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A comparative analysis of contemporary 155 mm artillery projectiles

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Abstract

Purpose – To recover the growing deficit between American and near-peer mobile artillery ranges, the US Army is exploring the use of the M982 Excalibur munition, a family of long-range precision projectiles. This paper aims to analyze the effectiveness of the M982 in comparison to the M795 and M549A1 projectiles to further the understanding of what this new asset contributes.

Design/methodology/approach – Based upon doctrinal scenarios for target destruction, a statistical analysis is performed using Monte Carlo simulation to identify a likely probability of kill ratio for the M982. A values-based hierarchical modeling approach is then used to differentiate the M982 from similar-type projectiles quantitatively in terms of several different attributes. Finally, sensitivity analyzes are presented for each of the value attributes, to identify areas where measures may lack robustness in precision.

Findings – Based upon a set of seven value measures, such as maximum range, effective range, the expected number of rounds to destroy a target, and the unit cost of a munition, the M982 1a-2 was found to be best suited for engaging point and small area targets. It is noted, however, that the M795 and M549A1 projectiles are likely better munition options for large area targets. Hence, an integrated targeting plan may best optimize the force's weapon systems against a near-peer adversary.

Originality/value – The findings provide initial evidence that doctrinal adjustments in how the Army uses its artillery systems may be beneficial in facing near-peer adversaries. In addition, the values-based modeling approach offered in this research provides a framework for which similar technological advances may be examined.

Keywords Monte Carlo simulation, Artillery projectiles, United States army, Value-based modelling

Paper type Research paper

Introduction

Over the past thirty years, the US Army has undergone a philosophy shift to adapt to an unconventional adversary. Through both World Wars and the Cold War, the USA needed to

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maintain the ability to mass large amounts of fires quickly as maneuver elements moved about the battlefield. This was critical to supporting the freedom of maneuver for the decisive operation. However, this capability was not as paramount moving into the twenty-first century. During the invasion of Iraq in 2003 troops were met with adversaries that fought among the civilian population rather than on the front lines of a battlefield. To adapt, the army focused on assets that more directly aided ground troops, such as available airpower. Today, the army's attention is shifting back toward near-peer threats, and the army must adapt its mission and doctrine accordingly. With these changes comes a renewed interest in bolstering field artillery assets. Retired Lieutenant General Sean MacFarland (former training and doctrine command deputy commander) noted, "the army is investing not only in quality but also quantity of fires" (South, 2018).

In the subsequent sections of this paper, a background of modern field artillery technology will address current solutions to the problem of limited range capabilities, as well as methods to evaluate these alternatives. These evaluation methods include accuracy and predictive models, decision analysis models and relevant case studies. Following a background of artillery system technology and a review of techniques used to measure firing effectiveness, a Monte Carlo simulation and value-based analysis will evaluate the M982 Excalibur series, the M795, and the M549A1 as alternatives to solving the long-range capability problem. The simulation will generate a probability of kill, expected a number of projectiles required for target destruction, and an effective range of each of these projectiles, which will form a baseline for the effective lethality of each projectile in an isolated context. Using these measures as inputs, a value-based analysis will compare the worthiness of the M795, M549A1, M982 1a-1 and M982 1a-2 as candidate solutions. Insights from this research may facilitate commanders in their operational decision-making and inform potential doctrinal changes within the field artillery branch.

Background: 155 mm projectile technology

The biggest issue the army is currently facing in terms of field artillery capabilities is matching, and ideally exceeding adversarial ranges. The standard 155 mm howitzer in the US arsenal has a maximum range of 14 miles, and the rocket-assisted 155 mm projectile increases the maximum range to almost 18 miles (South, 2018). Looking at one of the current near-peers, Russia's existing mobile artillery, the 2S35, has a range of 44 miles. This gives Russia the ability to devastate US forward forces before they can even get within firing range. However, technological advances being made to the 155 mm projectile are expected to push ranges of the current artillery assets between 44 and 62 miles, putting the USA well within reach of its near-peers' current standing.

Preliminary designs and technology (1995-2008)

Research into the topic of field artillery ranges became a Department of Defense priority during the Cold War Era, and these developments laid the groundwork for today's efforts. The three primary technological developments that will be discussed in this work are canard control technology, range correction modules and pulsejet technology.

The first key development in range extension technology occurred in 1995 with the addition of canards onto field artillery projectiles. Canards are pop-out fins mounted onto the projectile that is actively controlled using inertial sensor data. A non-linear simulation was developed to test the impact of the canards on the overall performance of the projectile. The canards were successful in adding substantial range to the projectile, and they enabled controllers to shape the projectile flight path (Costello, 1995). When the canards were activated at the apex of the projectile trajectory, they were able to achieve a maximum range of 41 km. However, these advances came at the cost of increased total flight time, decreased terminal velocity, increased nose-up attitude and increased aerodynamic angle of attack (Costello, 2001). The side effects contribute to an overall decrease in terminal accuracy, which can result in decreased lethality and increased collateral damage. Although the trade-offs for extended range using this mechanism are high, canard technology laid the foundation for precision-guided munitions.

Another approach taken to extend field artillery ranges was the preliminary design for artillery shell range correction modules in 1996. The design of the trajectory correction device would fit into the artillery shell similar to a traditional fuze. The first device used a global positioning system (GPS) transponder that processed the projectile's current position against the ground (Hollis, 1996). Subsequent designs incorporated the same GPS transponder technology with a combination of an inertial measurement unit, a central processing unit, a maneuver mechanism, a fuze function component, and a power source. The general operating concept was to increase the frontal area of the fuze, which increased the drag on the artillery shell. This increased drag was able to alter the direction of flight when desired (Hollis, 1996).

The final preliminary design enabling the development of today's premier field artillery munitions is the use of pulsejet technology on an artillery rocket for flight correction. This design was explored in 2008 to reduce impact point dispersion. The pulsejet ring was made up of a series of individual pulsejets, which would be mounted onto the rocket body (Gupta *et al.*, 2008). The lateral pulsejets would assist the flight control system to follow a previously programed trajectory. Coupled with a trajectory correction flight control system, the lateral pulsejets were able to yield minimum impact error compared to normal and uncontrolled trajectory. Additionally, pulsejet logic was also able to yield reduced impact point dispersion (Gupta *et al.*, 2008), increasing accuracy and lethality.

One of the most used contemporary rounds in the army ammunition arsenal for the 155 mm howitzer is the M549A1 rocket-assisted projectile. It was produced in 1977 specifically to extend ranges for 155 mm howitzer artillery. The round, which contains approximately 15 pounds of explosive, has a maximum range of approximately 30 km for the M198 howitzer (HQDA, Department of the Army, 1994). It has been used extensively in campaign operations since the 1970s and was further modified with new fuses and modification kits, as its initial development.

Another contemporary round in the army artillery arsenal is the M795 projectile, which replaced the long-standing M107 round with greater lethality and range in the early 2000s. Among the current array of projectiles for the 155 mm howitzer, it is considered the primary high-explosive round used in warfare. The M795 holds approximately 24 pounds of explosive and has a maximum range of approximately 22 km for the M198 howitzer. Modifications to the round include various fuses for timing projectile firing. Both the M549 and M795 projectiles have characteristics that are widely published in the defense literature.

Emerging technologies

The preliminary designs discussed above focused on improving both the range and the accuracy of field artillery projectiles. Moving forward, these developments coupled with modern-day propulsion technology help the army to achieve both range and impact point accuracy.

In 2018 the company Nammo developed what is being referred to as "extreme range" artillery. This 155 mm shell incorporates ramjet propulsion technology to achieve long-range precision fires. Without changing any of the features of the current howitzer design, the ramjet projectile can reach more than 100 km (Judson, 2018). This range is achieved through the addition of increased air flow into a solid-fuel rocket motor. This enables the motor to burn much longer than a traditional rocket motor. Additionally, an extra 20 km is gained by incorporating base bleed technology to reduce drag on the shell and using highly explosive insensitive munitions as a fuel source (Judson, 2018).

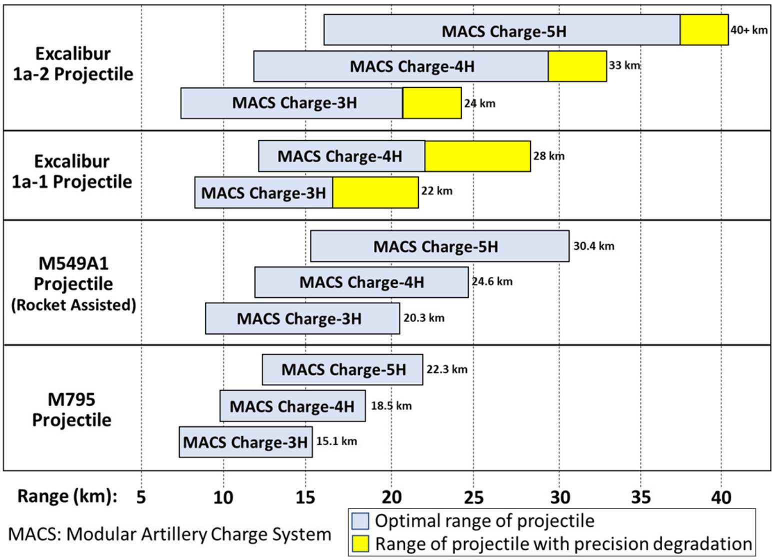
The base bleed technology produced by Nammo is also incorporated into the Excalibur guided-artillery projectile (Judson, 2018). At the forefront of the army's current development focus is the M982 Excalibur munition. This projectile contains GPS – inertial navigation system guidance conducts in-flight guidance and trajectory correction and is capable of penetrating urban structures (Milner, 2012). Additionally, because of its increased accuracy, it decreases the total volume of fire required to degrade or destroy targets in an engagement. The M982 brings all the benefits of the current 155 mm projectile, the M795, while more than doubling its range and accuracy as shown in Figure 1 below. Prime–Raytheon missile systems contracted both the 1a-1 and the 1a-2 increments of the Excalibur projectile, and the Army is in the process of evaluating how to integrate them into the conventional force.

Techniques for measuring firing effectiveness: a brief review

When new technology is introduced into the market, several levels of analysis are used to determine its effectiveness. In the context of field artillery, the first layer is an accurate analysis. Supplemental models that can aid in accuracy analysis are trajectory and predictive models. Often these models can serve as inputs into a larger simulation. Once the technology in question has passed through these preliminary screenings to determine its merit, a comparison is performed with other technologies.

Accuracy analysis

Accuracy is defined as the degree of correctness associated with a quantity or expression. In terms of field artillery, the accuracy of a projectile is the ability to hit a target without error.



Source: Milner (2012)

Figure 1. M982 tested ranges for 155 mm projectiles in comparison to the M549A1 and M795

A critical step toward evaluating emerging technology is to evaluate its accuracy because inaccurate technology is naturally considered ineffective. There are several ways to measure accuracy, and a few approaches will be reviewed here.

One approach to evaluating the accuracy of a projectile is to account for the array of errors that may impact projectile range. Matts and Ellis (1990) proposed a model that considered various factors that affect range or deflection, such as round-to-round variability, staleness, navigational error, and aiming error. A similar approach is to consider the probable error (PE) and mean point of impact error (MPI):

> The PE is the uncorrelated variation about the MPI for a given mission, typically affected by the ballistic dispersion effect, while the MPI error is associated with the occasion-to-occasion variation about the target, typically affected by the aiming error (Fann, 2006).

The ability to accurately impact a target depends both on the MPI and the PE. These factors, in combination with a trajectory model, serve as inputs to determine the range and deflection errors. "The range error is the error in the direction between the artillery unit and the target, while deflection error is in the perpendicular direction to the range direction" (Fann, 2006). These outputs provide a quantifiable measure of projectile accuracy. This approach is very useful in testing new technologies to determine their potential lethality.

Simulation modeling is a great approach for comparing several alternatives or measuring the effectiveness of one alternative in several scenarios. A recent study created a discrete event simulation to model the current capabilities of Marine corps artillery systems. It furthered a SurfaceSim model previously developed by incorporating real data for current artillery capabilities (Sheatzley, 2017). The simulation iterations varied the artillery task organizations, a number of projectiles fired, target location error, circular error of the impacting projectiles and the probability of kill to determine the most effective and least effective arrangements.

Another simple and flexible approach to measuring field artillery fire support effectiveness is the development and application of a Markov model. In 1988 a model was developed that given an indirect fire weapon system's parameters were able to yield measures of the weapon's effectiveness in providing fire support against maneuver elements (Guzik, 1988). In this case, "effectiveness" was defined as providing the maximum amount of fire support to maneuver elements while avoiding an enemy counterattack. To develop the model, the artillery battery was modeled as an irreducible, recurrent Markov chain with 5 possible states and 11 input parameters, which were a function of the weapon system and scenario (Guzik, 1988). Given the probabilities associated with falling into each of the five states, researchers were able to determine an optimal time to move the battery to a new position, which balanced the need for continued fire support and the need to avoid an enemy counter-battery attack.

Trajectory and predictive models

Many of the model inputs discussed previously are focused on trajectory predictions. This section describes two numerical models that can be used to bolster the analysis of firing systems.

Model 1 is a model of motion for conventional artillery projectiles. In a recent study, researchers explored the effectiveness of a mathematical model based upon a vector-based six degrees-of-freedom (6 DOF) system of differential equations (Baranowski, 2013). The subsequent system, which assumed a projectile could be represented as a rigid body, was formed using three 6 DOF models – a ground-fixed system, body axis system and velocity axis system. It was found through the evaluation of each model; the same computational accuracy can be obtained by varying the number of integration steps. To obtain a defined computational accuracy for a parameter, the model based on the body axis system should use the smallest integration step, the model based on the velocity axis system should use an integration step five times larger, and the model based on the ground-fixed system should use an integration step that is 100 times larger (Baranowski, 2013). The researchers subsequently calculated trajectory parameters to less than 0.1 per cent accuracy.

Model 2 is designed to serve as an alternative to traditional methods of computing firing angles for unguided artillery projectiles. The firing angle (azimuth and quadrant elevation) is one of the data points required to fire a projectile to engage a specific target. Typically firing angles are looked up in a pre-calculated firing table. However, the accuracy of this method can be compromised because of oversimplification (Chusilp *et al.*, 2012). To avoid this error, an iterative method has been developed as an alternative to the traditional lookup method. Firing angles are determined via a trajectory simulation in nonstandard conditions (as opposed to using standard conditions and adjusting later). As a result, the simulation can incorporate more advanced forecast meteorological data. This enables more accurate predicted fires, which increases the probability of achieving accurate first-round fire for effect on a target (Chusilp *et al.*, 2012). The iterative method, however, can be very time consuming; as such, it requires an algorithm that is extremely efficient. Otherwise, it would be faster to engage and adjust fires using the lookup method.

Decision analysis models

Cost is often a significant factor when considering alternatives. As such, cost-based models offer another technique widely used to measure effectiveness. They can determine the best option available by placing values on the inputs (costs) and outcomes (benefits) of given alternatives (Robinson, 1993).

Another method that can be used to analyze decisions involves taking a constrained optimization approach. The targeting problem (TP) is the issue of deciding how to best allocate weapon systems to targets so that the targets are adequately destroyed but minimum cost is achieved (Kwon *et al.*, 1997). Once the weapon systems are allocated to targets, the next step is to develop a firing sequence that minimizes the time required to complete a mission. This is known as the firing sequence problem (FSP) or scheduling problem. Using the outputs from the TP, the FSP can be solved using a heuristic method, whereby targets are allocated to specific time slots and the number of weapon systems used is maximized. The same procedures used to address the targeting and scheduling problem can be applied to find the most cost-effective firing arrangements in a short amount of time.

Modeling approach

Formulating a model

As previously mentioned, this project seeks to analyze the lethality of the M982 projectile in comparison to the M795 and M549A1 projectiles to further the understanding of what benefits this new asset brings to the force when facing a near-peer threat. Breaking down this task, the first step is to gain a better understanding of the system by analyzing the lethality of the projectile in comparison to traditional systems. In this case, lethality refers to the capacity to destroy any given target, which in the industry is 30 per cent fractional casualty (Fort, 2018). To establish a basis for estimating the lethality of the Excalibur series and its alternatives, variables are first assigned to the quantity of interest, lethality. The two variables that have the largest impact on a system's ability to destroy a target are the target type and the target location. It is more difficult to destroy a concrete compound than a consolidated infantry platoon, as more destructive power is required. Additionally, the significance of target range is of primary concern to the army, as a system cannot engage a target if it is out of range. So, again the variables assigned to lethality will be defined as target type (X_t) and target range (X_r). This work will consider three target types – an infantry platoon, a command post and a radar. The target range will be limited to integers between 15 and 40 km, the overall minimum and maximum range of current US assets.

Before defining a modeling approach, it is important to identify all assumptions regarding these variables. When a field artillery unit receives a fire mission, part of the information transmitted to the unit includes the target type and target location. These fire missions generally come in at random, so the guns must be ready to adjust to any combination of target type and range. These characteristics form the first two assumptions that will follow the problem through formulation and execution. The first assumption is that X_t and X_r are independent. This implies that the target type does not impact the target range. The second is that X_t and X_r are uniformly distributed. For example, it is just as likely to get a 15 km target as it is to get a 40 km target. The third assumption is that the number of projectiles needed to destroy a target is a known constant. This assumption is valid because once the guns have bracketed onto a target, they will fire for effect until target completion. So, the number of projectiles fired is only influenced by the target types. The final assumption is that there is an inverse relationship between the number of projectiles fired and the lethality of the individual projectile. In other words, as the lethality of the individual projectiles increases, the number of projectiles required for the destruction of a given target type decreases. This assumption is critical as it will allow for the extraction of the lethality of each projectile from the output of the Monte Carlo simulation. The sensitivity and robustness of these assumptions will be evaluated in future work. The complete question formulation is shown below:

Variables: X_r = target range (km), an element of $\{15, 16, 17, \ldots, 40\}$

$$X_t = \begin{cases} 1 & \text{Infantry Platoon} \\ 2 & \text{Command Post} \\ 3 & \text{Radar} \end{cases}$$

$$R = \text{Number of projectiles fired} = \begin{cases} n & X_{\min} \leq X_r \leq X_{\max} \\ 0 & \text{otherwise} \end{cases}$$

Objective: determine the number of projectiles, R, fired, given some X_t and X_r.

The specific number of projectiles (n) fired for a target in the range is defined in an input matrix for each system being analyzed (Table I).

		Projectiles required for target destruction (# rounds)		
Target #	Target	M795 (Standard HE)	M549 (HE-RAP)	Excalibur
1	Infantry platoon	43	25	3
2	Command post	78	54	6
3	Radar	11	10	1

Source: Milner (2012)

Table I. Monte Carlo simulation projectile input information

Because of the inherent random nature of fire missions, and in turn, target type and location, this problem lends itself to a Monte Carlo simulation. This is a technique that can be applied to any probability model to estimate one or more measures of performance of a system (Meerschaert, 2013). A probability model consists of random variables (X_t and X_r) and a probability distribution for each random variable. This simulation can be repeated several times to determine the expected number of projectiles fired.

In defining the model formulation, the notation "Random$\{S\}$" denotes a random pair of target characteristics from the set S made up of all possible target types and ranges. In this simulation, the target range is represented by a random integer from the interval [15, 40]. The number selected will determine if the system can engage the target based on the projectile's minimum/maximum range. The target type is represented by a random integer from the interval [1, 3]. If the system can engage the target based on the range, the target type number selected will determine the number of projectiles to fire to achieve target destruction.

Variables:

p_t = probability of a given target type;

p_r = probability of a given target range; and

X_r = target range (km), an element of $\{15, 16, 17, \ldots, 40\}$.

$$X_t = \begin{cases} 1 & \text{Infantry Platoon} \\ 2 & \text{Command Post} \\ 3 & \text{Radar} \end{cases}$$

$$R = \text{Number of projectiles fired} = \begin{cases} n & X_{\min} \leq X_r \leq X_{\max} \\ 0 & \text{otherwise} \end{cases}$$

```
Inputs: Xt and Xr
 Process: Begin
        Random { [ Xr, Xt ] }
              If Xmin ≤ Xr ≤ Xmax, then
                if Xt = 1, then
                       R = n
                if Xt = 2, then
                       R = n2
                if Xt = 3, then
                       R = n3
              Else
                R = 0
         End
```

Monte Carlo simulation

A simulation generates 5,000 iterations using the uniform distribution to define p_r and p_t (sample output provided in Appendix). The outputs analyzed included the M795 Standard HE, the M549A1 HE-RAP (rocket-propelled), Excalibur 1a-1 and Excalibur 1a-2. The M549A1 was examined to help bring additional depth in understanding the spectrum of available ranges for current artillery assets. Table II displays the number and percentage of targets that were out of range for each artillery system, leaving them incapable of engaging.

The probability mass function (PMF) and cumulative distribution function (CDF) of the estimated number of projectiles fired by each system were also developed to determine the average number of rounds fired for each munition type (Table III).

As shown in the comparison chart below, the Excalibur series not only decreases the number of projectiles required for target destruction but also decreases the variability in the number of projectiles required. Figure 2 shows the average change in the number of projectiles required because of a new projectile type, with vertical lines denoting the range in the possible number of rounds fired for each type.

A key point that was mentioned while defining assumptions was the inverse relationship between the projectiles required for target destruction and projectile lethality.

As the numbers of projectiles fired decreases, as shown in Figure 2, the lethality of the projectile must increase to still achieve target destruction. This relationship enables the prediction of a simulated probability of kill or lethality. These outputs are shown in Table IV, along with the calculations for the expected value and variance of the number of projectiles fired by each system.

Before extending the findings of the Monte Carlo simulation, it is important to examine the sensitivity of the simulation-based upon the established assumptions. This is critical to

Criterion	M795	M549A1	Excalibur 1a-1	Excalibur 1a-2
# Targets not Engaged	3,487	3,130	3,659	1,741
% of total	69.74	62.60	73.18	34.82

Notes: For the purposes of this analysis, targets not engaged do not help evaluate the lethality of the projectile. Because of this, these fire missions were recorded then removed from the simulation results

Table II. Number and percentage of targets out of range

	PMF		CDF
M795			
11	0.33512	11	0.33512
43	0.31906	43	0.65418
78	0.34582	78	1.00000
Excalibur 1a-1			
1	0.32660	1	0.32660
3	0.33021	3	0.65681
6	0.34319	6	1.00000
M549A1			
10	0.32226	10	0.32226
25	0.34354	25	0.66580
54	0.33420	54	1.00000
Excalibur 1a-2			
1	0.31904	1	0.31904
3	0.33632	3	0.65535
6	0.34465	6	1.00000

Table III. PMFs and CDFs

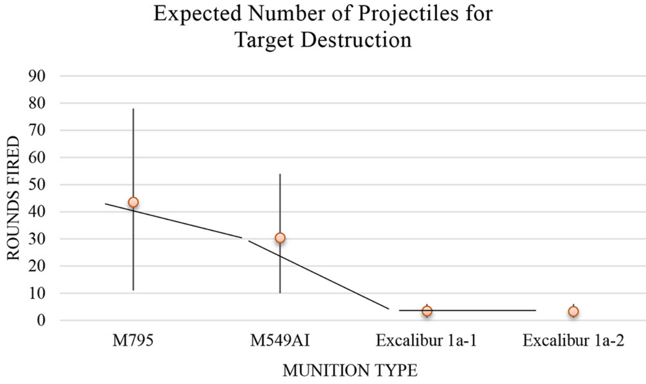


Figure 2.
Expected number of projectiles required per munition type

Table IV.
Expected value and variance of the number of projectiles fired per system, with an associated probability of kill

Item of interest	M795	M549AI	Excalibur 1a-1	Excalibur 1a-2
Expected value	44.380	29.858	3.376	3.396
Variance	764.876	329.966	4.256	4.221
Probability of kill	55.143	69.751	96.625	96.669

ensure too much was not assumed in building the model and render future conclusions based on these assumptions inaccurate. The final assumption used in developing the Monte Carlo simulation was the doctrinal prescription of projectiles required for target destruction per munition type. To determine the sensitivity of this assumption, the number of projectiles fired given a target was varied between −30 and 30 per cent, then used as an updated input into the model. The impact of changing the projectiles required on the probability of kill can then be observed (Table V). Because of the accuracy of the Excalibur, even a 30 per cent increase in the number required for target destruction had almost no impact on the probability of kill. However, given a 10 per cent change in projectiles required for target destruction, the M795 and M549 showed a −7 and −4 per cent change in probability of kill.

Table V.
Monte Carlo simulation probability of kill sensitivity analysis

Model parameter	Variable	−30%	−20%	−10%	0%	10%	20%	30%
M795	Infantry platoon	30	34	39	43	47	52	56
Projectiles	Command post	55	62	70	78	86	94	101
Required	Radar	8	9	10	11	12	13	14
	Probability of kill	69.29	65.34	60.31	55.14	51.54	46.86	43.78
M549	Infantry platoon	18	20	23	25	28	30	33
projectiles	Command post	38	43	49	54	59	65	70
required	Radar	7	8	9	10	11	12	13
	Probability of kill	78.34	75.84	72.76	69.75	67.57	64.17	62.45
Excalibur	Infantry platoon	2	2	3	3	3	4	4
projectiles	Command post	4	5	5	6	7	7	8
required	Radar	1	1	1	1	1	2	2
	Probability of kill	97.63	97.31	97	96.6	96.3	95.65	95.33

Although this demonstrates the model is sensitive to the projectiles required of M795 and M549 munitions, given the percent change in the probability of kill is less than the percent change in the projectiles required, it is reasonable to conclude the probability of kill for the Excalibur is relatively robust in its measurement. This probability of kill will be used as an input in the quantitative value-based analysis.

Analysis and value modeling

Looking at the output of the Monte Carlo simulation (the expected value of projectiles required for target destruction), a first action that may seem intuitive is to calculate the associated cost per mission. Using this logic, the commander would look at the expected number of projectiles required for each munition type, and the cheapest total option would be used. This type of judgment would always result in the employment of the M795 projectile because of its relatively low cost in comparison. The flaw with this approach is it fails to consider many factors other than unit cost. In a combat situation, cost factors may generally be given less priority than a weapon's effectiveness. Because of the presence of additional factors, value-based modeling can be used to further differentiate the various projectiles.

In value modeling, both qualitative and quantitative value models are used to identify the needs of the stakeholder, develop a test plan and evaluate the data collected. Qualitative values reflect the stakeholder preferences regarding the decision process, while quantitative value models evaluate how well candidate solutions fulfill stakeholder wants and needs (Parnell *et al.*, 2011). A value hierarchy is developed for the army's long-range artillery problem, and a quantitative value model is used to evaluate the M795, M549A1, M982 1a-1 and M982 1a-2 projectiles as candidate solutions.

The decision problem the army is facing is the need for extended range field artillery assets, and the direction they are taking is to find a solution to updating the 155 mm projectile. The fundamental objective of this problem is to develop a long-range munition that impacts its intended target rapidly and accurately. Functions that are required to achieve this objective are the ability to destroy the target, avoid collateral damage and effectively use resources. Objectives within these functions provide a preference statement regarding the values derived from the stakeholder needs/wants. Each of these objectives has at least one associated value measure that provides a quantitative means of evaluating how well a munition achieves the stated objectives (Parnell *et al.*, 2011). The objectives and respective value measures are defined below:

- *Objective 1.1*: Maximize the probability of kill. Probability of kill is the per cent chance a single projectile of the given munition destroys the desired target at its given location.
- *Measure 1.1.1*: The probability of kill for each munition is gathered from the output of the Monte Carlo simulation (Table V).
- *Objective 1.2*: Maximize range. A percentage of the fire missions are unable to be serviced by a given munition because of its minimum and maximum range. Because of this, maximize range will be broken down into two components: maximum range (km) and effective range (per cent of targets engaged).
- *Measure 1.2.1*: Maximum range (km). This is the farthest target a projectile can reach when launched from a 155mm towed howitzer.
- *Measure 1.2.2*: Effective range (per cent). This is the per cent of fire missions that fall within the minimum and maximum ranges of the projectile. This measure is an output of the Monte Carlo simulation.

- *Objective 2.1*: Minimize circular error probability (CEP). The smaller the CEP, the more precise the weapon system.
- *Measure 2.1.1*: CEP at 20 km. The value for CEP that will be used for each of the munitions is the size of the circular radius that contains 50 per cent of the fired projectiles.
- *Objective 3.1*: Minimize cost. An important factor in almost every decision is cost. This will be measured using the unit cost of a munition.
- *Measure 3.1.1*: The unit cost is the price per projectile.
- *Objective 3.2*: Minimize projectiles required for target destruction. Reducing the number of projectiles required for target destruction reduces both the time and cost per fire mission, allowing batteries to support more units. Both value measures will be pulled from the Monte Carlo simulation.
- *Measure 3.2.1*: Expected value. The expected value is the average number of projectiles required for target destruction.
- *Measure 3.2.2*: Variance. The deviation of observations from the expected value.

This qualitative value model outlining the stakeholder's needs and a plan for evaluating the objectives is consolidated in the value hierarchy (Figure 3).

A quantitative value model is used to determine how well the M795, M549A1, M982 1a-1 and M982 1a-2 projectiles serve as candidate solutions to the overall objective of expanding current artillery asset capabilities. The first step is to construct functions for each of the value measures, which will convert the raw data to a standard "value" (Parnell *et al.*, 2011). These values are then weighted to scale the value measure relative to its overall importance. The maximum overall weighted score reflects the optimal candidate solution. Each of the value measures that are used to evaluate the worthiness of the candidate solution have different units. Value functions convert these varying units to a common measure that reflects the overall utility.

The first value measure to convert is the probability of kill (Figure 4). This value has constant returns to scale (RTS) because the probability is proportional to the utility gained. As such, it is modeled with a linear RTS function.

Maximum range (Figure 5) is highly valued up to 60 km to surpass the assets of American near-peer adversaries. Beyond this range, there is less utility as the army switches

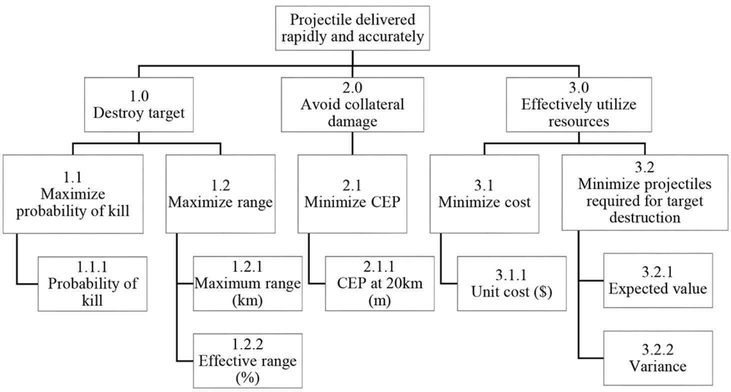


Figure 3.
Value hierarchy for the army's long-range artillery problem

to other assets, such as rockets. As a result, maximum range is modeling with a decreasing RTS function.

Effective range (Figure 6) experiences a similar effect. Once an asset is unable to service more than half its fire missions, there is little utility in using it in that setting. As a result, it is modeled with a decreasing RTS function.

The CEP (Figure 7) generally experiences constant RTS like the probability of kill but given a 50 m burst radius for all munitions, there is relatively equal value at the ends of the value curve.

Minimum cost (assuming all else constant) is always more desirable. As such, unit cost (Figure 8) is negatively correlated with value. However, this value function is modeled with an increasing RTS (convex) rather than linear RTS because the Excalibur is projected to be able to decrease unit costs from $150,000 to $68,000 while maintaining all other capabilities. Given this, the Army will require substantial improvements to justify a unit increase in cost.

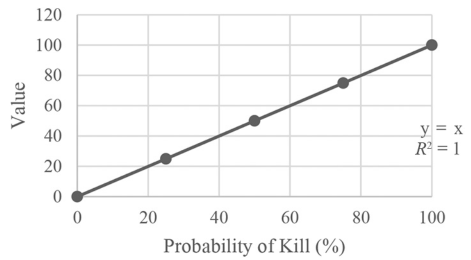


Figure 4.
Probability of kill value function

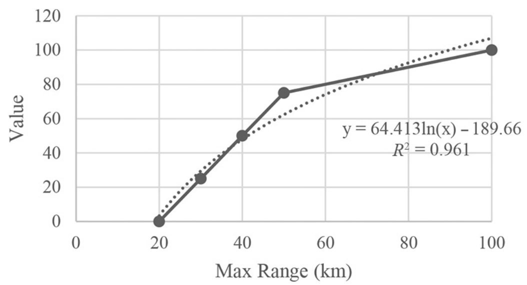


Figure 5.
Maximum range value function

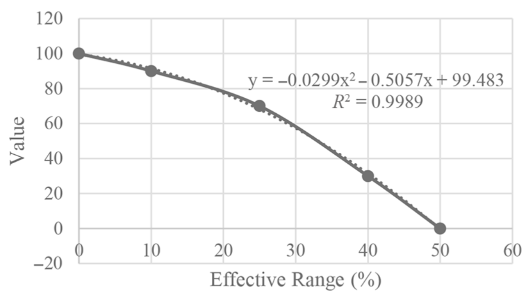


Figure 6.
Effective range value function

The expected value (Figure 9) has constant RTS because the number of projectiles required is proportional to the utility gained. As such, it is modeled with a linear RTS function.

Variance (Figure 10) is modeled using a decreasing RTS because as the variability approaches infinity, there is no value. Minimum variability allows the Army to develop standard operating procedures (SOPs) to increase effectiveness. If there is no predictability in the expected value, no SOPs can be published, and it will make it very difficult for small tactical artillery units to determine the munition requirements necessary to achieve the desired effect on the battlefield.

Each of the value functions described previously transforms the respective raw data consolidated in Table VI as inputs into the values shown in Table VII as outputs.

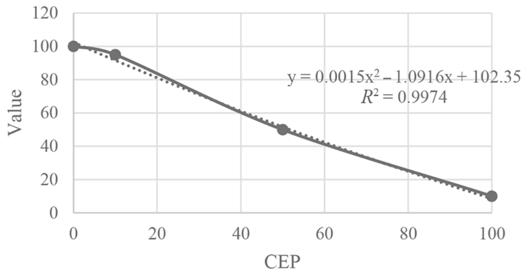


Figure 7.
CEP value function

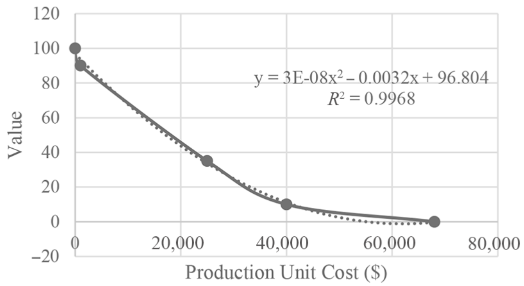


Figure 8.
Unit cost value function

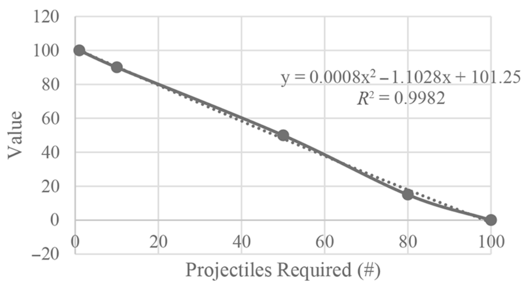


Figure 9.
Expected number of projectiles required value function

Research findings

Results and analysis

The radar plot in Figure 11 provides a visual of the consolidated value matrix in Tables VI and VII, showing the total weighted value of each munition. This displays the deficiencies of each munition type and the additional value the M982 1a-1 and M982 1a-2 technological advances have contributed.

In a problem without constraints, each value measure would be maximized, and the candidate solution would have zero imperfection. Unfortunately, this is not a realistic solution as there are limitations to the technology available, as well as the budget approved for this project. As a result, swing weights are applied to model the tradeoffs that must be made to balance these conflicting objectives. These weights rate a value measure's relative importance to the overall problem. Because of the Department of Defense's expressed interest in the range, maximum and effective range received the highest two weights along with unit cost, as the military is forced to operate within a budget. Secondary in importance are the probability of kill and CEP. Although it is possible to compensate with additional projectiles on target, these value measures directly impact the timeliness and first-round effectiveness of the

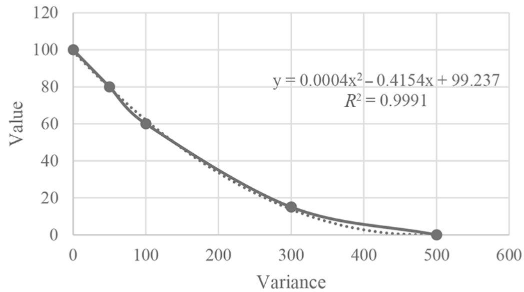


Figure 10. Expected number of projectiles required value function

Table VI. Value measure raw data

Munition	Unit cost ($)	Prob of kill	E[X]	Var	CEP	Max range	Eff range (%)
M795	333	57.3	42.7	740.6	114	22.3	69.8
M549A1	995	70.5	29.5	327.1	108	30.4	62.3
M982 1a-1	150,000	96.6	3.4	4.3	3.8	28	73.9
M982 1a-2	150,000	96.7	3.3	4.3	3.8	40	34.2

Table VII. Transformed value matrix

Munition	Unit cost ($)	Prob of kill	E[X]	Var	CEP	Max range	Eff range
M795	95.7	57.4	55.7	11.0	0	10.3	0
M549A1	93.7	70.5	69.4	6.2	2.0	30.3	0
M982 1a-1	0	96.6	97.6	97.5	98.2	25.0	0
M982 1a-2	0	96.7	97.6	97.5	98.2	48.0	59

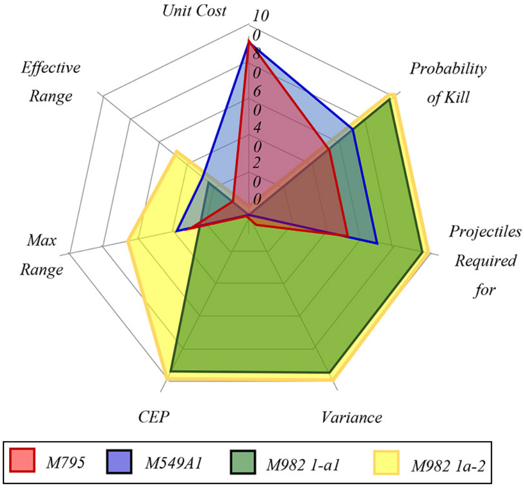


Figure 11.
Value measure scores of current 155 mm (total area represents the total value of the projectile)

munition. The factors of lowest importance are expected value and variance. These factors aid in the planning and preparation of fire missions, but the fundamental objective of getting projectiles to their intended targets can be accomplished without a strong score in these categories. Table VIII consolidates these measures into a global swing weight matrix.

Using an inner dot product, this global swing weight matrix is applied to the value matrix (Table VII) to achieve a weighted score for each candidate munition (Table IX).

Based upon the results of the value-based modeling, the M982 1a-2 appears to be the preferred solution toward accomplishing the army's goal of expanding long-range artillery assets. It is noted that this case study is considering only point and small area targets. It is highly likely that the M795 and M549A1 projectiles are likely better munition options for large area targets, where unit cost will have a greater overall effect on value.

Table VIII.
Global weight matrix with scaling

Item of interest	Unit cost ($)	Prob of kill	E[*X*]	Var	CEP	Max range	Eff range
Swing weight	90	75	70	40	75	90	100
Global weight	0.167	0.139	0.130	0.074	0.139	0.167	0.185

Table IX.
Weighted scores for each projectile type

Munition	Weighted score
M795	33.51
M549A1	40.00
M982 1a-1	51.13
M982 1a-2	65.87

To aid in further development, it is also useful to conduct a sensitivity analysis. The sensitivity of each value measure will be explored relative to its effect on the total weighted value of the projectile. If the total value is found to be highly sensitive to a given value measure, this indicates this area is ideal for development. For a small per cent change in input (the value measure), there is a large percentage change in output (total value). Similarly, if the total value is found to be highly insensitive to a given value measure, this indicates this is a poor area for development. For a large percentage change in input (the value measure), there is a small per cent change in output (total value). The score of the value measures were individually varied by −30, −20, −10, 10, 20 and 30. The result is the per cent change in total value as a result of this deviation in input, all other value measures being held constant.

Looking at the M795 sensitivity radar plot in Figure 12, the value measures of the probability of kill, maximum range, and variance resulted in the largest per cent change in total value. This finding justifies the Army's decision to invest in Excalibur. Both 1a-1 and 1a-2 focus on improving these areas while generally ignoring the unit cost.

The M549A1 projectile sensitivity plot in Figure 13 depicts the need for an improved CEP. Again, there is little need for development in terms of unit cost and effective range.

The M982 1a-1 sensitivity radar plot in Figure 14 shows that the total value is insensitive to changes in CEP, variance, effective range, unit cost and the number of expected projectiles required. The maximum range and probability of kill, however, still offer some room for further development.

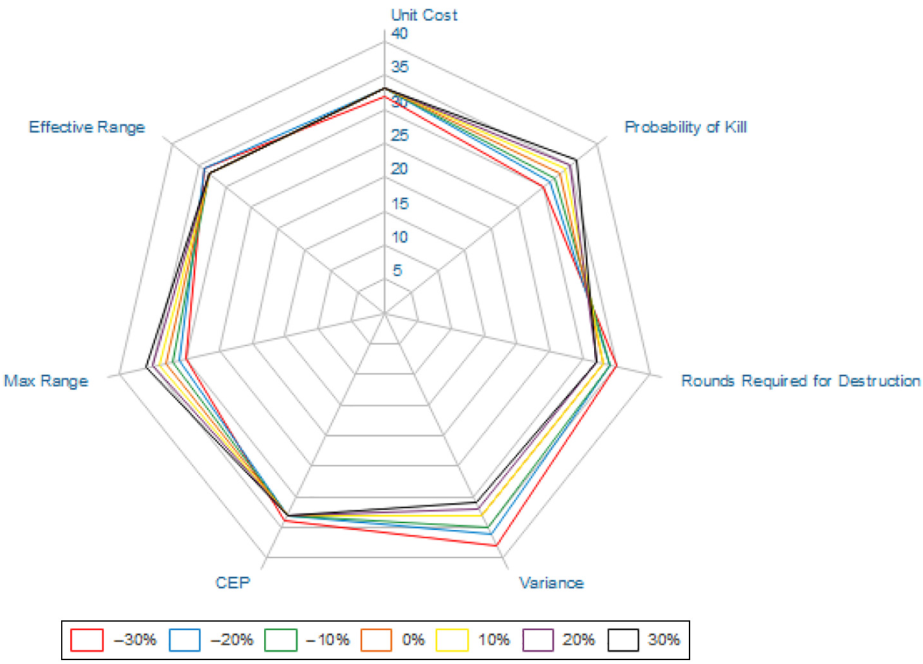


Figure 12.
M795 total value sensitivity

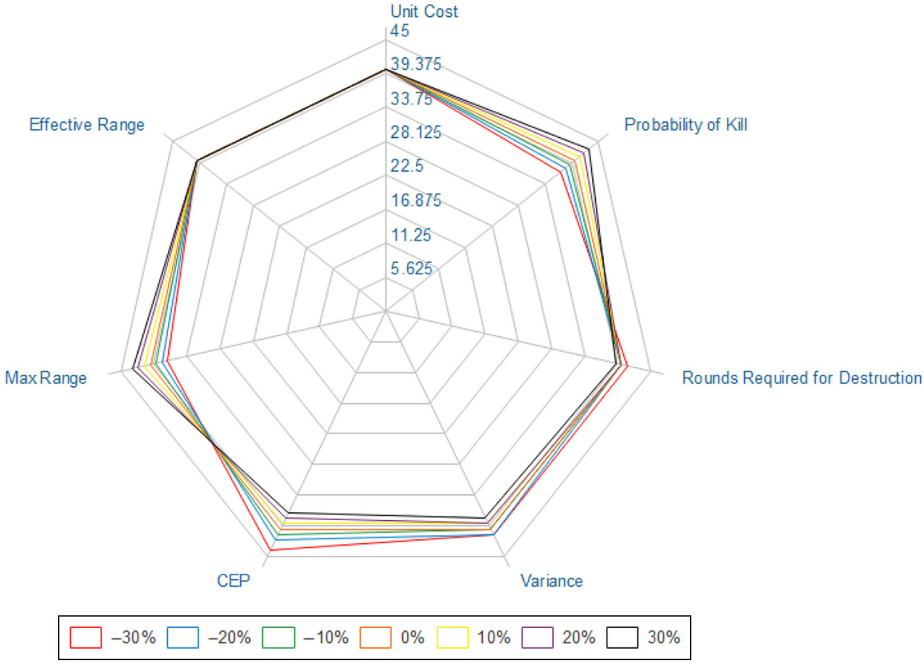


Figure 13.
M549A1 total value sensitivity

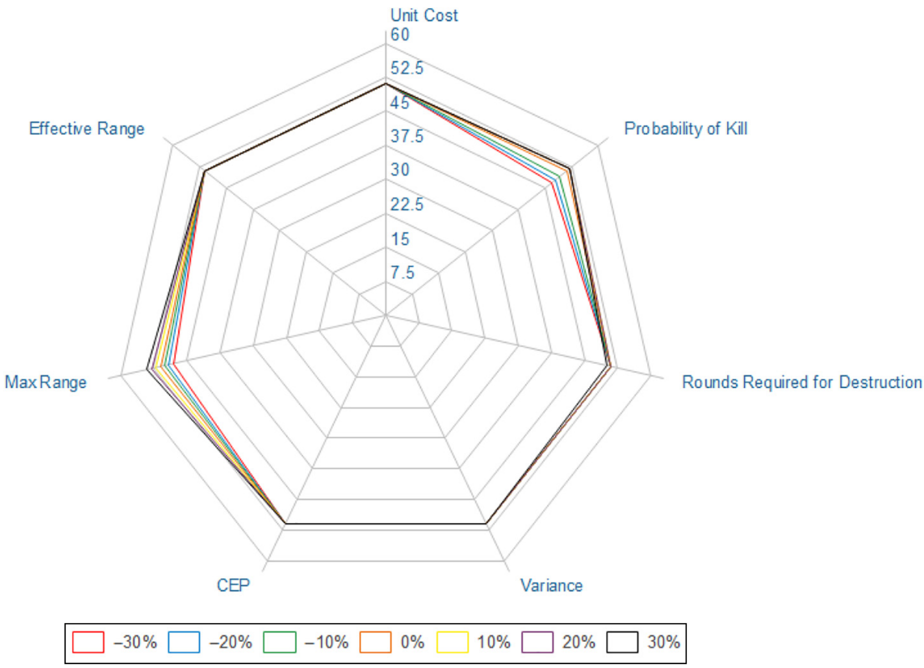


Figure 14.
M982 1a-1 total value sensitivity

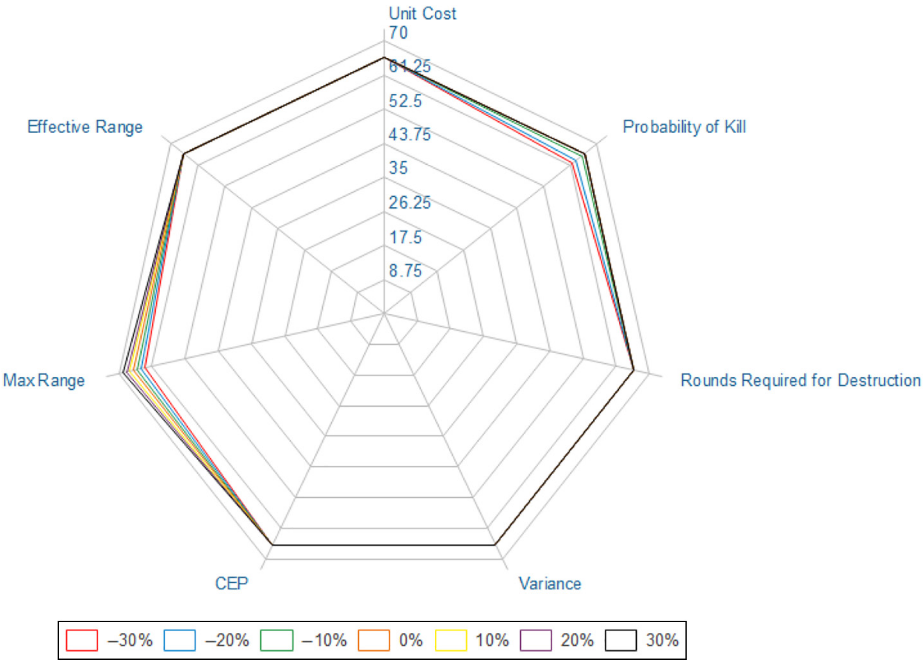


Figure 15.
M982 1a-2 total value sensitivity

In addition, the M982 1a-2 sensitivity plot in Figure 15 illustrates that the total value is insensitive to changes in CEP, variance, effective range, unit cost and the rounds required for destruction. As development is continued, the degree of sensitivity the total value experiences because of a per cent change in maximum range and probability of kill decreases. This is because of the candidate munition nearing the optimal solution. If the optimal solution were reached, there would be no change to the total value as a result of a change in input because the stakeholder could not receive any more utility from the product.

Model limitations

This value-based modeling approach is built upon attributes that are assessed to be critical aspects of evaluating a firing system. There are, however, some limitations that can be drawn from this approach. First, the cost attribute considered only the unit cost of a munition – it did not include the operational costs of each firing mission or the cost in terms of time, personnel and other external resources. There are also competing factors in some firing scenarios when attempting to maximize probability of kill and minimize the circle error probability. For this reason, subjectivity may be required to interpret a general measure, versus an evolving measure, which would depend on the specific wartime scenario. Finally, this model is built upon a number of firing assumptions for the variables outlined in the formulation of the model. If it is determined that X_t and X_r are not independent, are not uniformly distributed or that the number of projectiles needed to destroy a target is not known, this particular model would be limited in providing viable information.

Future work

To gain a greater understanding of the interactive nature of many of the factors in firing systems, a dynamical simulation should be used. Such an approach may then incorporate features of experimental design to evaluate the effects of resources and determine optimal system arrangements. It may also enable researchers to examine the effects of relaxing several assumptions related to the variable distribution and test stochastic firing processes. In addition, a dynamical simulation may evolve into a capability that can be used to compare and contrast our firing systems with those of near-peer adversaries in a scenario-driven environment. Moreover, it may be used to analyze the effects of firing decisions in certain situations. Addressing these extensions of the research may have dramatic implications on the doctrinal positioning of various firing assets on the battlefield.

Conclusion

In summary, the Department of Defense has highlighted a necessity for enhanced long-range field assets. A primary candidate solution is the Excalibur munition. To begin analyzing the effectiveness of these projectiles, a Monte Carlo simulation was developed to predict the expected number of projectiles required for target destruction. This output was used to determine the probability of kill and an effective range of a given munition. The findings were then extended to a value-based model for further analysis. Based on the results of the value-based framework, the Excalibur series munitions provide the most value. Given these findings, commanders should be encouraged to use the Excalibur 1a-2 for point and small area targets, such as radars and single structures, but consider the use of the M795 or M549A1 for large area targets. As technological improvements are made, updated data can populate the simulation to gather an up-to-date expected value, variance, probability of kill and effective range. Similarly, the value functions and swing weights should continue to be updated to reflect the needs of the army. The output of this updated analysis would determine if commander's guidance should be updated once again.

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Appendix

The probability mass function (PMF) and cumulative distribution function (CDF) of the number of projectiles fired by each system were also developed to determine that an average number of rounds fired for each munition type (Table III).

Below are the first 20 trials of the Monte Carlo simulation. The target range and target type are created using a random number generated set within their range. The number of projectiles fired is determined based upon the target specifications outlined in Table I (Table AI).

Table AI.
Monte Carlo simulation output (Trials 1-20)

Shot	M795 (standard HE) Target range	Target type	# Rnds	M549AI (HE-RAP) Target Range	Target type	# Rnds	Excalibur (1a-1) Target range	Target type	# Rnds	Excalibur (1a-2) Target range	Target type	# Rnds
1	17	1	43	15	1	0	20	2	0	37	1	3
2	25	1	0	20	1	0	29	1	0	23	1	0
3	39	1	0	29	2	54	22	1	3	26	3	1
4	30	1	0	39	3	0	38	3	0	22	3	0
5	21	3	11	22	3	10	31	1	0	26	3	1
6	28	2	0	37	2	0	23	2	6	32	2	6
7	31	3	0	15	3	0	18	3	0	21	2	0
8	15	2	78	19	1	0	27	1	3	22	1	0
9	15	1	43	29	1	25	31	3	0	18	1	0
10	28	1	0	31	3	0	23	2	6	20	2	0
11	31	1	0	29	2	54	40	3	0	24	3	1
12	30	1	0	21	1	25	29	1	0	17	3	0
13	24	2	0	15	2	0	16	2	0	36	2	6
14	19	3	11	23	1	25	23	3	1	28	2	6
15	23	3	0	31	3	0	18	3	0	40	2	6
16	19	1	43	37	1	0	35	1	0	39	2	6
17	36	1	0	27	2	54	28	3	1	37	3	1
18	31	2	0	34	3	0	34	2	0	33	2	6
19	27	3	0	21	1	25	27	1	3	21	2	0
20	24	1	0	34	1	0	33	1	0	22	2	0

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