrices shows that each service correctly classifies a certain target type with probability 1. Each service also has a weapon with a higher probability of kill than those of the other services against the target type that the service classifies correctly with probability 1. However, the weapons are not perfect against a target. This special target type is different for each service.

The times to classify, weaponeer, shoot, lose, and hide are all assumed to be independent and exponential; each has a minimum time, a constant added to a random exponential time is in the simulation. The minimum times are: classify-5 minutes (0.0833 hours), weaponeer-1 minute (0.0167 hours), shoot-6 minutes (0.1 hours), lose-1 minute (0.0167 hours), and hide-0.5 minutes (30 seconds or 0.00833 hours).

In this chapter the classification time rate for CROP is changed. The rate begins at 6.0 and is decreased to 4.0, 3.0 and then 2.4. The BDA Parameter used in the simulation for this chapter is 0.75.

C. OUTPUTS

The following tables and plots are of the probabilities of killing a target in time ≤ t, for both CROP and the Uncoordinated Services. Each simulation run, as in chapter V, replicated 1000 targets. The tables and plots are arranged by target type, and classification time rate to easily compare the CROP and Uncoordinated Services ability

to kill the three target types. The plots show the probability of killing the target in time ≤ t and the corresponding 95 % confidence interval (1.96 * standard error).

Classification Rate	Environment	Mean (std error)	Standard Deviation
6.0	CROP	22.44 (0.69)	21.68
	Uncoordinated	52.77(1.72)	54.27
4.0	CROP	27.44 (0.86)	27.05
	Uncoordinated	51.09 (1.66)	52.34
3.0	CROP	30.7 (0.92)	29.12
	Uncoordinated	52.54 (1.64)	52.00
2.4	CROP	33.63 (1.02)	32.18
	Uncoordinated	51.37 (1.56)	49.46

Table 33. Mean Times to Kill True Target Type 1 for Classification Time Rates

Classification Rate	Environment	Mean (std error)	Standard Deviation
6.0	CROP	22.06 (0.67)	21.06
	Uncoordinated	33.73 (1.02)	32.26
4.0	CROP	24.75 (0.73)	23.19
	Uncoordinated	33.54 (1.02)	32.32
3.0	CROP	27.68 (0.81)	25.59
	Uncoordinated	33.76 (1.03)	32.45
2.4	CROP	29.68 (0.87)	27.63
	Uncoordinated	33.85 (1.03)	32.41

Table 34. Mean Times to Kill True Target Type 2 for Classification Time Rates

Classification Rate	Environment	Mean (std error)	Standard Deviation
6.0	CROP	33.75 (1.06)	33.41
	Uncoordinated	43.75 (1.26)	39.86
4.0	CROP	36.98 (1.18)	37.4
	Uncoordinated	40.34 (1.17)	37.01
3.0	CROP	41.99 (1.31)	41.45
	Uncoordinated	40.32 (1.21)	38.18
2.4	CROP	46.53 (1.45)	45.72
	Uncoordinated	40.07 (1.21)	38.23

Table 35. Mean Times to Kill True Target Type 3 for Classification Time Rates

The closeness of the estimated standard deviations to the means in the above tables suggests that the exponential distribution may be an adequate approximation for the

distribution of the time to kill a target. The values in the tables above show as the classification time rates for CROP decrease, meaning the mean time for CROP to classify the target increases, the benefits of CROP fade and the mean time to kill the target becomes comparable to that of the Uncoordinated Services. The plots below illustrate this very well. They are grouped by target type and show the progression as the classification time rate decreases.

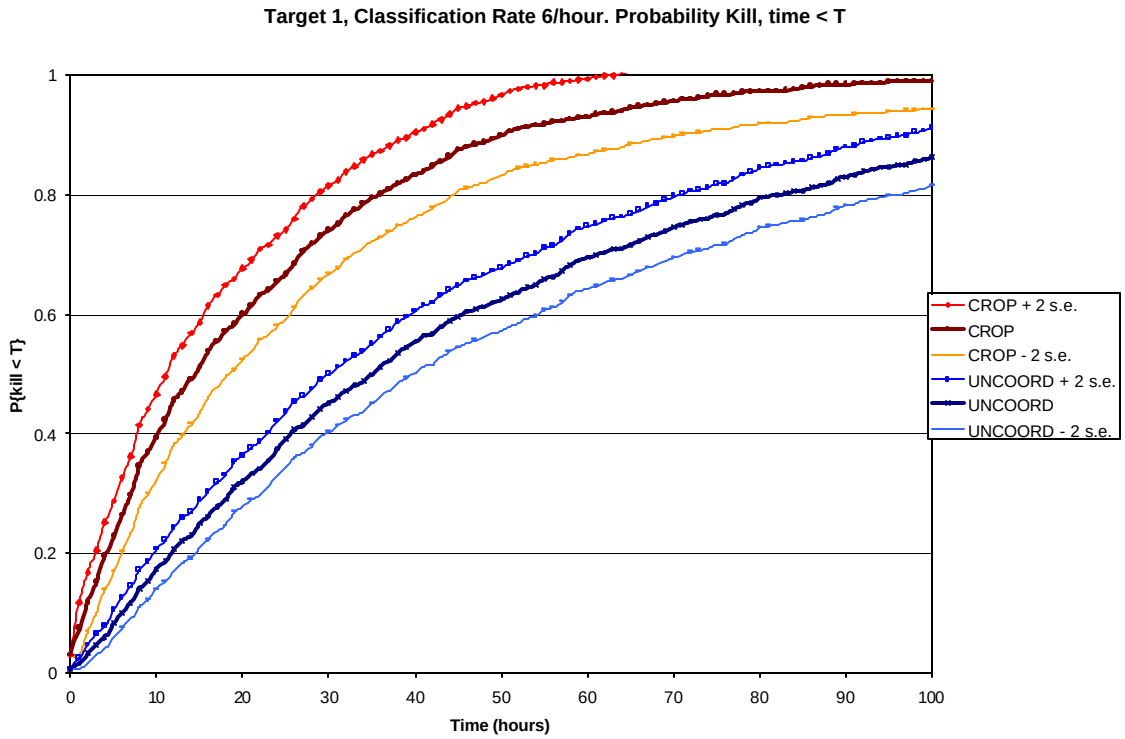

Figure 18. Classification Rate 6.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 1, time ≤ t, with 95% Confidence Interval

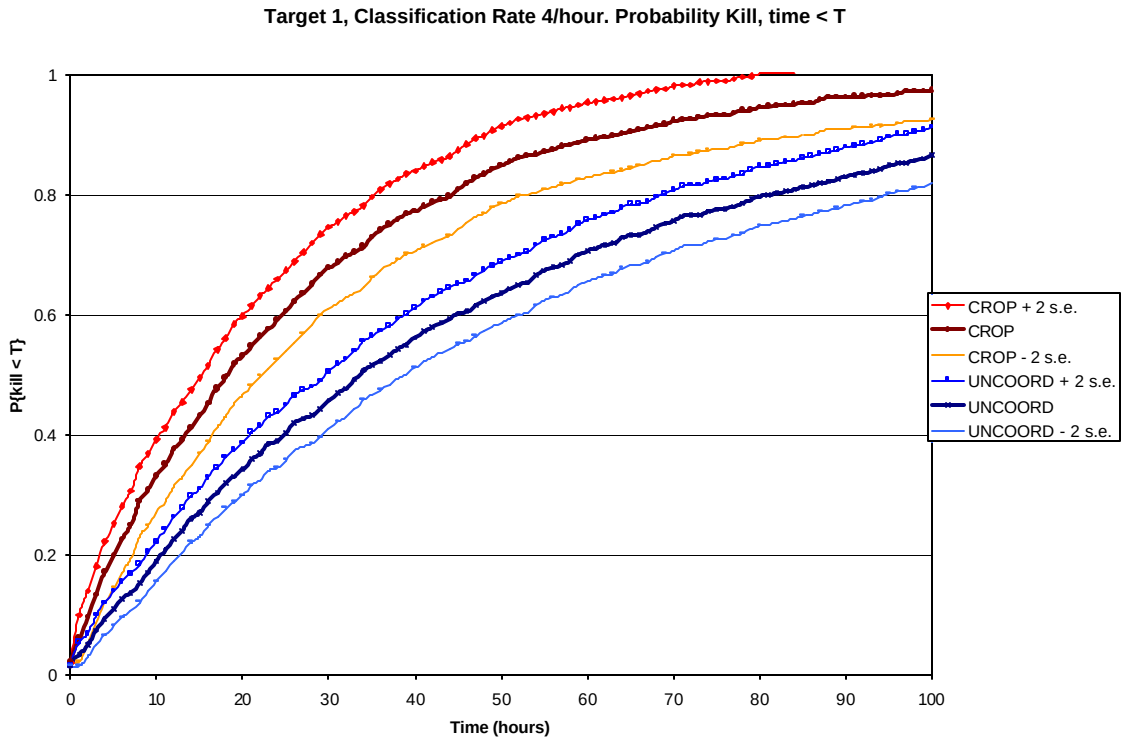

Figure 19. Classification Rate 4.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 1, time ≤ t, with 95% Confidence Interval

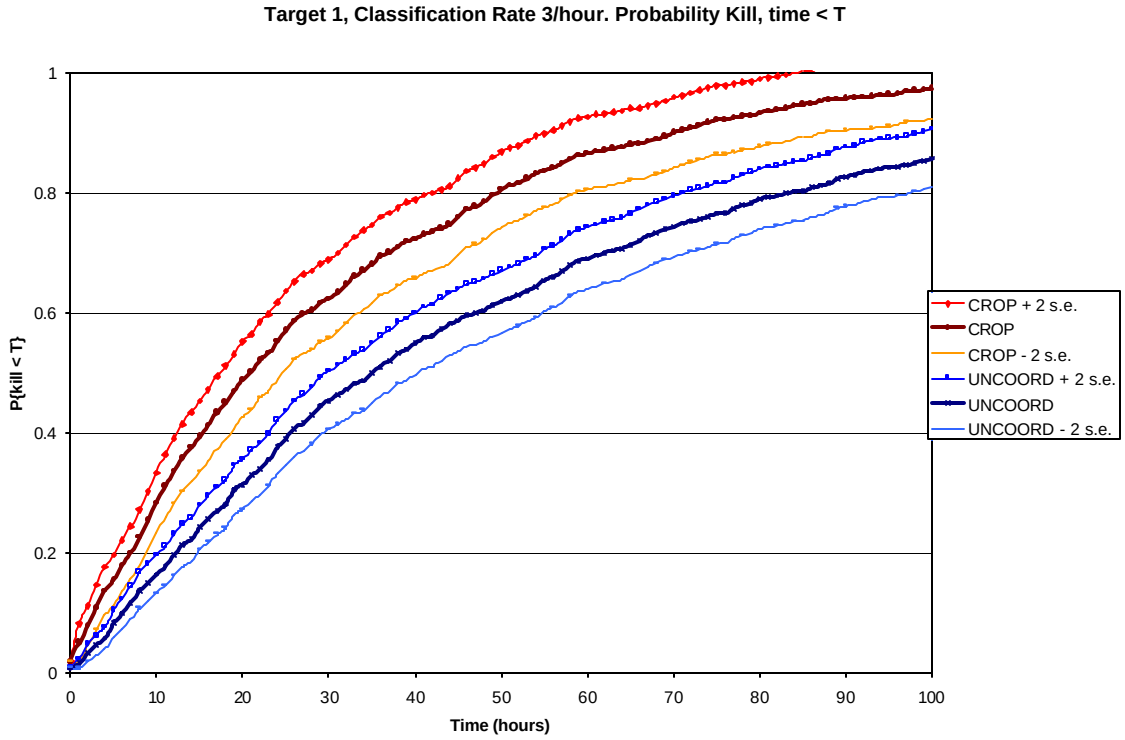

Figure 20. Classification Rate 3.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 1, time ≤ t, with 95% Confidence Interval

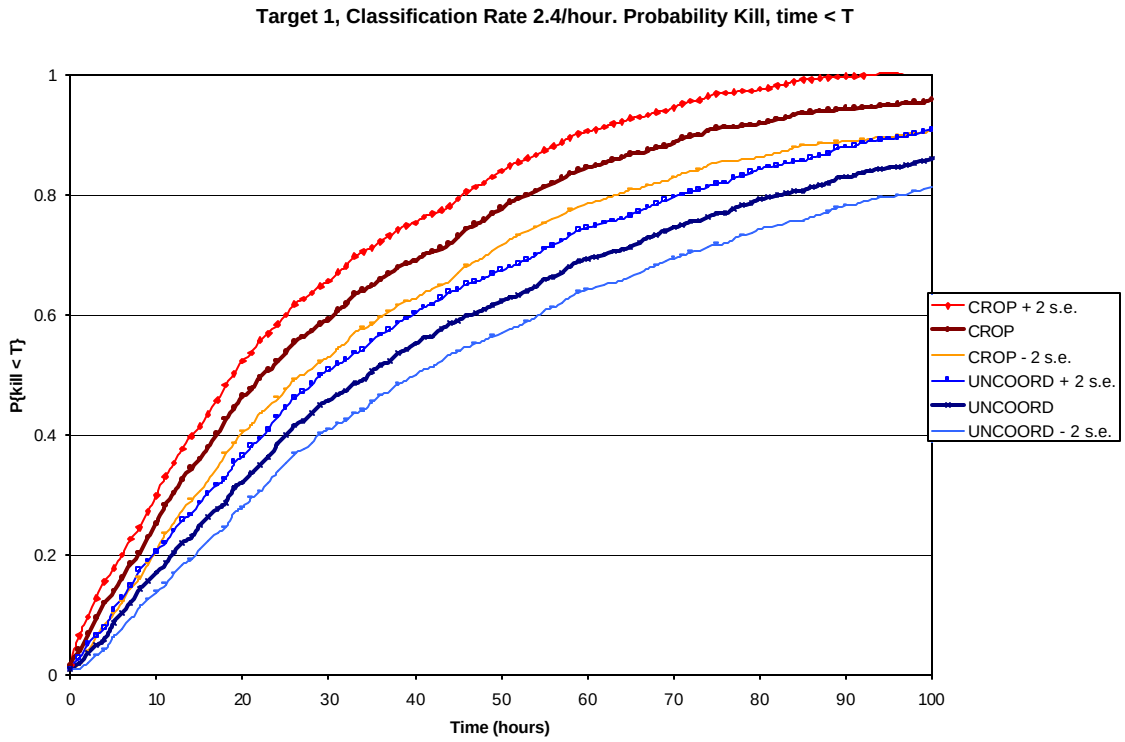

Figure 21. Classification Rate 2.4. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 1, time ≤ t, with 95% Confidence Interval

The figures above show the progression of the estimated probability that the time to kill is less than or equal to t plus and minus 2 standard errors, toward the corresponding estimated probabilities for the Uncoordinated Services. The classification time rate where CROP and the Uncoordinated Service's estimated probabilities are statistically the same is 1.2 / hour, or a mean time of 50 minutes for CROP to classify the target. The figures below show the estimated –ln (survival probability). The survival probability is 1-cdf of the time to kill. This is the probability that a target survives longer than time T. The estimated –ln (survival probability) graph is approximately linear.

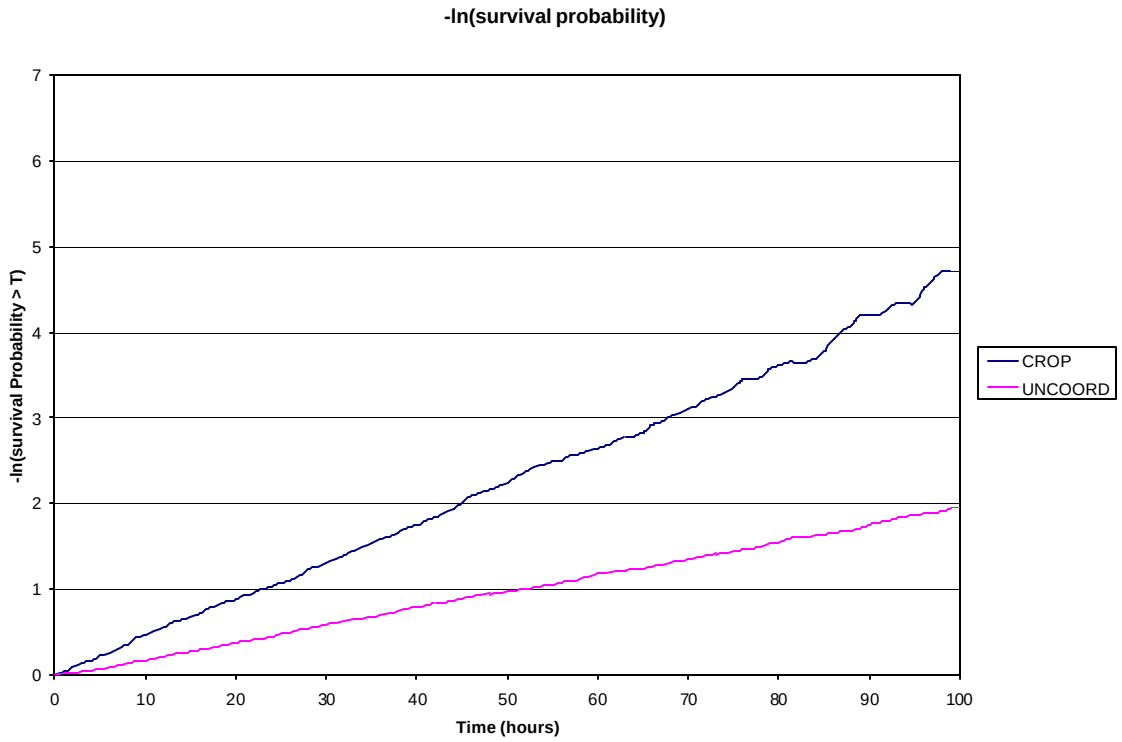

Figure 22. Estimated -ln(Survival Probability) Target Type 1 Classification Rate 6.0

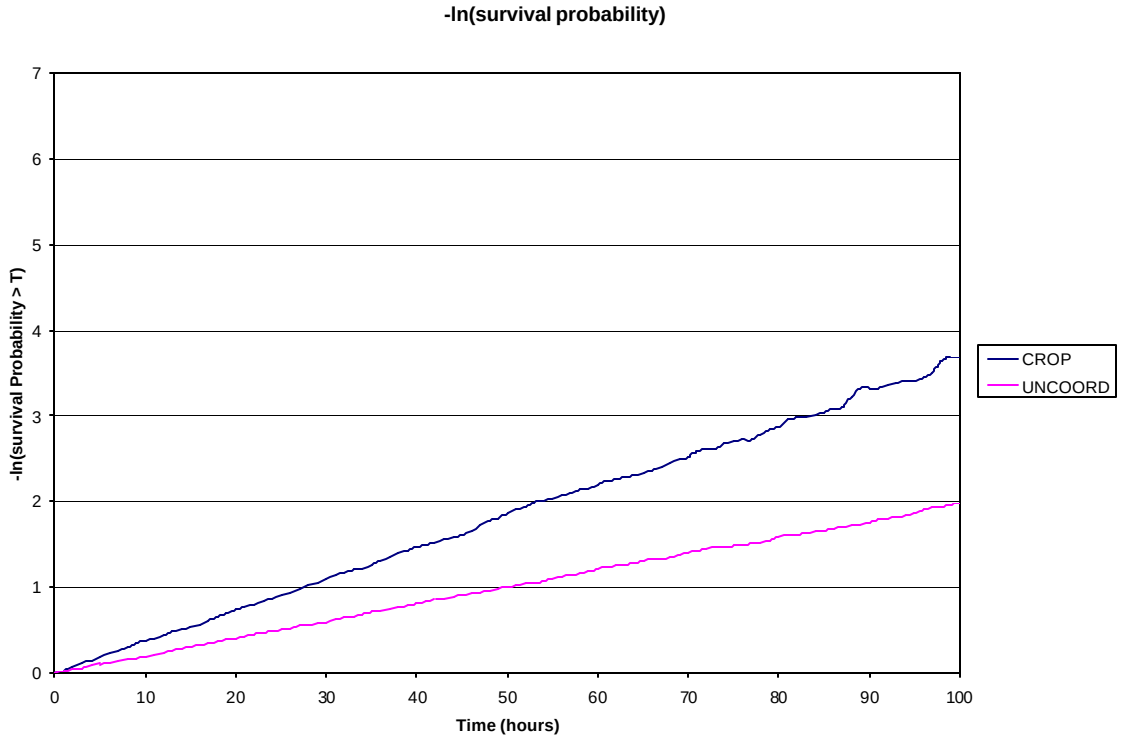

Figure 23. Estimated -ln(Survival Probability) Target Type 1 Classification Rate 4.0

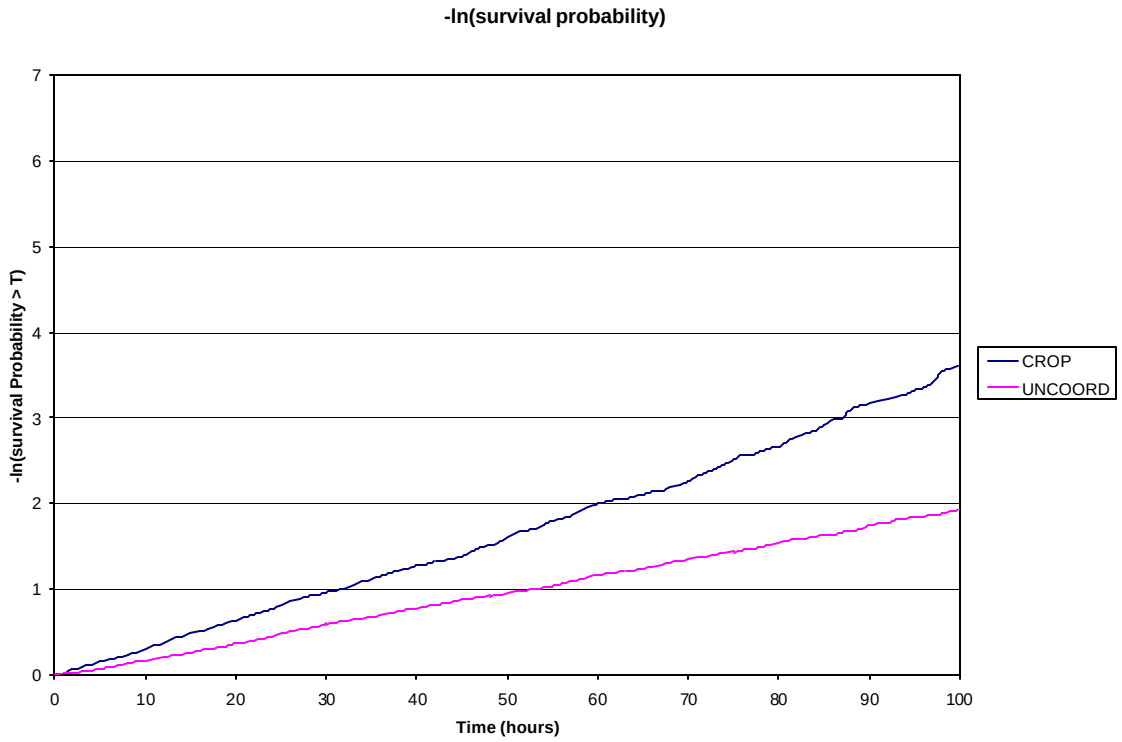

Figure 24. Estimated -ln(Survival Probability) Target Type 1 Classification Rate 3.0

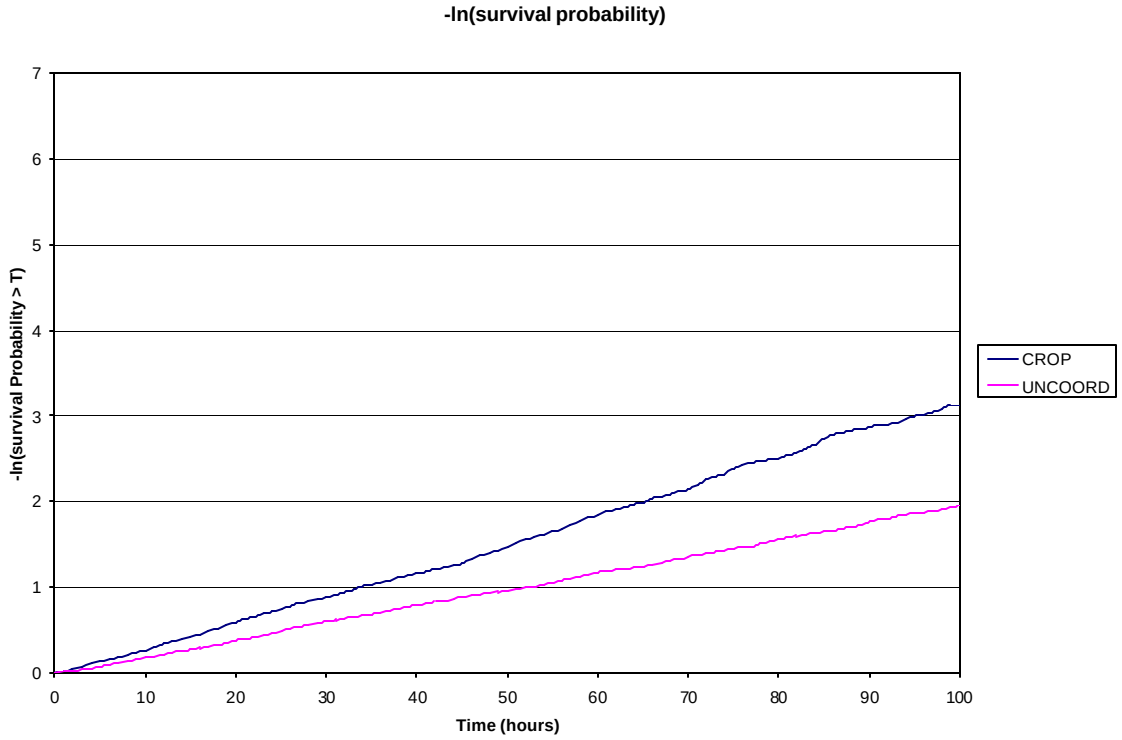

Figure 25. Estimated -ln(Survival Probability) Target Type 1 Classification Rate 2. 4

These plots, the estimated -ln(Survival Probability), show that the CROP ln survivor probabilities for the time to kill the target are approaching the Uncoordinated Services time to kill ln survival probabilities as CROP's classification time rate decreases. The linearity of the plots suggests that the exponential distribution is an adequate approximation to the distribution of the time to kill a target for the parameter values considered here.

The figures below show that for target types 2 and 3 the estimated probabilities of the time to kill the target is less than or equal to t become statistically similar for CROP and the Uncoordinated Services at a lower classification time rate.

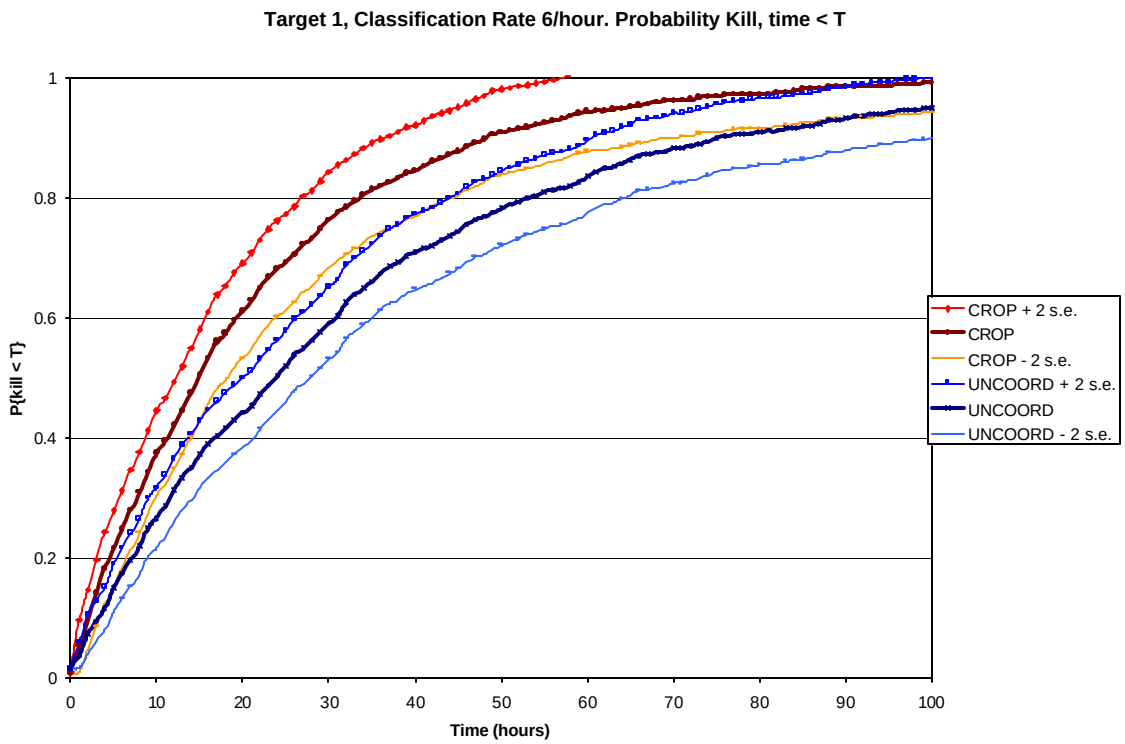

Figure 26. Classification Rate 6.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 2, time ≤ t, with 95% Confidence Interval

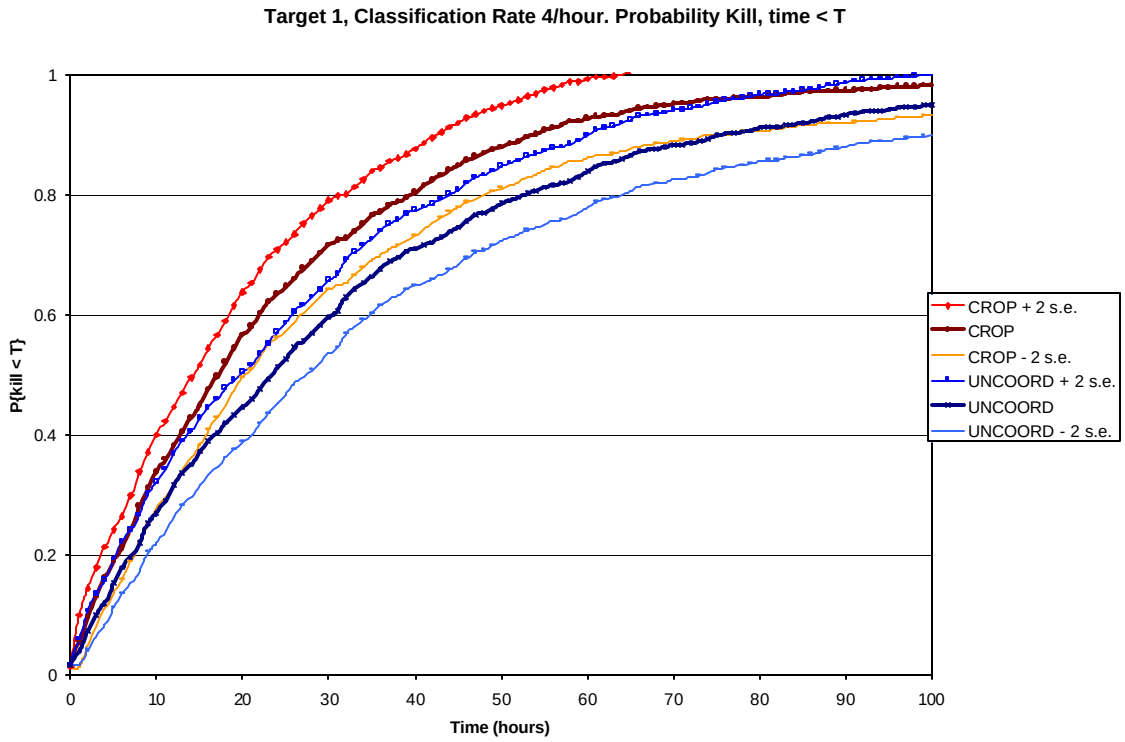

Figure 27. Classification Rate 4.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 2, time ≤ t, with 95% Confidence Interval

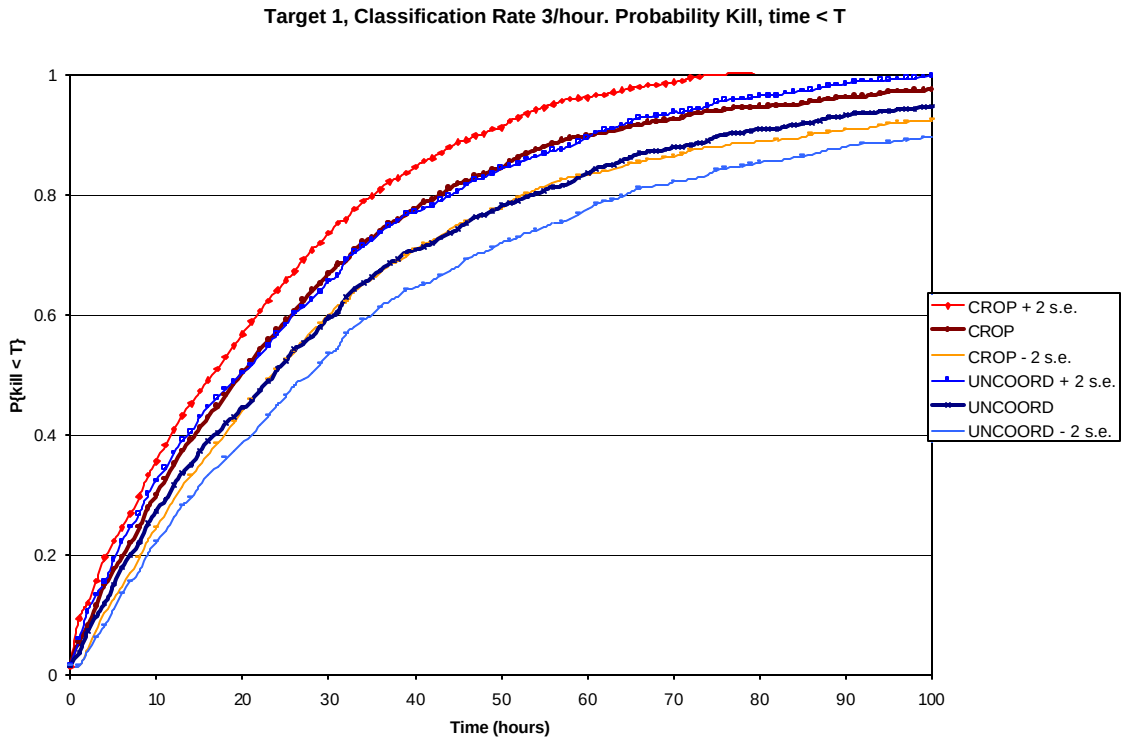

Figure 28. Classification Rate 3.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 2, time ≤ t, with 95% Confidence Interval

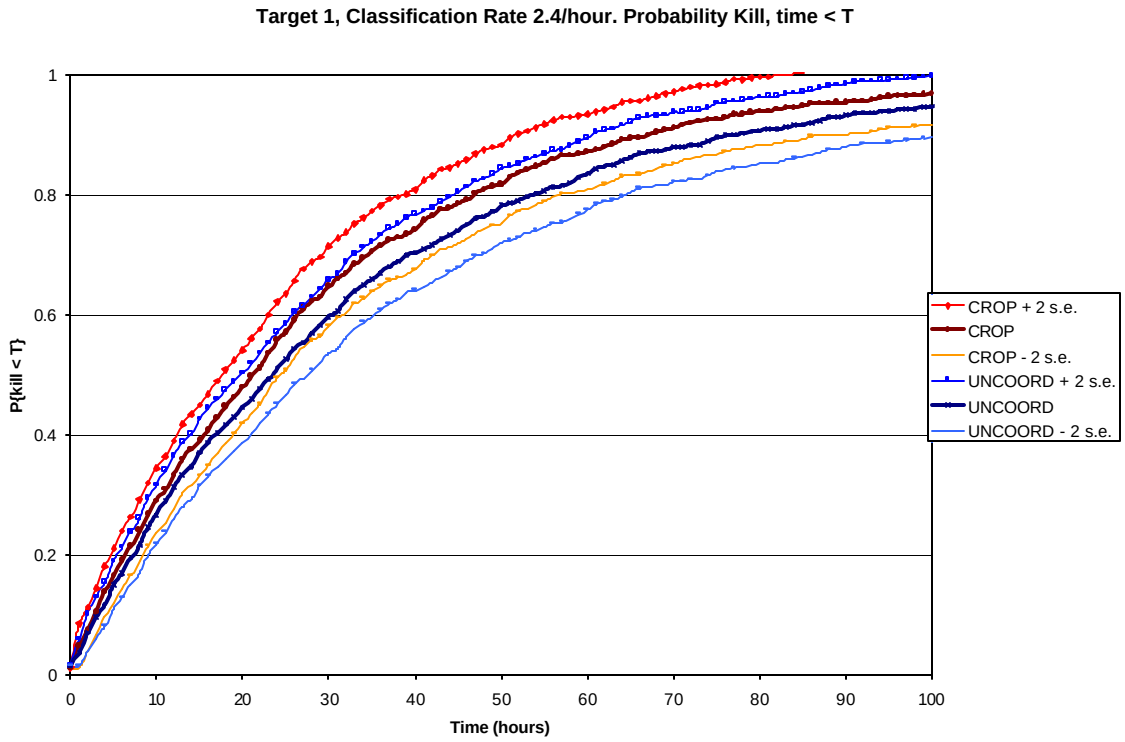

Figure 29. Classification Rate 2.4. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 2, time ≤ t, with 95% Confidence Interval

As with target type 1, as the classification time rate decreases the CROP estimated probability that the time to kill the target in time ≤ t, decreases for each time t. For target type 2, when the classification rate is 3.0 the 95% confidence intervals of the probability of killing the target in time ≤ t, for CROP and the Uncoordinated Services are very close but not overlapping, this is clearly shown in Figure 28. Decreasing the classification time rate to 2.4 clearly puts the two probabilities within the 95% confidence intervals. When the classification time rate is equal to 3.0, or 25 minutes (20 minutes + 5 minute minimum) the estimated distribution of the time to kill for CROP is on the verge of being statistically the same as the Uncoordinated Services. CROP has lost its benefit when the classification mean time gets to 30 minutes.

The estimated –ln(Survival Probabilities) displayed below confirms that the estimated distributions of the time to kill for the two environments become similar as CROP's classification time rate decreases.

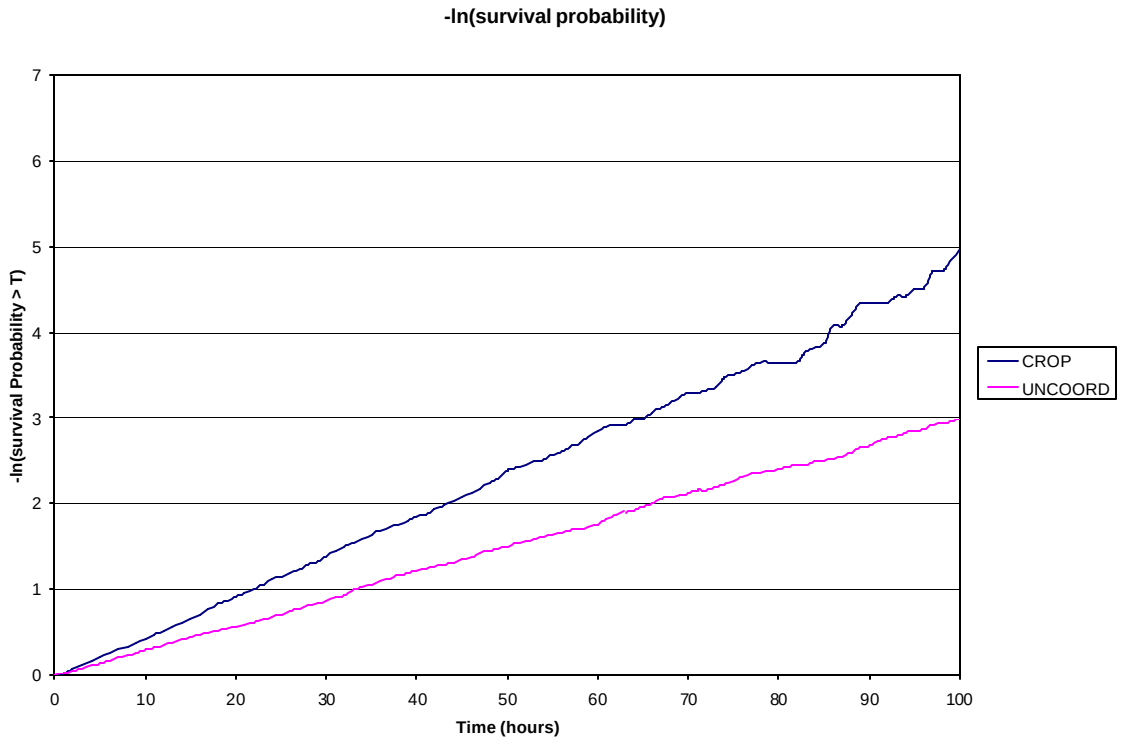

Figure 30. Estimated -ln(Survival Probability) Target Type 2 Classification Rate 6.0

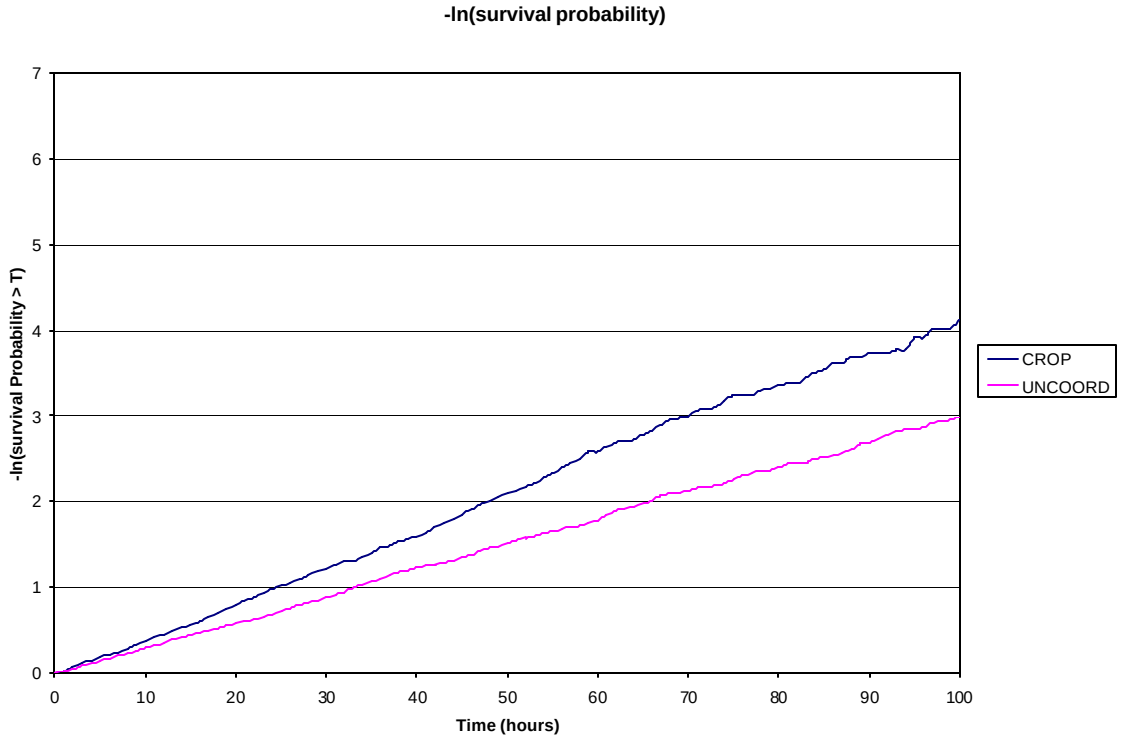

Figure 31. Estimated -ln(Survival Probability) Target Type 2 Classification Rate 4.0

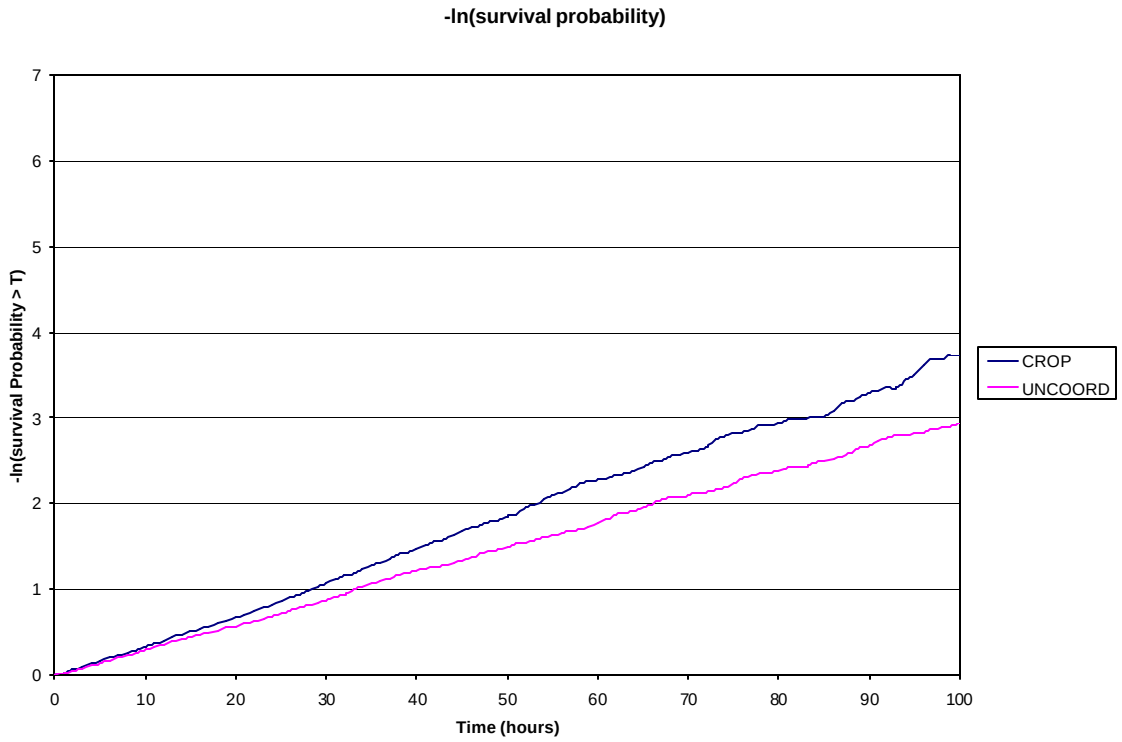

Figure 32. Estimated -ln(Survival Probability) Target Type 2 Classification Rate 3.0

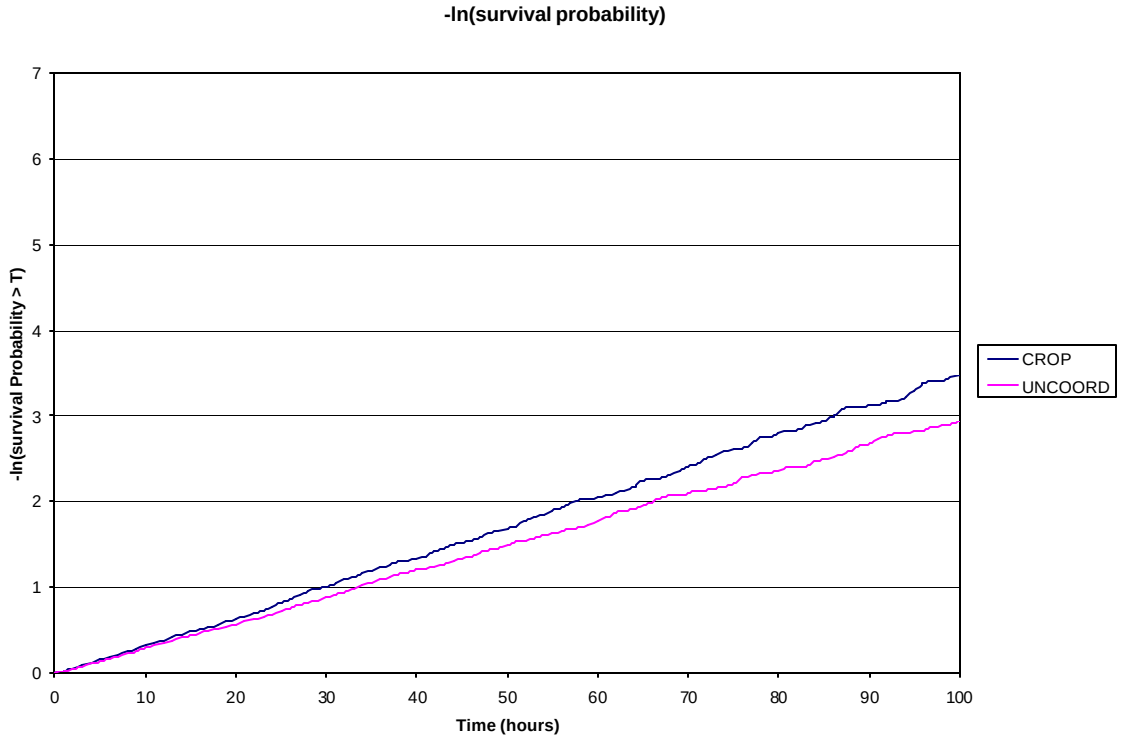

Figure 33. Estimated -ln(Survival Probability) Target Type 2 Classification Rate 2.4

These Figures, 30, 31, 32, and 33 show the estimated – ln survival probabilities of the time to kill a type 2 target; they clearly show that the estimated distribution of the time to kill for CROP becomes similar to that of the Uncoordinated Services, as the classification time rate decreases.

Target Type 3 plots are below.

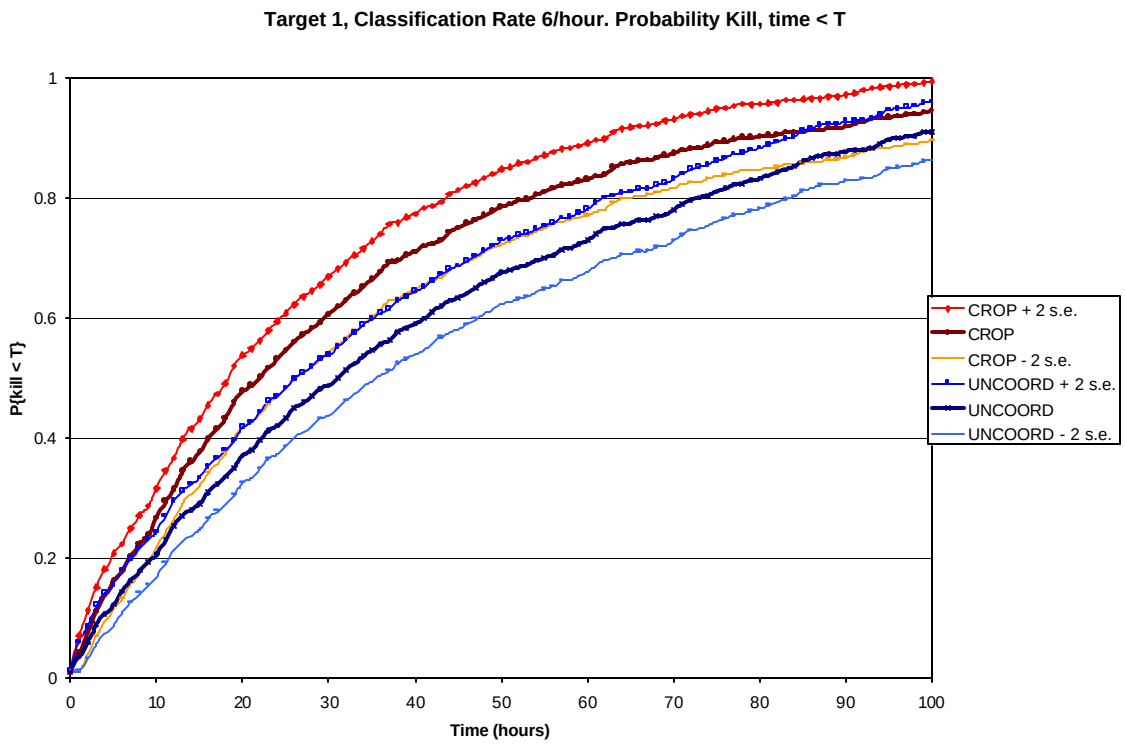

Figure 34. Classification Rate 6.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 3, time ≤ t, with 95% Confidence Interval

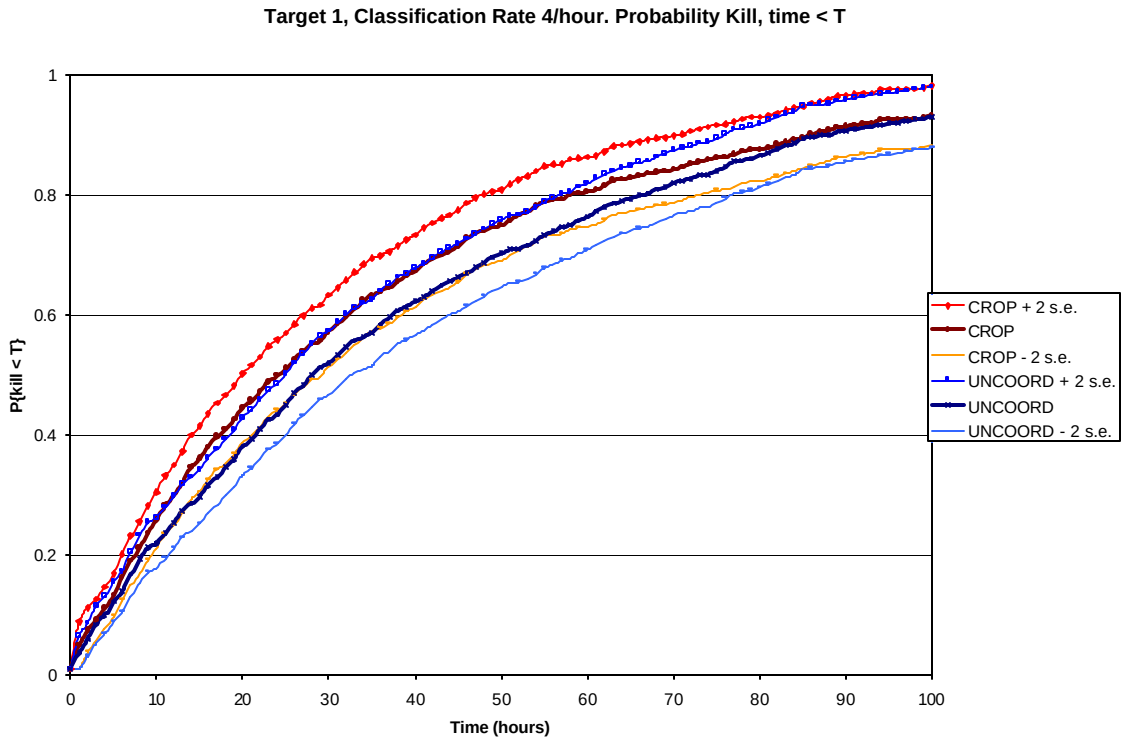

Figure 35. Classification Rate 4.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 3, time ≤ t, with 95% Confidence Interval

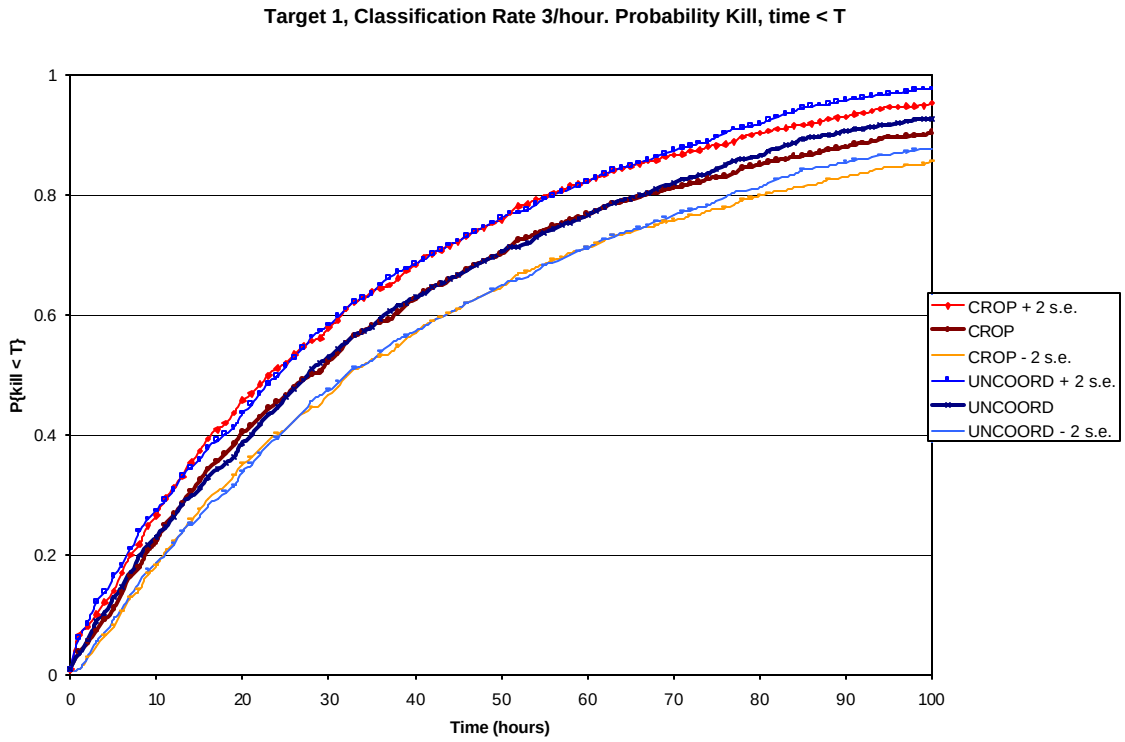

Figure 36. Classification Rate 3.0. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 3, time ≤ t, with 95% Confidence Interval

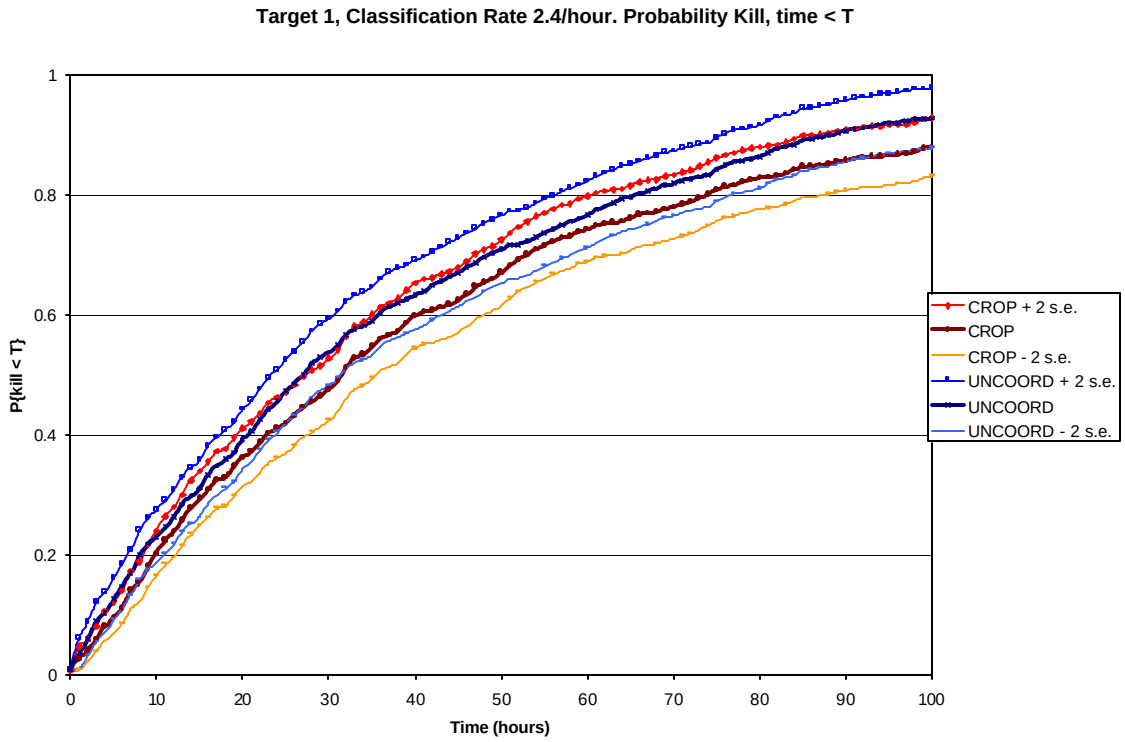

Figure 37. Classification Rate 2.4. CROP and Uncoordinated Services Estimated Probability of Killing Target Type 3, time ≤ t, with 95% Confidence Interval.

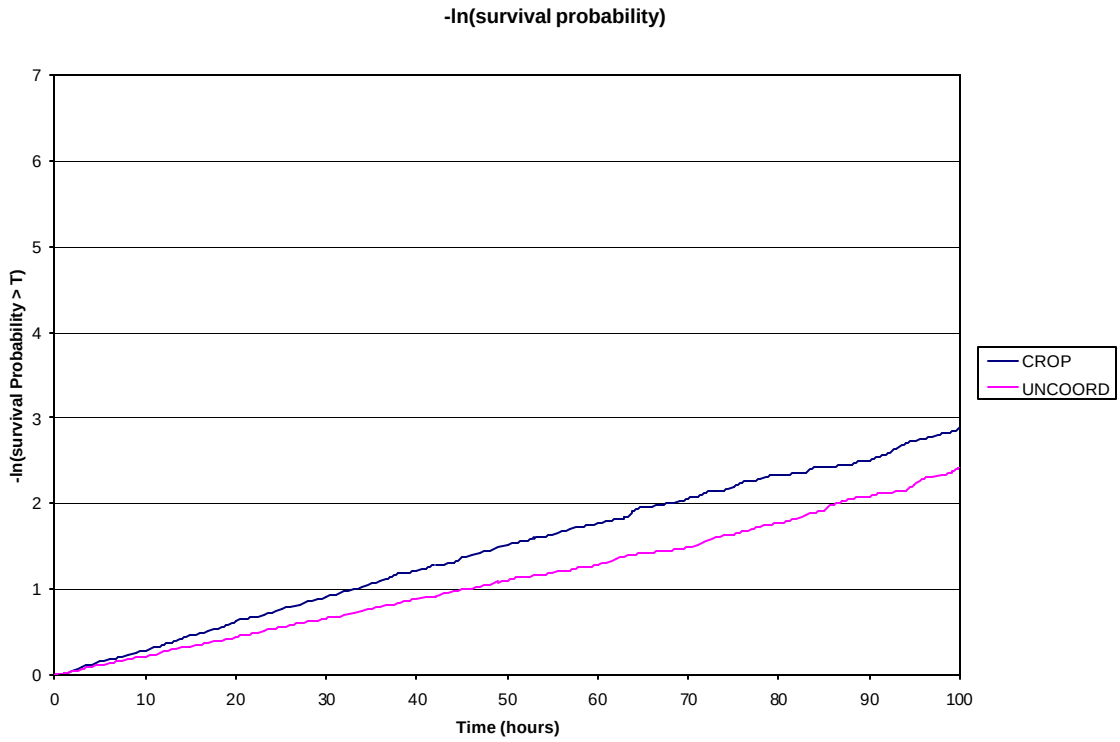

Figure 38. Estimated -ln(Survival Probability) Target Type 3 Classification Rate 6.0

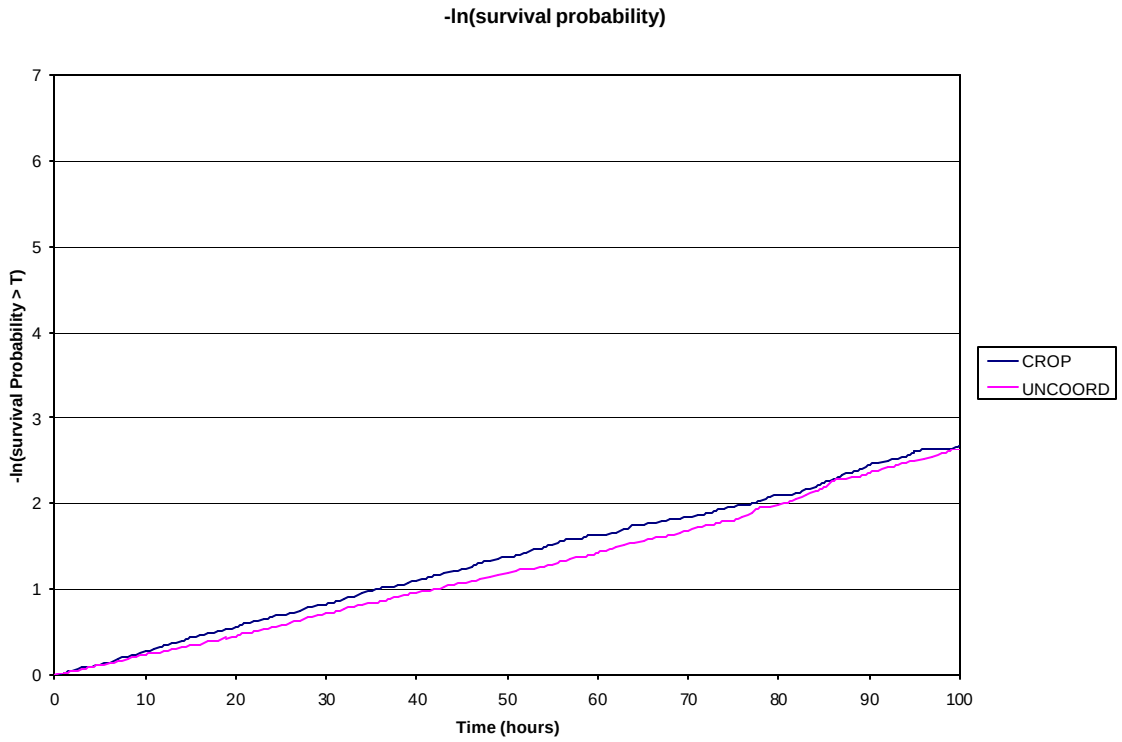

Figure 39. Estimated -ln(Survival Probability) Target Type 3 Classification Rate 4.0

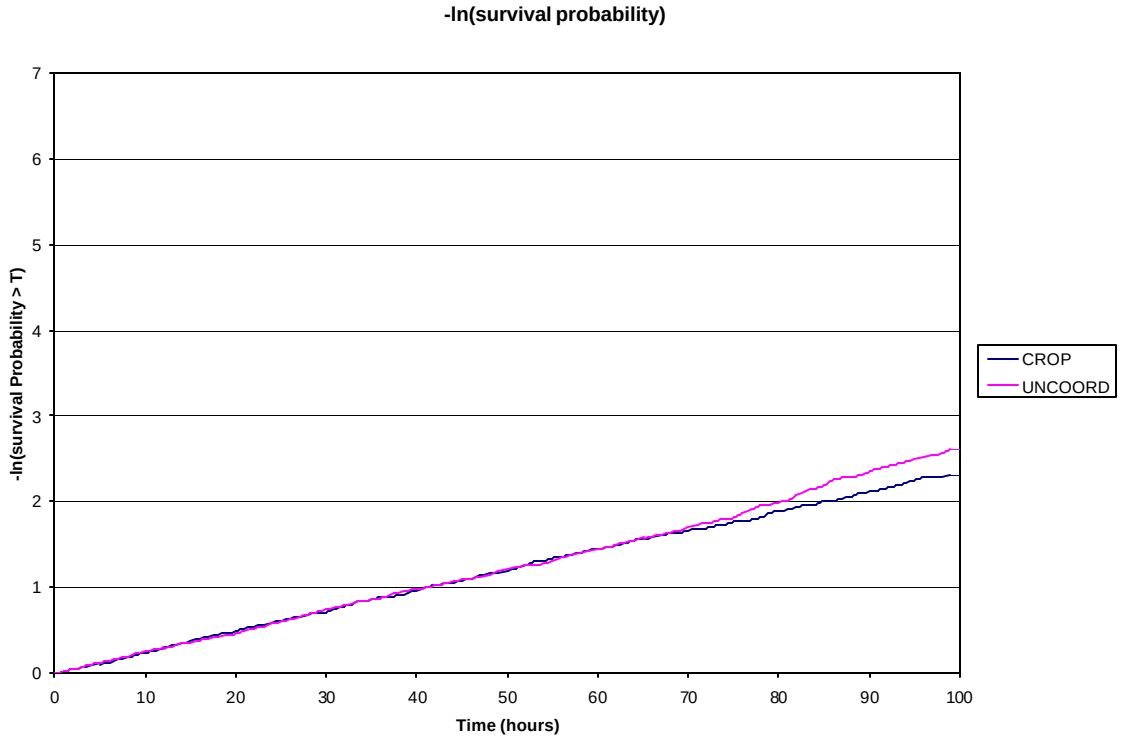

Figure 40. Estimated -ln(Survival Probability) Target Type 3 Classification Rate 3.0. (Note CROP and the Uncoordinated Services estimated Time to Kill '-ln survivor probabilities are almost exactly the same.)

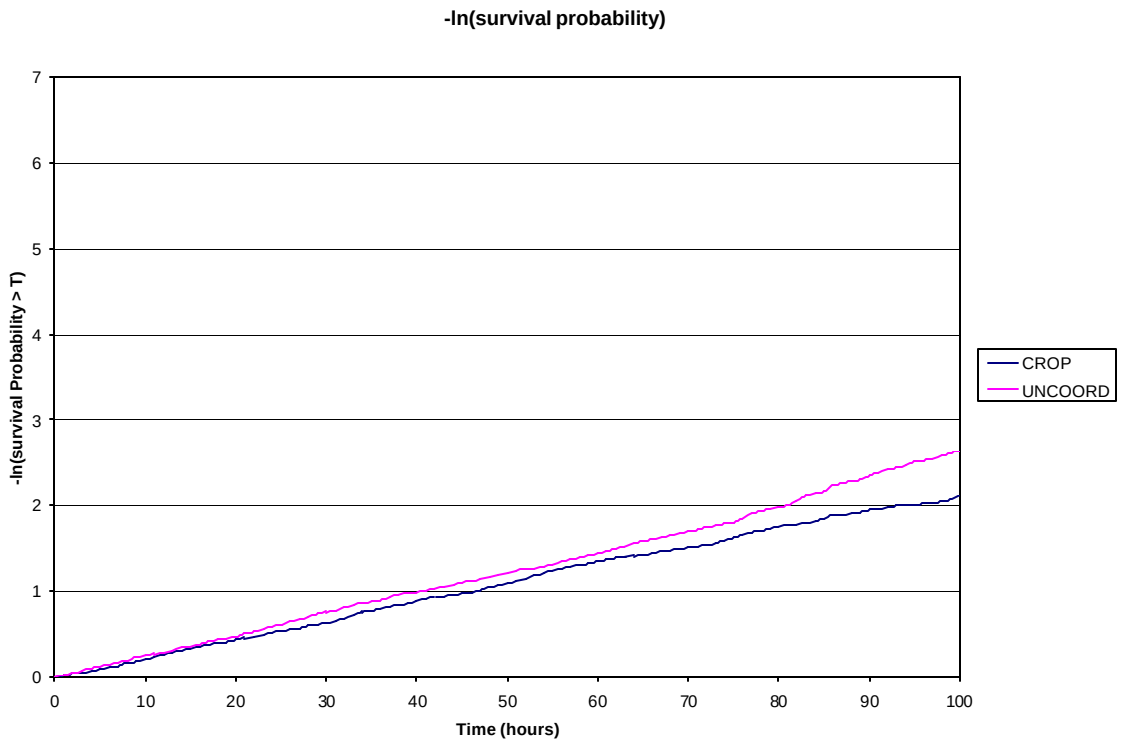

Figure 41. Estimated -ln(Survival Probability) Target Type 3 Classification Rate 2.4 (Note CROP's estimated –ln survivor probabilities are below the Uncoordinated Services estimated –ln survivor probabilities)

These figures for target type 3 show clearly that when the classification time rate gets to 2.4 CROP's estimated – ln (survivor probabilities) are lower than those for the individual services' time to kill. At classification rate 4.0 the 95% confidence intervals for probability the time to kill is less than or equal to t, for CROP and the Uncoordinated Services overlap for large times are within the 95% confidence interval.

D. DISCUSSION

CROP, with the fusion process used [reference 5] has a greater probability of classifying the target correctly than does the Uncoordinated Services organization. CROP also has a better probability of kill for a correctly classified target because of the weapon selection process. The weapon selected has the highest single-shot probability of kill against the classified target type. A weakness of CROP lies in the timeliness of fusing the data from the services to gain knowledge about the target and conduct a strike

on it with the "best" weapon. As the time to fuse this information from the services increases the benefit of the fused information, to get the "best" weapon on the target decreases.

The three target types react differently to the CROP classification time rate decreases. Target type 1 requires a longer CROP mean time to classify, or a lower CROP classification time rate to finally have CROP's effectiveness equal that of the Uncoordinated Services. This is due to the single-shot probabilities of kill and the loss rate. The loss rate for target type 1 is 2.5, which is higher than target type 2's, or target type 3's loss rate, 2.0, and 1.75 respectively. This means that the mean time before target type 1 is lost is lower than the other two target types, and target type 1 has a greater chance of being lost before it is shot. The single-shot probability of kill for each service's weapons also plays a role. Service 1 has credible weapons against each target type 1, 2, and 3. The probabilities of kill, respectively, are 0.7, 0.6, and 0.5. The other services do not have credible weapons against any target but the target they are specialized against; service i is specialized against target i for i=2,3. These two parameters give target type 1 an advantage over the other two target types. It is lost more often, because its mean time to loss is shorter, and it only has one service, service 1, with a credible weapon to kill it. The difference between the target type's, and specifically target type 1, reaction to CROP's classification time rate is because of CROP's ability to choose the "best" weapon against the perceived target. Whenever a target is perceived to be target type 1, the weapon selected will have a single-shot probability of kill 0.7 in a CROP environment. However, within the Uncoordinated Services a target perceived to be target type 1 will not always have a good weapon fired at it. This is why for CROP the classification time rate needs to decrease much further than for the other target types to be comparable to the Uncoordinated Services

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VII. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSIONS

The results of this simulation study show that increased awareness or knowledge about the battlespace is beneficial when the Measures of Effectiveness are the *Mean Time to Kill* a target and the *Mean Number of Weapons* expended to kill the target. The simulation runs for this thesis assumed specialized services. Each service is able to correctly classify one type of targets with probability 1. This target type is different for each service. Each service has an excellent weapon against the same target type. However, the service's ability to classify the other target types is 50%, and the weapons are very poor against the other target types.

The parameters used are not taken from any field data. They were arbitrarily chosen with time-critical targets in mind. The rates of the random times needed to classify, weaponeer, shoot, and for the target to be lost, and hide, were chosen in a way to keep the sums of the first three mean times close to mean time to loss. This was the method used to simulate a time-critical target. .

The classification time rates for CROP are obviously extremely important, quite possibly a limiting factor for a deployable CROP. With CROP, and a good fusion algorithm, the probability of classifying the targets accurately is higher. This higher probability leads to a better weapons pairing; the "best" weapon is more likely to be selected against the target. When the time to accomplish these tasks takes place on the same order of magnitude as occurs for the Uncoordinated Services, CROP does much better: the mean time to kill the target is consistently lower for the three target types. The figures in chapter VI with classification rate of 6.0 (corresponding to a mean time to classify of 10 minutes) show this clearly. When the CROP's classification time rate is decreased to 4.0 (corresponding to an increase in the mean time to classify to 15 minutes), CROP still maintains an advantage. However the effect on target type 3 is not so clear-cut. CROP's estimated probabilities that the time to kill is less than or equal to t remain above those for the Uncoordinated Services but they are very close to the upper boundary of the 95% confidence interval on the Uncoordinated Services probabilities.

This also occurs to target type 2 at the classification rate 3.0 (mean time to classify = 20 minutes). As for target type 1, CROP maintains the advantage until the CROP classification time rate nears 1.5 (mean time to classify = 40 minutes). The CROP classification time rate must decrease to 1.2 (mean time to classify = 50 minutes) before the estimated probability of killing the target in time less than or equal to t, for CROP and the Uncoordinated Services are statistically the same.

The BDA Parameter is the probability that BDA is correct, and is the measurement of BDA accuracy. Another Measure of Effectiveness for this thesis is the number of weapons expended against a dead target. It is shown in chapter V that there is a strong relationship between BDA accuracy and the number of weapons expended at a dead target. The number of shots taken after the target is killed clearly has a geometric distribution; the distribution of the number of failures before the first success for a sequence of Bernoulli trials. The probability of correctly declaring a target dead is equivalent to the probability of a successful trial, p. The probability of incorrect BDA is $(1-p)$. The probability of incorrectly assessing the status of a target twice before properly assessing it as dead is $(1-p)^2 p$. The expected value of this geometric random variable is $\frac{1-p}{p}$. In the simulation this corresponds to the sample mean number of weapons expended after the target is killed for the respective BDA parameters (0.1, 0.2, …, 1.0). However it actually is the number of "looks" a dead target gets before being recognized as dead. The simulation measures this by firing weapons at the dead target; the BDA evaluation only occurs, within the simulation, after a weapon has been fired. There is no portion of the classification process that determines if the target is already dead prior to the weapon being fired. Clearly, and intuitively, as the accuracy of BDA increases, (BDA Parameter approaches 1.0), the number of weapons expended after the target is killed decreases. As the BDA information gets more accurate there are fewer weapons fired at dead targets and there is less waste. There is a tradeoff between sensor/information system accuracy and weapon cost.

The main question entering this thesis is: "is information important?" A second question is: "does CROP add to the operational benefits of information superiority?" The answer to both questions is YES. Unfortunately there is always a "but". If CROP cannot

fuse the information from all the participating services in a timely manner, the gained information potential is lost and the information is useless. "Information is worthless if it is irrelevant to the task at hand. It is too often forgotten, that information is merely a means to an end, and not an end in itself" [reference 10].

B. RECOMMENDED FOLLOW-ON RESEARCH

There are numerous questions that remain. In no particular order here is a list of some:

- In this thesis the "best" weapon is chosen as that weapon that has the highest single shot probability of kill against the classified target type. Another weapons decision "algorithm" may be experimented with, such as selecting the weapon system with the shortest time to engage, or a weapon that conserves supplies of more capable weapons, or a weighting scheme considering both single-shot probability of kill and timeliness. [reference 11]
- The number of "servers" is "infinite" in this thesis, meaning that these resources are ample, and are never saturated. What would happen to CROP, and the Uncoordinated Services, if there were insufficient sensors or weapons systems available for the number of targets?
- This thesis examines the effects of the BDA Parameter on the number of weapons expended after a target is already dead. However, the study of BDA on a live target is also of interest. Knowing a target is alive and being able to get another weapon on it in a timely manner is very important.
- The simulation for the uncoordinated services assumes that only one service can prosecute a target at a time and all services know when the target is killed. Other assumptions are possible and their effects on the ability of the uncoordinated services to prosecute targets can be studied and compared.

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