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INVESTMENT PORTFOLIO PRIORITIZATION FOR EMERGING HOMELAND SECURITY THREATS

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ABSTRACT

Government agencies face the challenge of selecting and prioritizing research and development (R&D) investments to address security threats in a dynamic threat landscape. This challenge is compounded by the fact that proposed projects often span technology readiness levels (TRL), cost, and developmental timeframes. The following paper describes a probabilistic, risk-based method that assesses the future expected value of potential investments, incorporating uncertainty from the threat environment - both current and projected - and uncertainty in technology development. The developed method facilitates hedging strategies and redirection of investments at future decision points, based on shifts in threat and reduction of uncertainty; it also captures discounting of achieved value over time to balance projects that have a smaller but faster realization of risk reduction with longer-term solutions that have a large reduction. Ultimately, this approach to R&D investments produces clear, quantitative results for a balanced portfolio that maximizes expected risk reduction.

1 INTRODUCTION

Research and development investments that aim to mitigate emerging threats, specifically terrorism, possess a high level of uncertainty and risk. Prioritizing R&D efforts is particularly arduous due to the low maturity of technologies and the desired level of functionality, which leads to increased uncertainty in technological development. In addition to variable project costs and developmental timeframes, R&D prioritization efforts must account for the additional risk of stakeholder goals changing during the course of development as the realized frequency of emerging threats may fluctuate. Thus, to successfully manage these uncertainties and risks, a proactive R&D process is necessary to combat threats as they emerge.

Previous investment prioritization efforts, with the goal of improving mitigation and prevention, provided frameworks that focused more heavily on the threat assessment rather than the prioritization of projects responding to those threats. The threat assessment compares the magnitude, or relative magnitude, and the inherent uncertainty in the future frequency of occurrence of each hazard/threat type (e.g., vehicle ramming versus active shooter events).

While this method has proven to be helpful for evaluating the importance of emerging threats, agencies must address a number of other key elements that contribute to high return on investment, such as value optimization, budget maximization, and the incorporation of real option techniques. This paper aims to provide a holistic method for utilizing both a value and a threat assessment in a manner that sets the foundation for a risk-based project evaluation. The proposed two-stage - an initial investment period and option exercise period - method allows decision-makers to evaluate projects of varying TRL, cost, schedule, and performance by integrating uncertainty in the current and projected threat landscape with the value of a project.

2 REAL OPTIONS ANALYSIS

Real options analysis provides an analytical framework that allows stakeholders to identify and to select optimal solutions that best meet their mission needs. This framework is traditionally employed in the financial sector. An option is best understood as the right to an investment decision, but not the obligation to proceed with a specific strategy (Eckhause et al. 2009). For the R&D portfolio approach, the analysis provides an evaluation of investment hedging strategies, which specifically provides stakeholders with the ability to redirect investments as threat projections shift, threat uncertainty is reduced, and as projects mature. A stakeholder has the ability to exercise the option of allocating additional funds to projects that merit it, such as high project value for continued development. Table 1 shows an example of an executed investment option at a future period based on an initial project investment made in the present day. This two-stage investment strategy is applied in the method formulation process as described in Section 7.

Table 1: Option investment example.

	Present Day Initial Investment		Future Period Option Investment		Total Investment
Project A	$400K	+	$900K	=	$1.3M
Project B	$100K	+	$900K	=	$1.0M

3 RISK-BASED ANALYTIC FRAMEWORK

A risk-based analytic framework quantifies the risk that different threats/hazards pose against critical areas and/or facilities. The method described in this paper includes an evaluation of threat, vulnerability, and consequence, which taken together constitute risk, as recommended by Government Accountability Office (GAO) guidelines. A threat assessment estimates the frequency of a specific threat that could impact the critical area or facility. The vulnerability assessment evaluates the viability of the threat at the critical area and/or facility. Vulnerability should be considered as the conditional probability that a threat would be successfully executed, if attempted, given area characteristics (i.e., security measures). The consequence assessment, then, evaluates the expected losses or impacts to the critical area and/or facility. Typical loss areas include casualties/major injuries, business continuity impacts, and economic impacts.

4 THREAT PROJECTION

For the threat assessment component, it is critical to accurately assess the threat or hazard environment based on the uncertainty in that threat. To adequately assess this factor, the stakeholder must recognize that the estimated frequency of an emerging threat has the potential for change over the investment timeline, particularly in a dynamic and evolving threat environment. Using this assumption, we propose a method for estimating the threat range over the course of the investment process and at specific decision, or action, points.

A nested Monte Carlo simulation process based on stakeholder provided inputs is employed to probabilistically simulate the threat range of the emerging threat over a predetermined time horizon. Subject matter experts (SME) provide the mean frequency and the uncertainty bounds (i.e., 90% confidence interval) of the emerging threat over time. Stakeholders specify the time horizon (e.g., 20 years) and specific investment decision points (i.e., project option exercise point).

Using these inputs, the process simulates a large number of realized frequency cases within the uncertainty bounds. The process simulates the estimated frequency at present day, the projected frequency at a specified point for exercising an option (i.e., option exercise point), and the actual frequency at the time horizon for each simulated run. The nested Monte Carlo simulation should be considered as a linked double Monte Carlo simulation - an outside simulation and an inside simulation. The outside simulation estimates the mean frequency of the threat realized at the option exercise point projected from present day. The inside simulation estimates the mean frequency of the threat realized at the time horizon projected from the option exercise point. The goal is to simulate a large number of possible outcomes over the candidate time period. Accounting for potential change in the threat environment enables the stakeholders to adequately evaluate whether initial funding or supplementary funding is merited at the specific points for fully executing on an option. Figure 1 illustrates the probabilistic process used for the threat projection. The projected threat frequency over the time horizon is represented by the solid red line. The uncertainty bounds generated by the outside and inside Monte Carlo simulations are, respectively, represented by the purple and green dashed lines.

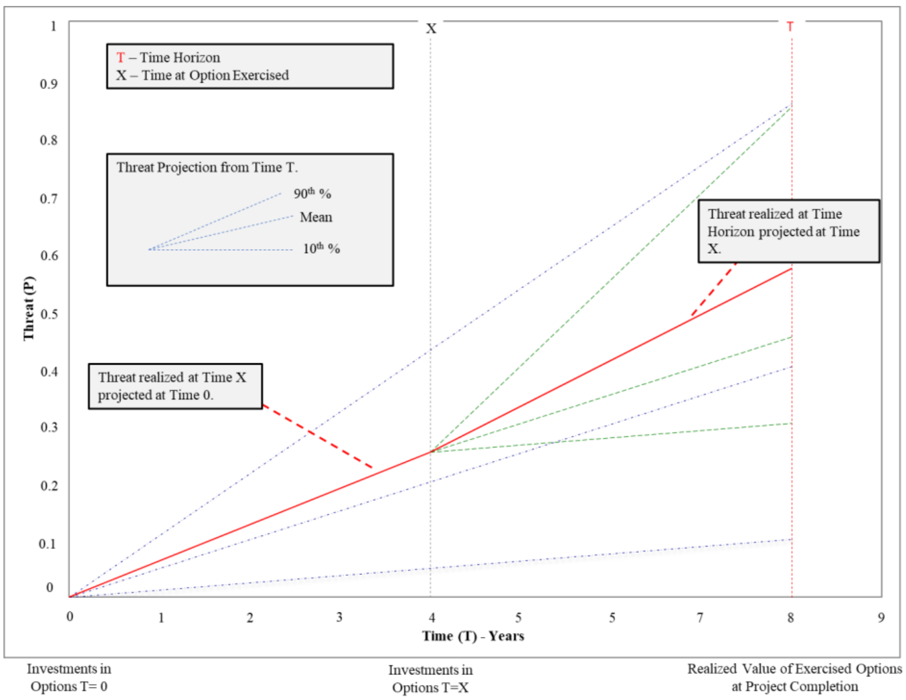

Figure 1: Threat landscape over time horizon.

5 PROJECT VALUATION

Project prioritization requires a metric that will adequately assess the value, or benefit, of implementing a specific R&D project against a threat or a set of threats. The risk-based approach we propose is a standard, established process that balances a perceived consequence by vulnerability and mission critical criteria. The described value assessment process is intended to provide an example of possible project valuation. The intent of our overarching risk-based method is to provide a robust statistical framework to support project prioritization and portfolio selection. The project valuation component can be customized to best meet the needs and mission of stakeholders and could be an existing valuation system that is integrated within the risk-based framework.

The following valuation process is typical and is used for the purposes of describing the component in the greater framework because it is a common process. This valuation scheme requires SMEs to evaluate the amount of potential consequence and vulnerability that could be reduced by the project against a standard consequence and vulnerability baseline, using a Delphi or alternate consensus building method. The potential vulnerability and consequence reductions resulting from a project are assessed with matrices that integrate a vulnerability and consequence reduction.

The total reduction value is formulated as follows:

$$Total\ Reduction\ Value\ (TRV)_{\ p} = \left(\overline{V_p} = \frac{\sum_{i=1}^{n} V_i}{n} \times \overline{C_p} = \frac{\sum_{i=1}^{n} C_i}{n} \right)$$

The following variables and indices are used:
V = vulnerability reduction value;
C = consequence reduction value;
p = index of proposed projects;
i = index of consequence and vulnerability scores 1…n where n is the number of SMEs.

Table 2 shows an example project vulnerability and consequence reduction evaluation where project vulnerability and consequence reductions are informed by SMEs and derived using a Delphi method.

Table 2: SME informed project vulnerability and consequence reduction example.

Project	Vulnerability Reduction		Consequence Reduction		Total Reduction Value (TRV)
A	0.88	X	0.62	=	0.55
B	0.92	X	0.77	=	0.71

Mission critical criteria, such as organization suitability, are scored by SMEs on a common scale also using a Delphi method. Consequence and vulnerability reductions and mission critical criteria are then integrated using pre-established weights to provide a composite total value metric. The total value metric is multiplied by a projected threat in the nested Monte Carlo process to produce an overall risk reduction metric for each Monte Carlo case. The risk reduction metric is used as a measure of desired R&D success and project valuation.

6 PROJECT MATURITY, COST AND SCHEDULE

Project prioritization necessitates an evaluation of project metrics, including maturity, development cost, and schedule, all of which are not necessarily captured by project valuation methods. Maturity relates to the project's current technological development stage. Many government agencies, such as the Department of Homeland Security (DHS), the National Aeronautics and Space Administration (NASA), and the Department of Defense (DoD), use TRLs to assess a project's technological maturity. The use of TRLs enable stakeholders to evaluate a project's current maturity level and the perceived level of effort required for full development and implementation of the project. Figure 2 displays the nine TRLs defined by DHS (Science and Technology Directorate 2013).

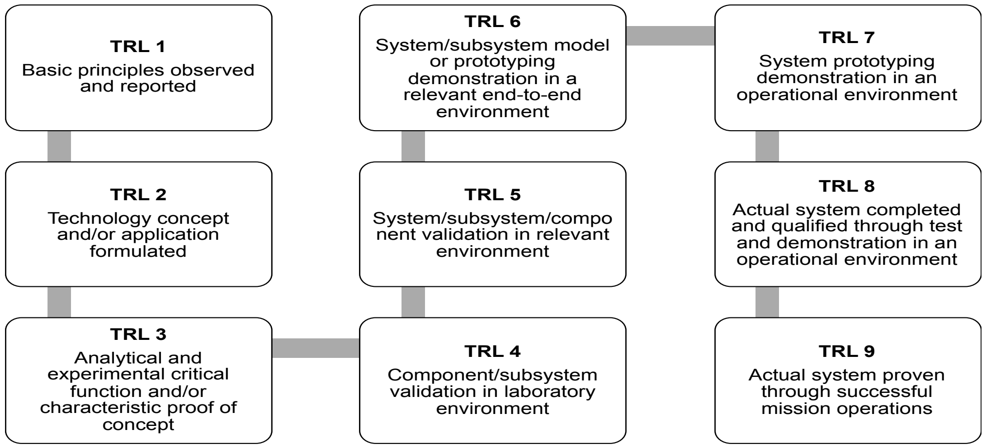

Figure 2: Technology Readiness Level (TRL) definitions.

Project cost and schedule estimates are key to producing an optimal selection of projects and to meet mission goals. Project cost estimates allow stakeholders to efficiently allocate funds subject to an investment constraint in both the initial investment period and the option exercise period. Similarly, project schedules allow stakeholders to evaluate and select projects that align with mission goals. Although project schedules are inherently variable, the schedules provide a useful measurement of time to compare against a common time horizon used to evaluate all projects. In the following section, we provide the risk-based framework for evaluating and prioritizing projects based on project metrics.

7 METHOD FORMULATION

This section outlines the general framework for the two-stage probabilistic, risk-based method. The method is based on the components described in the previous sections.

In the description, project cost and schedule estimates are fixed and only uncertainty in threat is evaluated to simplify the example. In an actual analysis evaluation of uncertainty can be included for any of the three parameters (i.e., project cost, schedule, and maturity).

7.1 Inputs

In addition to the proposed list of projects aimed at mitigating the emerging the threat, stakeholders provide the following inputs for the R&D investment analysis:

TH – time horizon for project evaluation (e.g., 8 years);
TX – time where the stakeholder exercises the project option (e.g., 4 years);
OIBC – option investment budget constraint at time TX;
C – cost for total project development by TRL group;
d – discount rate;
TR&D – current project TRL;
IBC – initial investment budget constraint at time T0. Investment constraints are imposed at the initial investment period and at the option investment period to produce an optimal portfolio that is within scope of out-year budgetary planning.

7.2 General Application

The stakeholder intends to fund a select number of projects, each with specific costs, schedule, and level of technological maturity (i.e., TRL). Prior to the allocation of funds, proposed projects are evaluated by SMEs for potential value at project completion, i.e., product of total vulnerability and consequence reduction and mission critical value.

The total project value at completion is formulated as follows:

$$Project\ Value\ at\ Completion\ (PV)_p = \sum \left(TRV_p \times w_i\ , MCV_p \times w_i\ \right)$$

The following variables and indices are used:

TRV = total vulnerability and consequence reduction value;

MCV = total mission critical value;

p = index of proposed projects;

i = index of weight factor.

Table 3 shows an example of total realized values at project completion. For method demonstration purposes, the proposed list of projects shown in Tables 1 and 2 has been expanded to include three additional projects.

Table 3: SME informed project value assessment example.

	Emerging Threat		
Project	**Total Reduction Value**	**Mission Critical Value**	**Total Value at Completion**
A	0.55	0.34	0.50
B	0.71	0.51	0.66
C	0.65	0.33	0.57
D	0.39	0.48	0.41
E	0.37	0.45	0.39
Weight	75%	25%	

At the initial investment period (T_0), stakeholders allocate funds based on organizational goals with respect to a predetermined investment constraint (I_{BC}). The initial investment is made with the intention of evaluating real options available for continued project development in terms of TRL.

Project selection at initial investment period is formulated as follows:

$$Total\ Initial\ Investment\ Cost = \sum_{i=1}^{n} C_n \times S_n$$

$$\text{subject to: } \sum_{i=1}^{n} C_n \times S_n \leq OI_{BC}$$

$$\text{where } S_n = \begin{cases} 1 & \text{if project } n \text{ is selected} \\ 0 & \text{if project } n \text{ is not selected} \end{cases}$$

The following indices are used:

$C =$ project cost by TRL;

$S =$ project selection by TRL; and,

i = index of project costs by TRL group 1…n where n is the number of projects.

Table 4 presents an example of an initial project selection (project selection is denoted with an "X"). For simplicity, TRLs have been grouped according to similar characteristics.

Table 4: Initial project selection example.

Initial Investment Budget Constraint	$3.0M

		Portfolio Investment Cost by TRL Group			**Portfolio Investment Selection by TRL Group**		
Project	**Current TRL**	**1- 3**	**4 - 6**	**7 - 9**	**1- 3**	**4 - 6**	**7 - 9**
A	4	-	$900K	$400K		X	
B	3	$100K	$600K	$300K	X		
C	4	-	$100K	$200K		X	
D	5	-	$1000K	$500K		X	
E	5	-	$900K	$500K		X	
					Total Cost		$3.0M

Following the initial investment selection, we incorporate a probabilistic approach for estimating the threat landscape over the determined time horizon.

7.2.1 Probabilistic Implementation

Given that the goal is to evaluate real options in terms of a risk-based solution, the potential risk reduction that can be achieved by the investment option is evaluated over the entire horizon. The expected risk reduction is calculated as the product of the SME-informed project value, threat history over the time horizon, and the baseline consequence and vulnerability of the emerging threat. The baseline consequence and vulnerability value should be considered the amount of expected losses from the emerging threat if no actions are taken. Additionally, all risk reductions are discounted over time based on a stakeholder specified discount rate.

A viable project option is determined using the initial project investment selection and the cost of the exercised option for the selected project or projects. A project is considered viable if the total cost of options exercised does not exceed the option investment budget constraint (OI_{BC}), as determined by the stakeholder. For example, based on the initial selection of projects as shown in Table 4 and an OI_{BC} of $2 million, Project A and project bundle, ABCE, are viable solutions with total costs of $0.4 million and $2 million, respectively, for the exercised options. Conversely, project bundle, ABCDE, is not viable because the total amount – $2.5 million – needed for all exercised options exceeds the available funding.

To accurately measure the risk reduction presented by the investment on the executed options, the threat landscape is probabilistically simulated using the nested Monte Carlo process. The nested Monte Carlo process utilizes a mean frequency and the uncertainty of the emerging threat, which is specified by the SMEs and rooted in historical data and developing trends. Using the mean frequency of the emerging threat, a nested Monte Carlo process simulates the estimated frequency at present day, the projected frequency at the time an option is exercised (T_X), and the actual frequency at project completion (T_H) for each simulation run. For each run, an initial set of project investments is specified. At the option exercise time, the analysis tool evaluates the projected value of all funded options based on the projected threat uncertainty at the time of project completion. The tool then selects the most effective set of options to exercise within the maximum budget for that case. The expected risk reduction of the investment on the executed options is derived using the realized threat frequencies and the expected value of the projects. Finally, the results from all runs are statistically evaluated to determine the performance over the range of possible threats and the risk reduction achieved by the executed options. Figure 3 shows the process for determining the project options.

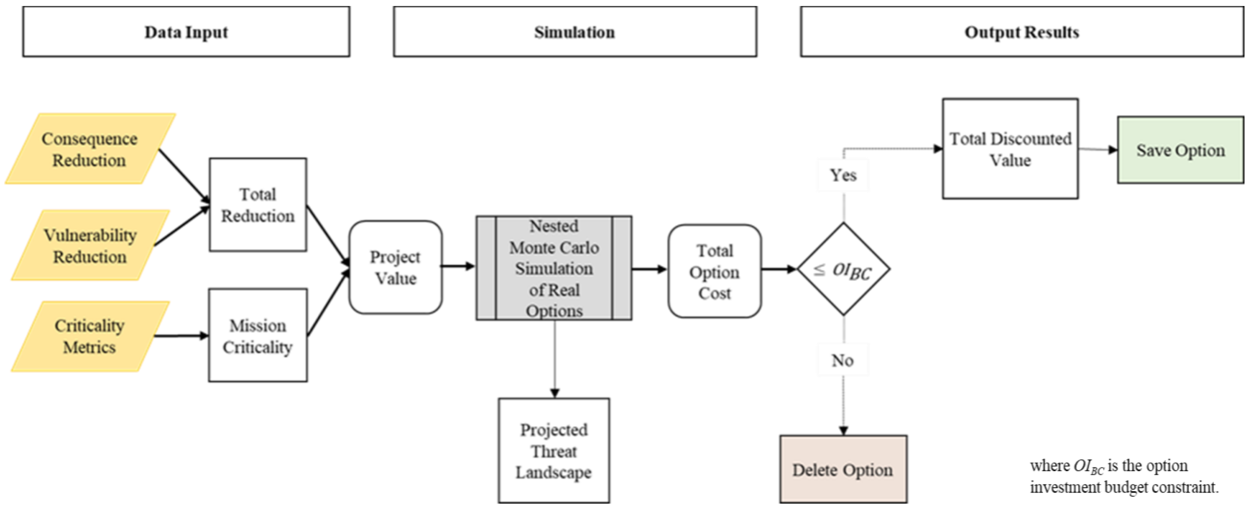

Figure 3: Real options process diagram.

7.3 Output – Expected Risk Reduction Value

The probabilistically determined discounted risk reduction values achieved by the project options are rank ordered in descending order according to their discounted value. The stakeholder may elect to fund a specific project or selection of projects that maximize risk reduction against the emerging threat as it matures over the time horizon. Table 5 provides a rank ordered list of the top 5 options based on an investment option budget constraint of $2 million.

Table 5: Real options analysis example results.

Investment Option Budget Constraint	$2.0M		
Rank	**Project Option**	**Total Option Cost**	**Total Discounted Value**
1	A, B, C, E	$2.0M	457.57
2	A, B, C, D	$2.0M	455.79
3	A, C, D, E	$1.6M	426.09
4	A, B, D	$1.8M	263.96
5	B, C, E	$1.6M	263.90

8 DISCOUNTING OF RISK OVER TIME

Project implementation time and discounting is accounted for in realized project value. Discounting of project value, or risk reduction, over time is critical to an accurate analysis and to an appropriate investment strategy given the extended and fluctuating timelines for R&D, as well as the dynamic threat landscape.

Project discounted risk reduction is formulated as follows:

$$Discounted\ Risk\ Reduction\ = \int_{t=0}^{T_H} \frac{R_t}{(1+d)^t}$$

The following variables and indices are used:
R = total project risk reduction;
d = discount rate; and,
t = index of time 0…time horizon (T_H)

By incorporating discounting, the method accounts for those technologies and projects that mature more quickly and may therefore have a greater inherent value as compared to projects that take longer to complete. This is particularly important as stakeholders strive to balance a portfolio between projects that present substantial risk reduction, but long timelines, with those projects that have lower potential risk reduction, but shorter development timeline (i.e., faster realization of risk reduction). Additionally, incorporating implementation time allows stakeholders to clearly understand the prioritization sensitivity to project schedules.

Figure 4 illustrates an example comparison of risk discounting between two projects. Project A has significant risk reduction but takes longer to develop and implement. Project B reduces less risk, but has a shorter development timeline, thereby providing greater integrated risk reduction over the same timeframe (20 years).

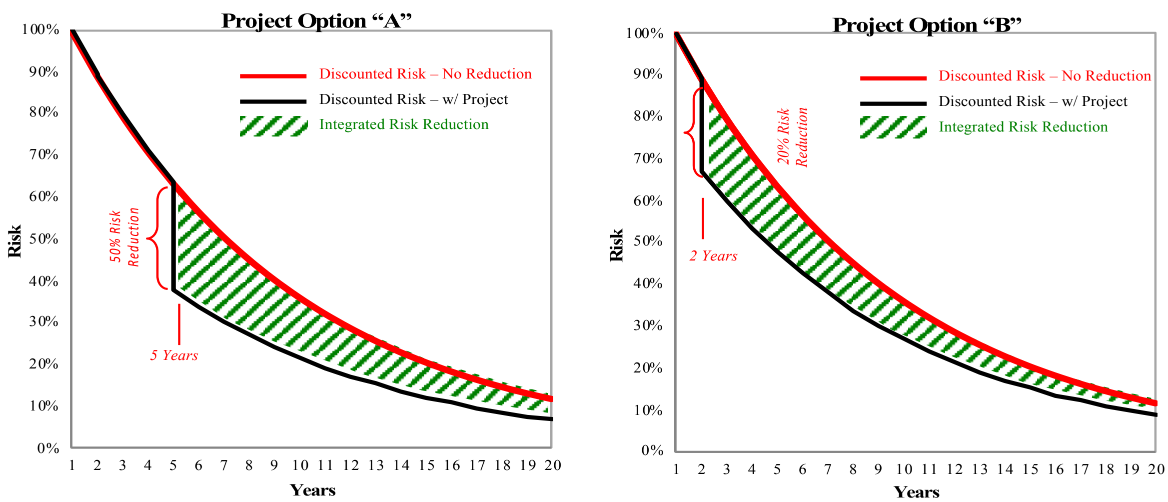

Figure 4: Option risk reduction discounting example.

9 CASE STUDY APPLICATION

A case study using notional data concerning vehicle ramming attacks as an emerging threat was chosen to demonstrate the method's capabilities. A vehicle ramming attack is defined as "a form of attack in which a perpetrator deliberately aims a motor vehicle at a target with the intent to inflict fatal injuries or significant property damage by striking with concussive force" (Cooper 2018). The frequency of vehicle ramming attacks in Western countries has increased significantly over the past decade with thirteen suspected or confirmed terrorist-related vehicle ramming events in 2017. The relative ease to acquire and commit the attack, as well as the encouragement and guidance by terrorist organizations has contributed significantly to the increased volume of attacks (G4S North America 2017). Of the thirteen vehicle ramming attacks in 2017, nine were executed using smaller vehicles such as cars, SUVs, or vans and four were executed using trucks. The proliferation of extreme ideology, as well as the shift to "lone wolf" attacks requiring minimal planning and simple weaponry, supports the need for continued efforts to develop technologies aimed at mitigating or protecting against vehicle ramming attacks.

Table 6 lists an example portfolio of projects that were identified to combat rented large commercial truck (i.e., a large, heavy motor vehicle) ramming attacks and/or non-rented personally-owned vehicle

(POV) (e.g., compact car, van, SUV) ramming attacks. The three candidate projects are in different stages of development (i.e., TRL), have varying costs, and different schedules. The projects were all evaluated over the time horizon from 2017 through 2020.

Table 6: Vehicle ramming project portfolio.

Project	Current TRL	Option Cost	Exercise Cost	Description
GPS Disable	4	$3M	$10M	GPS disable is effective against rental trucks - systems include virtual fencing.
SVD Device	5	$2M	$7M	Small Vehicle Disable devices are portable devices, carried by law enforcement officers, that can disable small cars, vans, and SUVs.
CCTV/Barriers	3	$5M	$15M	Placed at high value areas and intersections, barriers can deploy automatically based on observed behavior or manually.

All three projects were available for investment in the initial investment period, subject to a budget constraint of $7M. Next each project was evaluated for the amount of potential consequence and vulnerability that could be reduced against a standard baseline using a Delphi method. Projected value for each project against each threat is shown Table 7.

Table 7: Vehicle ramming project value.

Project	Value against POVs	Value against Rented Trucks
GPS Disable	0	0.8
SVD Device	0.6	0.1
CCTV/Barriers	0.5	0.3

The threat landscape was projected for both types of ramming attacks over the time horizon. Figure 5 illustrates the threat projections for both individual ramming types and for all ramming attack types.

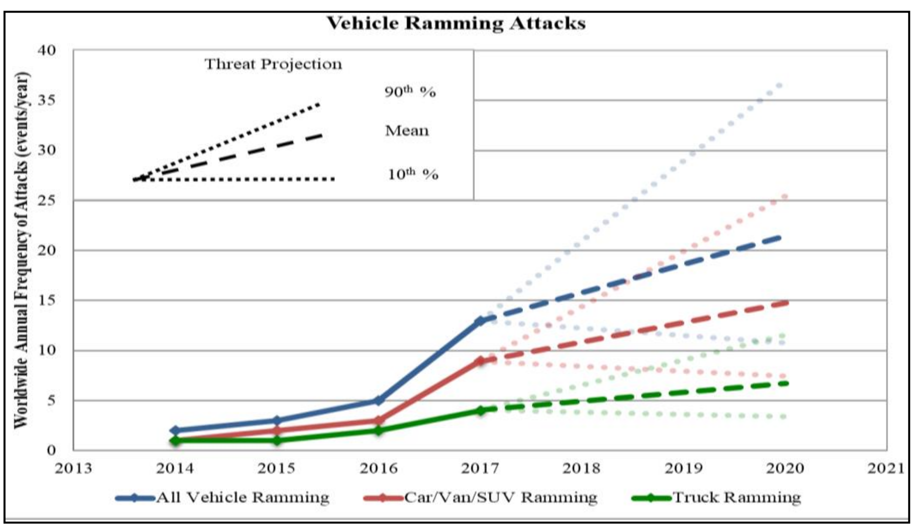

Figure 5: Vehicle ramming threat landscape.

Based on the discounted risk reduction achieved by each exercised project option, real option exercise was determined with respect to an option investment budget constraint of $15M. Figure 6 plots the available real options according to achieved total discounted risk reduction value.

Following analysis, a combined portfolio of options consisting of the GPS Disable and SVD Device achieves the greatest discounted expected risk reduction against both vehicle ramming threats - including the uncertainty involved in each threat. Additional sensitivity analysis will assist in successfully managing investment risk and uncertainty during the prioritization process.

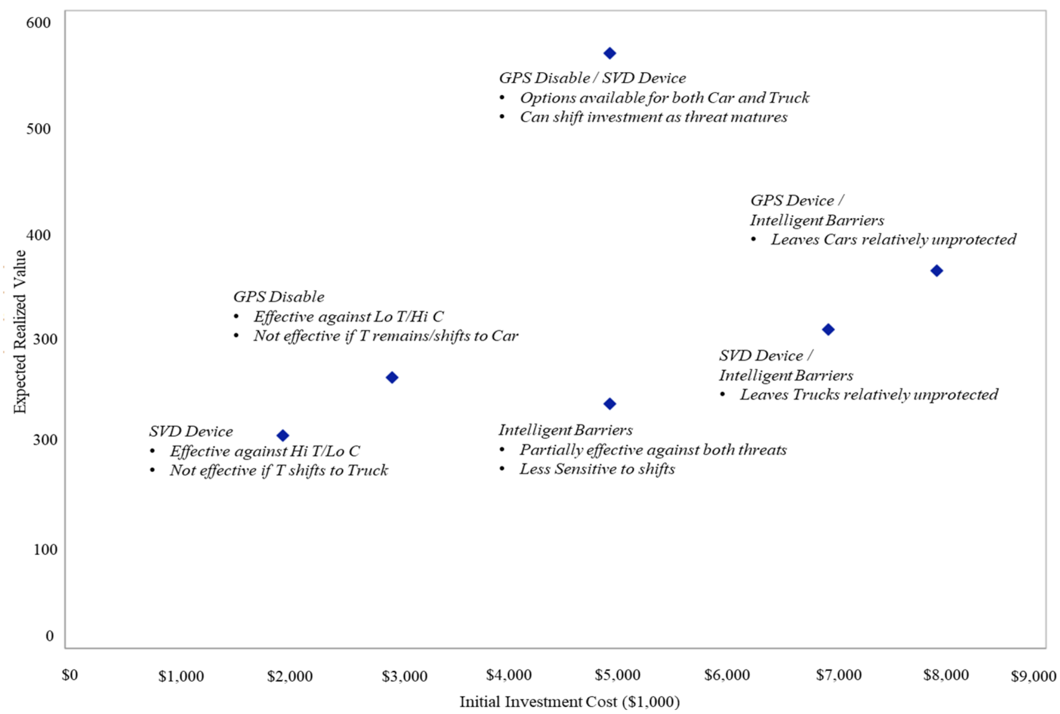

Figure 6: Vehicle ramming real options.

10 CONCLUSIONS AND FUTURE WORK

Overall the method provides many benefits to government agencies seeking to invest in R&D for emerging threats with a portfolio that has a high realized value. These benefits include probabilistic assessment of future expected value - including the impacts of in the threat landscape and in project performance; evaluation of investment hedging strategies - including the ability to redirect funds as threat projections shift and as projects mature; and discounting of achieved value over time in order to achieve balance and to recognize that technologies that mature more quickly may have a greater inherent value as compared to projects that take longer to complete.

However, there are also aspects identified for future growth and improvement as the method evolves with usage. As the method matures and decision-makers employ it in portfolio management, it will be possible to increase the use of quantitative data, specifically for the consequence and reduction analysis, to guide the approach toward a true quantitative risk analysis. The use cases will provide an even better understanding of the types of projects and associated data points necessary to move toward a higher fidelity analysis. Also, in future expansions, the method will progress toward the incorporation of probability and uncertainty of development success based on TRLs. Development success will encompass variability in schedule (e.g., delays), cost, and general technical success.

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