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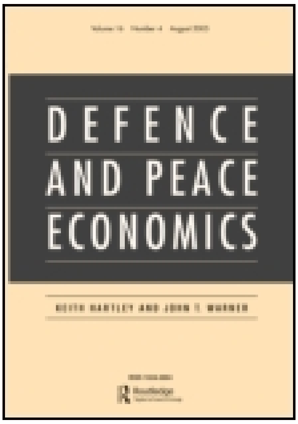


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# ON THE CHOICE OF MULTI-TASK R&D DEFENSE PROJECTS: A CASE STUDY OF The ISRAELI MISSILE DEFENSE SYSTEM

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# ON THE CHOICE OF MULTI-TASK R&D DEFENSE PROJECTS: A CASE STUDY OF THE ISRAELI MISSILE DEFENSE SYSTEM

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Investments in R&D constitute a major share of the expenditures of the hi-tech industry since, generally, they enable firms to successfully compete in the rapidly and constantly changing markets for hi-tech products and services. The role of R&D projects is particularly important in the areas of defense and homeland security due to the nature of warfare and the continuous threats posed by arms races and by terror organizations. This study analyzes the choice of the R&D projects designed to counter multiple related military threats. It develops the methodology required to assess whether it is preferable to develop one project to thwart several related threats, or several distinct projects, each of which provides an answer to one specific threat or a partial set of the threats. An analytic solution is provided and assessed for two simple models with two related threats. A solution of the model is then provided for any number of related threats, using a dynamic programming methodology. Finally, we demonstrate the usefulness of our model and methodology to Israel's missile defense problem; that is, we show how to optimally develop systems aimed at thwarting the multiple threats of short-, medium-, and long-range missiles.

*Keywords:* Defense R&D; Multi-task projects; Missile defense system

*JEL classification:* D74, D78, H41, H56, H57

## 1. INTRODUCTION

Developing the 'right' new products is critical to the firm's success and is often cited as the key to a sustained competitive advantage. 'Innovate or die' is the message of numerous papers in the academic and popular literature (Kavadias and Chao, 2007). The business world is often characterized by a very rapid and ever-increasing demand for innovations which must be met by investments in R&D (Tishler and Milstein, 2009). The total 2009 investment in R&D by the 1400 largest firms worldwide was approximately $400 billion (European Industrial R&D Investment Scoreboard, 2010). Similarly, developing the right security products (e.g. offensive weapon systems and missile defense systems [MDS]) is crucial for any country under a sustained threat of being attacked. In fact, it may be argued that the single most important success factor in the fight against terror organizations or in an arms race between rivals is advanced technology (see, e.g. Van Creveld, 1991).

Since World War II, expenditures on defense R&D have risen steadily, with a noticeable acceleration following the 9/11 terror attack in the USA. The USA invested $67

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billion in defense R&D in 2008, which amounts to 15% of its $447 billion defense budget (Department of Defense, 2008). The disconcerting increase in the threat of international and local terror has led countries all over the world to establish and strengthen agencies entrusted with the responsibility for developing solutions for potential terror or the threats of rival militaries to their civilians (such agencies include, for example, ‘DARPA’ – the Defense Advanced Research Projects Agency, in the USA, and Israel’s ‘DDR&D’ – the Directorate of Defense Research and Development, or ‘Mafat’ – to use its Hebrew acronym).

In this paper, we explore the merits of the decision-making process of choosing a *multi-task* R&D project or several *single-* or *partial-task* R&D projects in order to thwart several related military and/or terror threats. We demonstrate the usefulness of our methodology to Israel’s missile defense problem and show how to optimally develop weapon systems aimed at thwarting the threats of short-, medium-, and long-range missiles.

Specifically, the study’s objectives are (a) to define and characterize the properties of single- and multi-task R&D projects; (b) to determine when a multi-task project is preferable to several single-task projects; and (c) to determine the optimal choice among several (single- and multi-task) projects of different dimensions.

The methodology of this study can be applied to a more general managerial decision-making problem about multi-task R&D project alternatives. For example, it can be applied to the question whether Apple should have focused on a larger (smaller) number of products that provide solutions for music, telephony, computing, and more, rather than on its iPod, iPhone, iPad (Tablet), and MacBook Air. Table I presents the line of Apple’s products and their intended use. Clearly, Apple made the choice to produce iPods, iPhones, iPads, and laptops. However, in principle, they could have chosen to produce, for example, only one product for telephony, music, video watching, and camera, and one product to cover the uses of the iPad and the MacBook Air. Presumably, producing all four products gives Apple a competitive advantage and, most probably, higher overall profits.

The defense R&D projects that we consider in this paper are characterized by very high uncertainty, their economic value at the initiation stage is difficult to estimate, and the particular nature of each conflict may strongly influence the choices. Moreover, selecting the ‘right’ defense R&D projects from all the relevant alternatives requires large budgets and may eventually be crucial to the well-being of the country. It would therefore be useful to develop a robust methodology for assessing the choice of the R&D projects designed to counter multiple related military threats.

This paper is organized as follows. Section 2 presents an overview and an example of multi-task vs. single-task R&D projects. Section 3 develops two basic models and Section 4

TABLE I Apple’s Products and Their Intended Uses

| Product | Main use | Other features | Versions of the product |
|---|---|---|---|
| iPod (Nano, classic, touch) | Music player | Video player, picture viewer, playing games, simple applications, etc. | Some versions of iPod Nano |
| iPhone 4 | Cellular phone | Music and player, camera, internet, simple applications and games | iPhone, iPhone2, iPhone3, iPhone3 GS |
| iPad | Mini laptop for e-mail and surfing the web | ‘Mobile office’ and applications | iPad1, iPad2 |
| MacBook Air | Strong laptop for work | Camera, video and music player | |

*Notes*: A description of Apple and its strategy can be found, for example, in ‘Here’s why Apple stock is going to $1000’, Business insider, 17 December 2010. http://www.businessinsider.com/gene-munster-apple-presentation-2010-12?op=1 (accessed 23 December 2011).

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presents a more general model. The application to the Israeli MDS is in Section 5. Section 6 concludes.

## 2. OVERVIEW

Consider the threat of steep-trajectory firing. This threat can be divided into many subthreats such as mortar shells, short-range rockets, medium- and long-range rockets, missiles, etc. Suppose that a country is attempting to thwart the potential damages from very short-range rockets (up to 4 km) and rockets with longer ranges (up to 70 km). The problem facing the decision-makers on which weapon system(s) to develop to defend their country can be summarized as follows: should we develop two individual rocket defense systems, one for each type of threat (single-task projects), or should we develop only one rocket defense system which can be used against both the very short-range and the longer-range rockets (multi-task project)?

This decision problem is not new. It has been assessed by many governments during the last several decades. For example, David and Limor (2008a) describe the Israeli decision-making process in contending with the rockets being fired by Hamas and Hezbollah on Israeli cities and settlements. David and Limor (2008b) discuss the Second Lebanon War (2006) and Hezbollah's use of rockets, in comparison to the use of Scuds by Saddam Hussein in the First Gulf War (1991).

Reality is generally more complicated than this example of just two threats and two alternatives (two single-task projects or one two-task project). In fact, in most situations decision-makers are faced with an operational problem of many threats and several alternatives of solutions. Figure 1 illustrates six threats which require one multi-task solution or a combination of several multi-task and single-task solutions or six single-task solutions. Decision-makers confronted with such a problem must find the optimal combination of R&D projects to defend their countries from the relevant threats. That is, they have to find, for example, the mix of single- and multi-task R&D projects that features the minimum cost of the projects subject to predetermined performance levels of the products to be developed by the projects. Clearly, the required performance level of the products (outcomes) of the R&D projects may vary across threats. For example, though the short-range rockets and mortar shells are 'close' threats, in terms of the magnitude of the damage they can inflict or the technology that is required to thwart them, the level of performance that the decision-makers demand to thwart mortar shells (about 40%) may be lower than that required to thwart short-range missiles (about 50%) since the latter are likely to cause greater damage. Similarly, the performance level required from weapon systems designed to thwart long-range ballistic missiles (100%) is, clearly, much larger than that required from weapon systems designed to thwart long-range rockets (about 80%). Long- and short-range rockets are also close threats, but the two types of ballistic missiles are more distant from each other, because long-range ballistic missiles are capable of inflicting very extensive damage if they hit their intended targets.

The greater flexibility in production or operation that is required for weapon systems capable of thwarting several threats is costly. Fine and Freund (1990), for example, assess whether it is beneficial (profitable) to invest in flexible capacity or in dedicated nonflexible capacity. Van Mieghem (1998) expands the analysis of Fine and Freund (1990) to highlight the important role of price and cost mix differentials, which, in addition to the correlation between product demands, significantly affect investment decisions and the value of flexibility. Childs and Trianitis (1999) develop a procedure to obtain the optimal dynamic investment policy for an R&D program by showing that dynamically altering a funding

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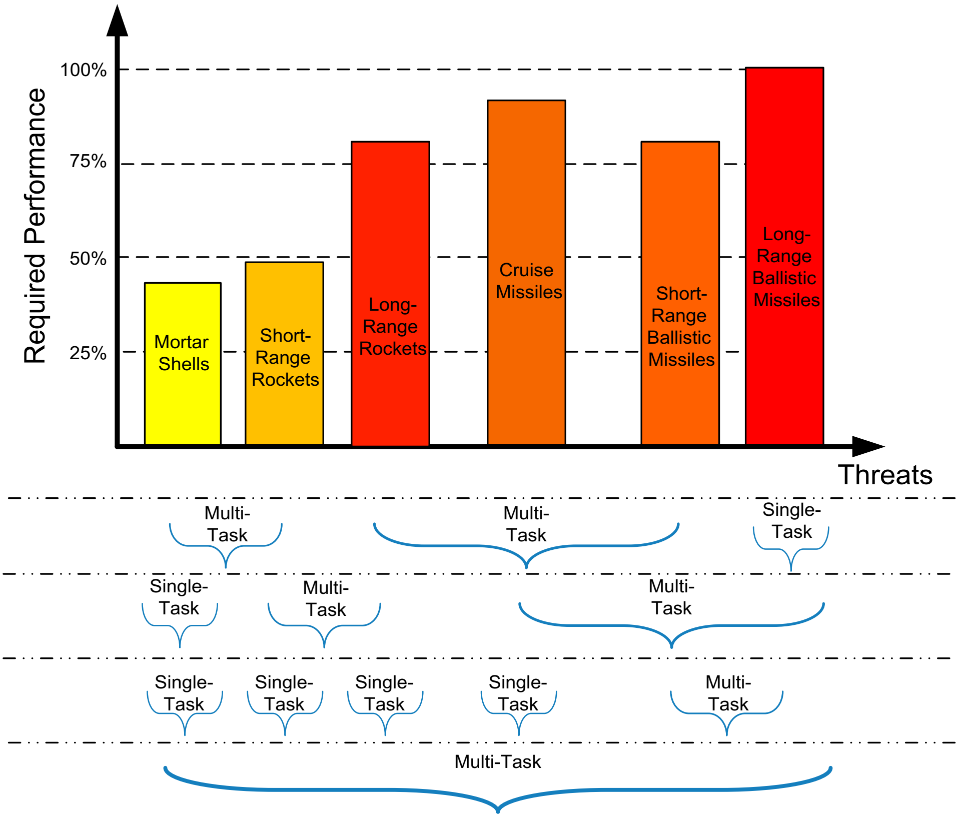


FIGURE 1 Missile threat spectrum: the threats and the required performance
*Note:* The required performance level for each threat in this particular example is arbitrary.

policy (by accelerating, shelving, or abandoning projects) resolves uncertainty. Thus, optimization and resource allocation techniques are normally used to obtain maximum performance (and/or flexibility) for a given cost, or minimum cost subject to predetermined performance level (Rogerson, 1990; Hirao, 1994; Lipow and Feinerman, 2001; Kagan *et al.*, 2005; Setter and Tishler, 2007).

The US military has long been planning its development programs by using optimization techniques such that it will be best prepared, in terms of capabilities and flexibility, for current and future military and terror threats. The US Space Command uses a Space Command Optimizer Utility Toolkit, a mixed integer linear program that selects a set of assets from a pool of candidate assets, and the Space Command's Space and Missile Optimization Analysis to assemble strategic master plans to be submitted to Congress (Brown *et al.*, 2003). The US Air Force developed an analytical framework, which uses operations research tools to enhance a multi-attribute decision analysis and identify key system concepts and technologies for achieving air and space dominance in the year 2025 (Parnell *et al.*, 1998).

Uncertainty about a project's technology or needs is likely to complicate the R&D process. Much research has been conducted on various types of project uncertainty by researchers from a variety of disciplines (Manglik and Tripathy, 1988; Iyigun, 1993;

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Chapman and Ward, 2000). Clearly, opting for a project aiming to fulfill many tasks increases uncertainty as well as the developing time and costs. It also complicates the project and, in turn, increases the risk that the end products (outcomes) will not be capable of contending with all the tasks the project was initially planned to perform. In contrast, Tishler (2008) shows that choosing the higher-risk R&D program from among several alternatives is a dominant strategy under Bertrand or Cournot competition. Real options valuation is another tool which can be used to balance the investment in high-risk projects (Huchzermeier and Loch, 2001). New Product Development, strategic buckets, and 'Product Family Based' are policies which can aid decision-makers in deciding which components of the new technology (project development) can be taken from previous or existing products, and which components should be developed afresh for the new product. These policies can also aid in deciding how innovative and how risky the new project should be (Kavadias and Chao, 2007; Krishnan and Ramachandran, 2007; Setter and Tishler, 2007; Chao and Kavadias, 2008).

## 3. BASIC ANALYTICAL MODELS

This section presents two basic models for choosing between developing two single-task projects, each providing a solution for a single threat, or developing one project to counter both threats. A more general model is presented in the next section.

Consider two different threats. A decision-maker has to choose between two alternatives: two different specific solutions, one for each threat, or one solution for both threats. For simplicity, we assume that the project costs are linear[1] and that the multi-task project must meet the required performance of each of the two single-task projects (the required performance levels are exogenously given).

Hence, we assess three types of R&D projects indexed by $j$, project $j \in$ A, B, M where A and B represent single-task projects and M represents a multi-task project. Let $C_j$ denote the total development costs of project $j$ which provides a given performance level $P$. The value $P$ is decided by the decision-makers according to their needs and requirements. Let $\alpha$, $\beta$, and $\lambda$ be constant parameters, where $\lambda$ measures the 'closeness' in the developing costs of the two solutions when both threats are being accounted for by a multi-task project, and let $I_j$ be the fixed cost of project $j$. That is, development costs are given by:

$$C_{\mathrm{A}} = I_{\mathrm{A}} + f_{\mathrm{A}}(P) = I_{\mathrm{A}} + \alpha P, \; C_{\mathrm{B}} = I_{\mathrm{B}} + f_{\mathrm{B}}(P) = I_{\mathrm{B}} + \beta P \tag{1}$$

$$C_{\mathrm{M}} = I_{\mathrm{M}} + f(C_{\mathrm{A}}, C_{\mathrm{B}}) = I_{\mathrm{M}} + \lambda(f_{\mathrm{A}}(P) + f_{\mathrm{B}}(P)) \tag{2}$$

The breakeven performance for two single-task projects and one multi-task project, $P$, for which the costs of operating one multi-task project or two single-task projects are identical, is obtained by solving Equations (1) and (2). That is,

$$C_{\mathrm{M}} = C_{\mathrm{A}} + C_{\mathrm{B}} \rightarrow I_{\mathrm{M}} + \lambda(\alpha P + \beta P) = I_{\mathrm{A}} + \alpha P + I_{\mathrm{B}} + \beta P,$$

which yields:

[1]This assumption, which sometimes may be a good approximation of reality, is made for simplicity. Later on we analyze exponential costs due to the increasing costs of R&D (see Tishler, 2008).

$$P = \frac{I_A + I_B - I_M}{(\lambda - 1)(\alpha + \beta)}. \quad (3)$$

TABLE II The Choice Possibilities of the Decision Maker

| | Fixed costs | | |
|---|---|---|---|
| | $I_A + I_B < I_M$ | $I_A + I_B > I_M$ | $I_A + I_B = I_M$ |
| *Closeness of variable costs* $\lambda$ | | | |
| $\lambda < 1$ | $\hat{p}$ | Multi-task | Multi-task |
| $\lambda > 1$ | Single-task | $P^*$ | Single-task |
| $\lambda = 1$ | Single-task | Multi-task | Indifference |

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Table II summarizes the choice possibilities of the decision-maker. The values $P^*$ and $\hat{P}$ denote solutions in which the optimal solution, for single- or multi-task projects, depends on the specific values of all the model's parameters. We focus our attention on cases in which the relevant solution is $P^*$ (the total fixed costs of the two single-task projects are larger than those of the multi-task project, and the total variable costs of the two single-task projects are smaller than those of the multi-task project) or $\hat{P}$ (the total fixed costs of the two single-task projects are smaller than those of the multi-task project, and the total variable costs of the two single-task projects are larger than those of the multi-task project), since they require the computation and assessment of the optimal solution.

In reality, despite the savings in fixed costs, the complications of developing a multi-task project can lead to a lengthier development time. Thus, generally, it is plausible that variable costs are higher for a multi-task project (see Tishler and Milstein, 2009). Hence, in the rest of this study we analyze and assess the solution $P^*$ that combines $\lambda > 1$ and $I_A + I_B > I_M$.

Suppose, for example, that $I_A = 20$, $I_B = 35$, $I_M = 40$, $\alpha = 0.3$, $\beta = 0.8$, and $\lambda = 1.1$ (these values were chosen arbitrarily and are not necessarily related to real projects). Total development costs as a function of the required performance level of the solution are presented in Figure 2 (for the sake of simplicity, the value $P$ is set to be identical for all projects), which demonstrates that when the required performance level is 'low' or 'moderate', the total costs of the multi-task project are smaller than the total costs of the two single-task projects due to the advantage of the multi-task project in fixed costs. This situation changes when the required performance is 'high'; in this case, the importance of the variable costs becomes greater and the development of two single-task projects is less costly than that of one multi-task project.

In reality, project costs are often nonlinear. It is a common assumption that R&D costs are convex (e.g. they increase exponentially with the required performance, see d'Aspremont and Jacquemin, 1988; Symeonidis, 2003; Tishler, 2008). Consider, for example, exponential variable costs. Specifically, let the cost functions be given by:

$$C_A = I_A + P^{\alpha}; \quad C_B = I_B + P^{\beta}; \quad C_M = I_M + (P^{\alpha} + P^{\beta})^{\lambda}. \quad (4)$$

The breakeven performance of two single-task projects and one multi-task project is obtained by comparing the costs of the multi-task project with the sum of the two single-task projects; that is,

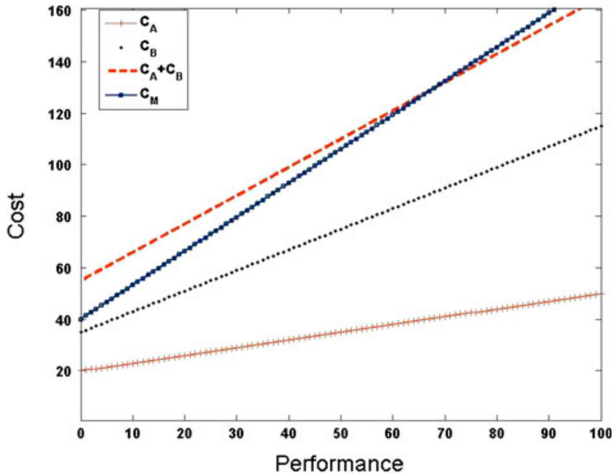


FIGURE 2 Cost as a function of required performance (linear costs)

$$C_{\mathrm{M}} = C_{\mathrm{A}} + C_{\mathrm{B}} \rightarrow I_{\mathrm{M}} + (P^{\alpha} + P^{\beta})^{\lambda} = I_{\mathrm{A}} + P^{\alpha} + I_{\mathrm{B}} + P^{\beta}. \tag{5}$$

Or,

$$(P^{\alpha} + P^{\beta})^{\lambda} - (P^{\alpha} + P^{\beta}) = I_{\mathrm{A}} + I_{\mathrm{B}} - I_{\mathrm{M}}. \tag{6}$$

Figure 3 illustrates the cost structure of Equation (6).

Figure 3, like Figure 2, demonstrates that when the required performance level is ‘low’ or ‘moderate’, the total costs of the multi-task project are lower than the total costs of the two single-task projects, due to the advantage of the multi-task project in fixed costs. This situation changes when the required performance is ‘high’; in this case, the importance of the variable costs becomes greater and the development of two single-task projects is less costly than that of one multi-task project.

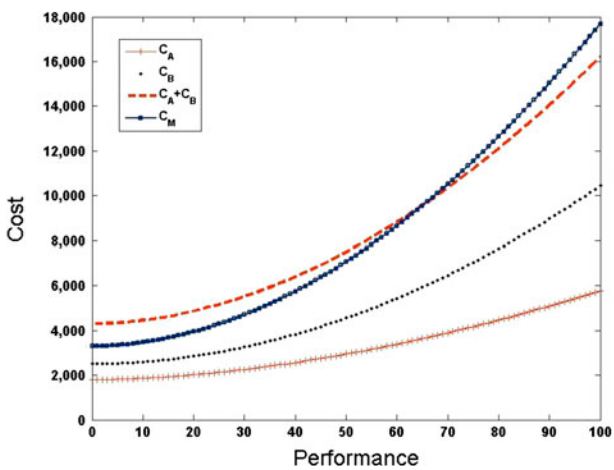


FIGURE 3 Cost as a function of required performance (non-linear costs)
*Note:* $I_A = 1800$, $I_B = 2500$, $I_M = 3300$, $\alpha = 1.8$, $\beta = 1.95$, and $\lambda = 1.02$.

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## 4. A MORE GENERAL MODEL

In most real-life situations, the decision-makers are faced with a decision problem involving several, possibly many, threats and several possible combinations of solutions. In addition, the performance requirements to successfully thwart different threats are likely to differ across the threats. Figure 4 demonstrates an example of the choice that a decision-maker has to make when deciding on the development of a MDS for the country. This example involves 10 threats and requires one multi-task solution or 10 distinct single-task solutions or a mix of multi- and single-task solutions. We assume that the decision-maker attempts to find the optimal mix of projects, that is, the mix with the minimum development and procurement costs subject to predetermined performance levels to thwart the 10 threats.

Note that in the example of Figure 4, the required performance of the solution for threat $t_6$ is lower than that for threats $t_5$ and $t_7$. This can be the situation when other systems or solutions already exist. For example, suppose that, in addition to a new solution of an in-flight hit, threat $t_6$ can be thwarted by other means such as an existing system that can destroy it on the ground before it is launched.

Let $PR_{i,j}$ denotes the R&D project which aims to develop a solution to threats ranging from $i$ to $j$ (inclusive of $i$ and $j$; $j \geq i$). When $j = i$, $PR_{ii}$ denotes a single-task project. Let $N$ be the

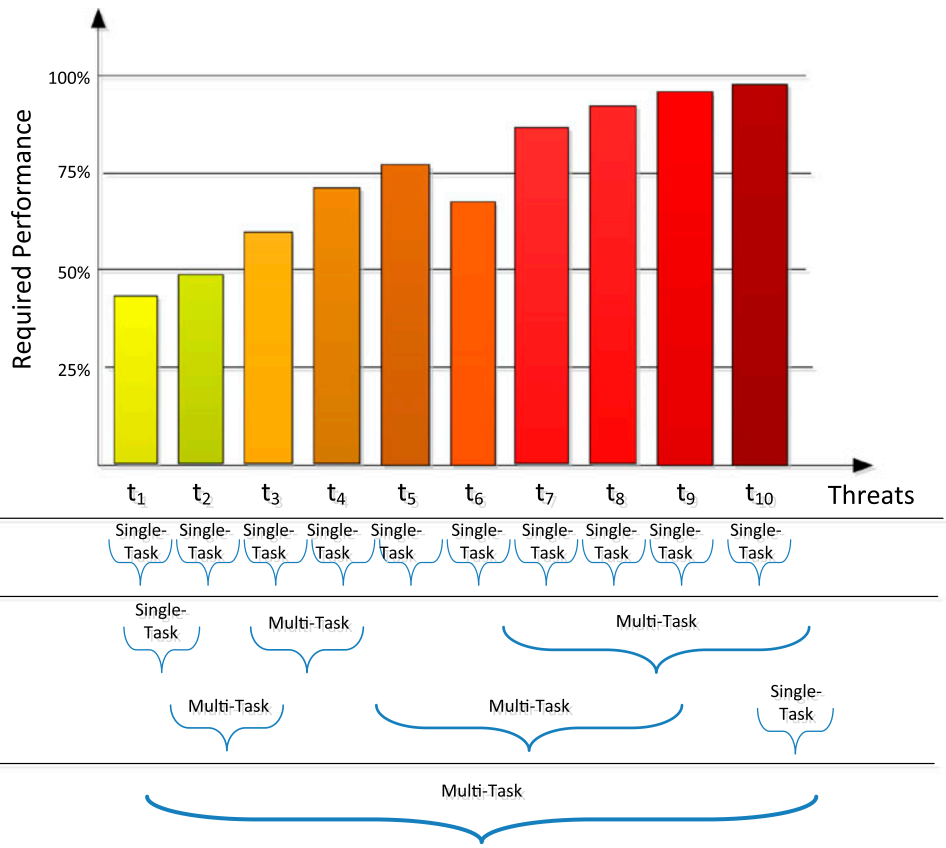


FIGURE 4 Missile threat spectrum

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number of threats; that is, the project indices are $1 \le i, j \le N$. Note also that each threat can be resolved by at least one feasible solution (such as the single-task project solution).

Let $I_{i,j}$ be the fixed cost for developing $PR_{ij}$. Let $\lambda_{ij}$ be the measure of 'closeness' in the development costs of a multi-task project ($j > i$) and let $C_{ij}$ be the total development and procurement costs of $PR_{ij}$. Thus, for example, $C_{ij}$ for a multi-task project $PR_{ij}$ is given by $C_{ij} = I_{ij} + \lambda_{ij}(\sum_{z=i}^{j} \alpha_z P_z)$, where $P_z$ is the (exogenously given) required performance of the solution for threat $z$ and $\alpha_z$ is a known constant. We also assume that if the $ij$th project is not feasible due, for example, to technological constraints, then $C_{ij} = \infty$.

The optimal solution is obtained by using the following set of binary decision variables, $d_{ij}$,

$d_{ij} = 1$ if threat $j$ is resolved by a (single- or multi-task) project which starts with the $i$th threat in the *optimal* combination set of projects, $j \ge i$. That is, $d_{ij*} = 1$ for any $j^*$, $i \le j^* \le j$, if $PR_{ij}$ is included in the *optimal* mix of projects.

$d_{ij} = 0$ if threat $j$ is *not* resolved by a (single- or multi-task) project which starts with the $i$th threat in the *optimal* mix of projects, $j \ge i$. That is, $d_{ij*} = 0$ when all $PR_{ij}$, $j^* \le j \le N$, are *not* included in the *optimal* mix of projects

The optimization problem is formally expressed as follows: choose $d_{ij}$ such that,

$$\text{Min} \sum_{i=1}^{N} \sum_{j=1}^{N} d_{ij} C_{ij} \tag{7}$$

s.t.

(1) $$\sum_{i=1}^{n} d_{ij} = 1 \; \forall j = 1, 2, \ldots N$$

(2) $$d_{i,j} = \text{binary}$$

That is, an algorithm which solves optimization problem (7) searches for the combinations which lead to the minimum total cost. The first constraint verifies that each threat receives a response by exactly one project. This constraint prevents the use of more than one solution for any particular threat. The second constraint ensures that the decision variables obtain only binary values such that they reflect the types of threats for which each project has to provide a solution.

In formulating the model, we employ the following assumptions. First, $P$ is defined to obtain values in a range of 0–100%. Second, $C_{i,j=1}$ is defined for every single-task project. Third, we use the cost functions that we developed previously: (a) for a single-task project $C_{i,j=I} = I_{i,j=i} + \alpha_j P$ and (b) the marginal cost of a multi-task project is given by $C_{i,j=i+1} = I_{i,j=i+1} + \lambda_{i,j=i+1}(\alpha_j P + \alpha_{j+1} P) - C_{i,j=i}$. Fourth, we assume that the fixed cost of each multi-task project is never higher than the cumulative fixed costs of single-task projects developed to find solutions for the same set of threats. In addition, we set $I_i, \alpha_j > 0$. Finally, we also assume that it is cheaper to perform a multi-task project for a less complicated threat (lower $j$) and add to it the cost of developing a more complicated threat (higher $j$) than to start from a more complicated threat and add to it the cost of developing a less complicated one.

We employ a dynamic programming algorithm to optimally solve problem (7).[2] The algorithm searches for the optimal group of potential projects, either single-task or multi-

[2]Optimization and dynamic programming are described in Bellman (2003) and Bertsekas (1987). Dynamic programming has been employed in the defense literature by Daula and Moffitt (1995).

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task, that covers all possible threats at the minimum total cost. We assume that each threat can be thwarted by at least one feasible project (a single-task project). However, the optimal solution may contain any feasible combination of single- and/or multi-task projects.

To solve problem (7), we employed a backward recursive function which accounts for any general problem with an exogenous number of threats (say $N$). The procedure inputs are: (a) the number of potential threats to be resolved with either single-task or multi-task projects; (b) a cost matrix that contains all the information about costs (fixed and variable costs; required performance).[3] The cost matrix is assumed to be triangular (projects can be performed only for $i \leq j$).

Generally, the recursive function works as follow:

(a) A counter, decreasing from $N$ to 1, presents the current threat $j$ which is being analyzed in the threat interval $(j,N)$.
(b) For $j = N$ and a threat interval of $(N, N)$, a specific (single-task) project is the only feasible, hence optimal, solution.
(c) For each $i \leq j < N$, all possible alternative sets are checked (some based on previous calculations) with a combination of single- and/or multi-task projects. That is, the procedure searches for the minimum total development cost (hereinafter TC) among all possible sets of projects for threats $j$ to $N$ (inclusive)

Where:

$$\mathrm{TC}(j,N) = \mathrm{Min}_{j \leq z \leq N}[C_{jz} + \mathrm{TC}(z+1,N)]. \tag{8}$$

(d) When $j = 1$, the procedure finds the optimal set of projects that resolve threats 1–$N$ (inclusive). That is, we solve Equation (8) for TC(1,$N$).
(e) Throughout the algorithm, the results (cost) and logs of the optimal project path of threats $(j,N)$ for any $j$ are saved and compared.

Experience shows that the dynamic programming algorithm described above yields optimal solutions to problems with many threats (such as $N = 30$) using very little computing time (up to a few minutes; usually only a few seconds). Even though we did not pay much attention to the algorithm's efficiency, it covers all realistic defense problems that involve choosing alternatives for similar threats. Larger problems (larger $N$) may be heuristically solved with the same algorithm with the initial feasible solution being the group of all single-task projects. Figure 5 presents the time needed for obtaining an optimal solution as a function of the number of threats ($N$).[4] The exponential nature of the dynamic programming algorithm can be gleaned from Figure 5. Realistic problems (e.g. $N = 5$ or $N = 10$) can be solved within seconds.

[3]The cost matrix can be computed prior to the optimization process for any potential project (resolving threats from $i$ to $j$) and the desired performance levels. The cost of nonfeasible projects (e.g. those that cannot be performed due to technological constraints, say) is set to equal infinity.

[4]These computations employed Matlab 7.9.0 on a PC computer, Dual Core E6550 2.33 GHz processor, 2.00 GB Ram.

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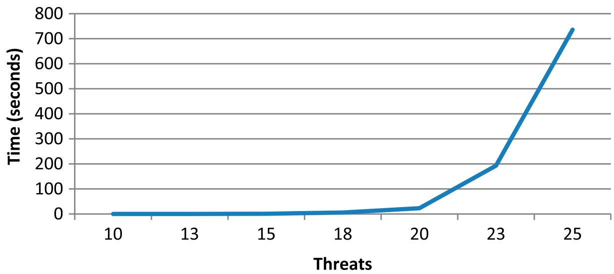


FIGURE 5 Running time to obtain an optimal solution for $N$ threats

## 5. AN APPLICATION TO ISRAEL'S MDS

We applied the methodology of Section 4 to Israel's MDS.[5] The threat spectrum includes seven types of missiles or mortar shells: mortar shells (0–4 km), short-range rockets (4–20 km), medium-range rockets (20–40 km), long-range rockets (40–70 km), cruise missiles and very long-range rockets (70–200 km), short-range ballistic missiles (200–800 km), and long-range ballistic missiles (more than 800 km). The potential damages that the threats can inflict are radically different from each other. A mortar shell that hits a road or even takes a life cannot be compared to a ballistic missile with, potentially, an unconventional warhead which can destroy a very large area.

The Israeli defense apparatus is currently focused on the development and procurement of two different systems to counter short- to medium-range threats: Iron Dome and David's Sling. These two systems aim at providing Israel with a defense layer against missile threats not covered by the already available Arrow system, which is relevant for defense against short- and long-range ballistic missiles. The main features of the Iron Dome, David's Sling and Arrow systems are as follows:[6]

- *Iron Dome*. Produced by RAFAEL, it is a mobile defense solution for countering short-range rockets and 155 mm artillery shell threats with ranges of up to 70 km. The interceptor is launched if it is estimated that the rocket/shell trajectory will inflict serious damage on its intended target.
- *David's Sling*. Produced by RAFAEL and Raytheon, the system's compatibility with established canister and rail launchers provides operational and deployment flexibility. It is a solution against short-range ballistic missiles, large-caliber rockets, and cruise missiles with a range of up to 250 km.
- *Arrow Weapon Systems (AWS)*. Produced by the Israel Aerospace Industry (IAI) and Boeing as a joint venture of Israel (represented by the Ministry of Defense) and the USA (represented by the Missile Defense Agency), AWS can reach and destroy targets at long distances with exceptional precision. The fact that the system elements are transportable means that batteries can be deployed to protect different geographical areas from incoming ballistic missile attacks. The Arrow 2 is already operational and the Arrow 3 is under development. While the Arrow 2 intercept altitudes are from a minimum of 10 km up to a maximum of 50 km and the maximum intercept range is approximately 90 km, the Arrow 3 will feature interception capabilities at

[5]All the data on the cost of the weapon systems that we describe in this section, on their ranges and on the areas that they are designed to defend are based on public information. Detailed descriptions of the systems' capabilities and costs are available in the appendix.

[6]See Ben-Ishay (2011), http://www.rafael.co.il, and http://www.iai.co.il.

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heights of more than 100 km (outside the atmosphere) in ranges which exceed 90 km.

Israel is planning to use the three very different systems described above to intercept missile threats and, thus, deter its potential rivals from attacking. These systems are not interconnected; they employ different command and control systems and their operating staffs require different training. Note that the current Arrow solution can be identified as a pure *single-task* solution which intercepts only short-range ballistic threats. The other two solutions have some characteristics of *multi-task* solutions, because they can be used to counter several threats.

In addition to the Iron Dome, David's Sling, and the Arrow systems, Israel considered several other defense systems which are being developed by the US military to counter what it perceives to be missile threats to the USA and its allies. Several of these solutions are described below:

- *Vulcan Phalanx (VP)*.[7] Developed and produced by Raytheon, the Phalanx close-in weapon system is a rapid-fire, computer-controlled, radar-guided gun system designed to contend with antiship missiles and other close-in air and surface threats. A self-contained package, Phalanx automatically carries out functions usually performed by multiple systems, including search, detection, threat evaluation, tracking, engagement, and kill assessment.
- *Nautilus/Skyguard*.[8] Northrop Grumman's Skyguard is a laser-based counter rockets, artillery, and mortars (C-RAM) system designed to protect civilians and deployed military forces from attack by aerial targets such as rockets, missiles, and artillery shells. The target is intercepted and destroyed by a highly focused, high-power laser beam, delivered by a chemical laser, with enough energy to explode it in midair.
- *SM-3*.[9] The Standard Missile 3 is designed to intercept and destroy using 'hit-to-kill' technology, which means that the interceptor collides directly with the target missile or warhead, and destroys it using only the force of the collision. Although primarily designed as an antiballistic missile, the SM-3 has also been employed in an antisatellite capacity against satellites at the lower end of the low Earth orbit. The SM-3 is being used and tested primarily by the US Navy. It is also being used by the Japan Maritime Self-Defense Forces. Several versions of the SM-3 system are under development by Raytheon.
- *THAAD*.[10] Terminal High Altitude Area Defense (THAAD) is a ground-based MDS developed by Lockheed Martin that operates in a unique battle space intercepting both endo- and exo-atmospheric short- to intermediate-range ballistic missiles. The interceptor collides directly with the target missile or warhead, and destroys it using only the force of the collision. It is planned to be rapidly deployable with high mobility.

We applied the algorithm of Section 4 to the Israeli MDS, accounting for seven threats (and, hence, a maximum of seven single-task solutions) and the seven solutions that were

[7] http://www.raytheon.com/capabilities/products/phalanx/ (accessed 14 November 2011).

[8] http://www.globalspec.com/reference/15637/121073/northrop-unveils-skyguard-laser-air-defense-system (accessed 14 November 2011).

[9] See O'Rourke (2012).

[10] http://www.lockheedmartin.com/products/thaad/index.html (accessed 14 November 2011).

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described above. In the analysis, we examined a realistic group of about 20 single- and multi-task alternatives (feasible projects, each covering at least two threats).

The data on R&D and the computations of the procurement costs that we employ in this paper are based on publicly available data and are detailed in the appendix. First, we estimated the cost matrix, which includes the total development and procurement costs of each feasible project. To establish an appropriate unit of measurement to compare the development and procurement costs of the different solutions (MDSs), we computed the cost of each solution for the number of physical units of the solution that would have to defend a given area in Israel (for example, a medium-size city in Israel such as Beer Sheva or Ashdod) against the relevant threats. The solution set includes the Israeli and American systems described above. The computations were based on publicly available data.

We assumed that defending a medium-size city in Israel against one or more of the following threats – Kassam, Katyusha, and Grad rockets, over ranges of 4–70 km and with 80% success rate ($P = 0.8$) – would require two units of the Iron Dome solution (a radar system, a fire control unit, a command and control subsystem, and three launchers which can operate 20 interceptors each; see Shaphir, 2011), or two units of the Skyguard solution or 'one-third' of a unit of the David's Sling solution.[11] The total (fixed and variable) cost for the procurement of one unit of the Iron Dome system is about \$66 million, and the R&D per unit is about \$9 million (see appendix for details). This cost would rise the Iron Dome solution be employed to intercept longer-range threats due, primarily, to additional R&D and integration costs. We also estimate that 4, 12, and 20 units of the VP system would be required to defend a medium-size Israeli city, at 80% success rate, against mortar shells (up to 4 km), Kassam and Katyusha rockets, respectively.[12]

Next, we assumed that each unit of the David's Sling system can defend three medium-size Israeli cities,[13] and will be equipped with 240 interceptors at a cost of \$700,000 each.[14]

The cost of the Arrow solution was computed using a similar methodology. Each physical unit of the Arrow is designed to defend an area equal to about half of Israel, and this area served as a benchmark for comparing all the systems designed to contend with the same threats (e.g. Arrow, SM-3, and THAAD against Shihab). The R&D cost of the Arrow system is estimated at \$1600–2300 million and we assumed here that each unit will be equipped with 150 interceptors of Arrow 2 at a cost of \$3.5 million per interceptor (\$3 million for Arrow 3).[15]

Setting the costs of all nonrelevant and/or nonfeasible multi-task projects equal to infinity, we then employed the dynamic programming algorithm of Section 4 to obtain the optimal solution. Table III presents the cost matrix (threats in the columns and projects in the rows) and the optimal solution (classification of projects and total cost).[16] The optimal solution, which is given with its cost expressed in bold type, provides the least cost solution to all seven threats.

[11]The required performance level of each solution depends on the damage that can be caused by the threat that the solution it is designed to thwart. We set $P = 0.8$ for countering Kassam, Katyusha, and Grad rockets; $P = 0.85$ for thwarting Zilzal rockets and $P = 0.9$ for thwarting ballistic missiles (Scud and Shihab); see details in Stav (2004) and Rubin (2008).

[12]See http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news/LASE07136.xml (accessed 23 December 2011).

[13]See http://www.armedforces-int.com/news/davids-sling-weapon-system-for-israeli-defence.html (accessed 23 December 2011).

[14]See Efrati (2011).

[15]See Efrati (2011). Arrow 2 is intended to intercept threats like the Scud. Arrow 3 is intended to intercept threats like the Shihab.

[16]See the appendix for a detailed description of the entries in Table III.

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TABLE III The Israeli MDS: Cost Matrix and Optimal Solution (US$ Million, 2010)

| | Threat name | Mortar shells | Kassam rockets | Katyusha rockets | Grad rockets | Zilzal rockets | Scud (BM) | Shihab (BM) |
|---|---|---|---|---|---|---|---|---|
| Possible solution: Active defense | Threat target (km) | <4 | 4–20 | 20–40 | 40–70 | 70–200 | 200–800 | >800 |
| **VP** | | **100** | 300 | 500 | | | | |
| **Iron Dome** | | | **150** | **150** | **160** | | | |
| Nautilus/Skyguard | | | 170 | 175 | | | | |
| **David's Sling** | | | | | 375 | **200** | 800 | |
| SM-3 | | | | | | NA | 2,300 | 2,300 |
| **Arrow** | | | | | | | **1,425** | **1,700** |
| THAAD | | | | | | | | 2,900 |

*Notes:* The costs were taken from various press publications: Global Military (http://www.global-military.com/tag/anti-rocket-system); GAO (http://www.gao.gov/assets/590/589695.pdf); Aviation Week (http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news/SM3080409.xml&headline=SM-3%20Upgrade%20Program%20Cost%20Increases) (references were accessed on 6 August 2011).

This solution is very similar to the one adopted by the Israeli military, except for the VP system which was initially considered as a solution to the mortar shells threat, but was later scrapped due to the collateral damage that it may inflict. That is, the Iron Dome system (with the possible aid of the VP system for very short range threats such as mortar shells and Kassam rockets) would thwart missiles in the 4–40 km range, the David's Sling system would counter threats in the range of 40–200 km and the Arrow would counter ballistic missiles in the range of 200 km or more.

Table III shows that the David's Sling system has the capability of intercepting both Grad rockets and Scud missiles in addition to intercepting Zilzal rockets (for which it is the optimal choice). However, the high cost of the David's Sling interceptor, relative to that of the Iron Dome, prohibits its use to thwart Grad rockets. Table III also shows that as a single task solution the David's Sling system is more cost effective than the Arrow system in intercepting Scud missiles. However, the Arrow 3 system can intercept both Scud and Shihab missiles, rendering the Arrow 3 system more cost effective than the David's Sling system in intercepting Scud missiles.

## 6. SUMMARY, LIMITATIONS, POSSIBLE EXTENSIONS AND CONCLUSIONS

The purpose of this study is to shed light on particular aspects of R&D by asking the following question: 'Should we develop one multi-task project, several multi-task projects, or many single-task projects to thwart multiple related threats?'

The analytical part of the study, employing linear costs and accounting for two threats and two possible single-task solutions or one two-task solution, shows that the distance (span) between the threats is an important parameter in the decision on the optimal set of the R&D projects. We find that the closer the threats are in terms of the magnitude of the damage they can cause or the technology that is required to thwart them, the greater the likelihood of developing a multi-task project. We show that the critical (breakeven) performance at which the decision makers are indifferent between a multi-task project and several single-task projects is the key for our results. Using a non-linear cost structure does not affect the nature of our results.

Next, a combination of single- and multi-task projects aiming to provide solutions to multiple threats is developed and analyzed. We show that this model and the solution algorithm can be used to optimally solve an NP-hard R&D problem of reasonable size. Finally,

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we demonstrate the usefulness of the model by applying it to Israel's dilemma of optimally choosing its MDSs.

The solution that we derive here is very similar to the one adopted by the Israeli government. That is, the Iron Dome system (combined with the VP system for very short-range threats such as mortar shells and Kassam rockets) would thwart missiles in the 4–40 km range, the David's Sling system would counter threats in the range of 40–200 km and the Arrow system would counter ballistic missiles in the range of 200 km or more.[17]

This paper does not account for all the budget constraints, the urgency of initial operation capability, defense industry interests, and other parameters which are also likely to be relevant in real-world decisions. In addition, the analytical models and the application in the paper are fairly simple and, thus, exhibit several limitations which may be amended in future research. First, we solve a static model which is likely to provide a good approximation in a stable (slowly changing) environment. Clearly, adding the time dimension to the model will make it more practical to decision makers. This extension can be carried out by adding additional discrete constraints to the existing model. Using a dynamic model which can account for non-linear (concave or convex, say) improvements in the capabilities of the threats and the technologies designed to thwart them is not a simple task, but may improve our model and results. Second, casting the model in the context of an arms race may be useful in real-world decision problems. That is, we assume that the required performance level ($P$) is exogenously given (set by the Ministry of Defense or the government, say). The analysis can be enriched by extending the model to endogenously determine the performance level required against each threat as a function of the potential damage which can be caused by the threat. In fact, it may be useful, though not simple, to estimate the performance level required to thwart each threat by setting a model (game) accounting for the preferences and objectives of the entities that procure (and/or produce) the threats and the country that is seeking to thwart these threats. Finally, the current model employs linear R&D costs. Extending the model to account for convex R&D costs may also improve our results.

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[17]Some of the differences between the solution in Table III and the solution chosen by the Israeli government are due to the maturity (or lack thereof) of various technologies, disagreements about the capabilities of various systems, and costs which, due to inaccessibility of data, were not accounted for in our model (see Aviram, 2010).

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## Appendix A: data development

Data on the cost of the weapon systems that are described in this paper, on their ranges and on the areas that they are designed to defend are based on publicly available information.

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The VP, Iron Dome, Nautilus/Skyguard and David's Sling's are mostly aimed to thwart relatively short-range threats and, hence, are designed to defend relatively limited areas (between several square kilometers to a number of cities). The SM-3, Arrow and THAAD are aimed to thwart more potent threats that can be launched from a large distance and, thus, are designed to defend much larger areas. Hence, we chose to use the following benchmarks: a medium size city (Beer Sheva or Ashdod, for example) is the benchmark for the VP, Iron Dome, Nautilus/Skyguard and David's Sling.[18] About half of Israel is the benchmark for the Arrow, THAAD and SM-3. The computations in this paper employ the same number of interceptors for a given type of threat and area that has to be defended: 400 interceptors to defend a city from the most common threats (mortar shells, Kassams, Katyushas and Grads), 80 interceptors to defend a city from long-range rockets (Zilzals), and 150 interceptors to defend half of Israel against ballistic missiles (Scuds and Shihabs).

### *A.1. Vulcan Phalanx*

The VP[19] system is capable of defending against mortar shells, Kassam and Katyusha rockets. Since the VP system is already operational, we account here only for its procurement costs. The procurement cost of a single unit of VP (cannon with radar), which can cover a strip of land about 1200 m long, is approximately $25 million.[20] Defending a medium-size city against mortar shells requires four units of VP, yielding a procurement cost of $100 million. Defending against Kassam (Katyusha) rockets requires about 12 (20) units of VP since the range of these rockets is much larger than that of mortar shells. The cost of 12 (20) units of VP is $300 ($500) million, respectively. Hence, the cost for defending a medium-size city from mortar shells, Kassam and Katyusha rockets with the VP system is as follows:

| Possible solution: active defense | Threat name<br>Threat target (km) | Mortar shells<br><4 | Kassam rockets<br>4–20 | Katyusha rockets<br>20–40 |
|---|---|---|---|---|
| VP | | 100 | 300 | 500 |

### *A.2. Iron Dome*

The Iron Dome system is capable of defending against Kassam, Katyusha and Grad rockets. The cost of the full-scale development phase (including two batteries and interceptors) is about $250 million.[21] The procurement cost of one unit (without interceptors) is approximately $50 million,[22] and the cost of each interceptor is $80,000.[23] We estimate that two units, each with 200 interceptors, can defend one medium-size Israeli city against Kassam and Katyousha rockets. Therefore, we set the R&D costs of the Iron Dome system at about $120 million for satisfactory cover of the Kassam and Katyusha rockets threats, and estimate that an additional $50 million are required for satisfactory cover of the Grad rockets threat. Following Shaphir (2011), we set the required number of Iron Dome units to cover Israel from Kassam, Katyusha and Grad rockets at 15. Thus, the total cost for covering a medium-size city (two Iron Dome units) against Kassam or Katyusha rockets is about $150 million ($100 million for procurement, $32

[18]The David's Sling system has the potential to thwart short- and long-range threats. Note that the benchmark for comparison of solutions for short-range threats is a medium-size city, while the benchmark for comparison of solutions for long-range threats (Scuds, Shihabs) is 'half of Israel'.

[19]http://www.raytheon.com/capabilities/products/phalanx/ (accessed 14 November 2011).

[20]http://www.haaretz.com/print-edition/news/barak-purchases-u-s-system-to-intercept-gaza-rockets-1.274499 (accessed 14 April 2012).

[21]http://defensetech.org/2010/07/21/israel-says-iron-dome-ready-idf-balks-at-price-tag/ (accessed 14 April 2012). http://www.reuters.com/article/2010/05/13/us-israel-usa-irondome-idUSTRE64C5JO20100513?type=politicsNews (accessed 5 May 2012).

[22]http://in.reuters.com/article/2011/05/26/idINIndia-57287720110526 (accessed 14 April 2012).

[23]http://www.themarker.com/news/1.1574410?redir=1&snopcmdt=1 (accessed 14 April 2012).

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million for 400 interceptors and about $18 million for R&D). The total cost for covering a medium-size city (two Iron Dome units) against Grad rockets is about $160 million ($100 million for procurement, $32 million for interceptors and $28 million for R&D). Therefore, the total cost (R&D and procurement) for defending a medium-size Israeli city with Iron Dome is:

| Possible solution: active defense | Threat name<br>Threat target (km) | Kassam rockets<br>4–20 | Katyusha rockets<br>20–40 | Grad rockets<br>40–70 |
|---|---|---|---|---|
| Iron Dome | | 150 | 150 | 160 |

### *A.3. Nautilus/Skyguard*

The Nautilus/Skyguard system is designed to defend against Kassam and Katyusha rockets. It is still under development.[24] The R&D completion cost is estimated to be about $825 million (to cover Kassam rockets) or about $870 million (to cover Kassam and Katyusha rockets), and the procurement cost of a unit can reach $30 million (provided a sufficient number of systems are produced and sold to eligible customers). Currently, the Nautilus/Skyguard system is aimed at intercepting threats up to 40 km. Two units of the Nautilus/Skyguard system are capable of defending a medium-size city.[25] We assume that the Nautilus/Skyguard, similarly to the Iron Dome, can defend Israel with 15 units (batteries). The total cost of two units of Nautilus/Skyguard systems for defending against Kassam rockets is $170 million ($60 million for procurement and $110 million for R&D) and for defending against Katyusha rockets it is $175 million ($60 million for procurement and $115 million for R&D). That is,

| Possible solution: active defense | Threat name<br>Threat target (km) | Kassam rocket<br>4–20 | Katyusha rocket<br>20–40 |
|---|---|---|---|
| Nautilus/Skyguard | | 170 | 175 |

### *A.4. David's Sling*

Assuming the DS has the ability to intercept relatively long-range threats (up to 250 km), each unit of this solution can defend three medium-size Israeli cities.[26] We assume that each unit of the DS will include 240[27] interceptors at a cost of about $700,000 each (Efrati, 2011). The procurement cost of each unit, excluding interceptors, is estimated at $150 million. We also assume that three units of DS will be procured by Israel. The total R&D cost for the DS is estimated to be $400 million.[28] We assume that an additional $450 ($550) million R&D will be required to

[24]It may also be developed to counter intercontinental ballistic missiles and other advanced threats, by providing laser interception from an airplane (airborne-laser) or satellites (space-based-laser). It should be noted that the Pentagon has announced that it will no longer develop this system to defend against long-range ballistic missiles, http://www.aviationweek.com/Article.aspx?id=/article-xml/asd_12_21_2011_p01-02-408678.xml (accessed 26 April 2012).

[25]http://www.globalspec.com/reference/15637/121073/northrop-unveils-skyguard-laser-air-defense-systeml (accessed 26 April 2012); http://www.globes.co.il/serveen/globes/docview.asp?did=1000052055 (accessed 15 April 2012).

[26]See http://www.armedforces-int.com/news/davids-sling-weapon-system-for-israeli-defence.html (accessed 23 December 2011).

[27]Based on the information that each canister can support 16 interceptors and the assumption that the DS is aimed to thwart long range rockets which are less abundant than short range rockets but more abundant than Ballistic missiles.

[28]See http://www.defence.pk/forums/military-forum/13322-u-s-israel-develop-davids-sling-missile-defense.html (accessed 25 April 2012).

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thwart the Zilzal rockets (Zilzal rockets and Scud missiles). Therefore, the total cost of one-third of a unit of DS (each unit can defend three medium-size cities) aimed at defending one medium-size city against Grad rockets is $375 million ($50 million for procurement, about $280 million for 400 interceptors and about $45 million for R&D), $200 million against Zilzal rockets ($50 million for procurement, about $56 million for 80 interceptors and about $94 million for R&D). About $800 million are required to defend against Scud missiles (the benchmark area for defending against Scuds is half of Israel, see the discussion about the Arrow system); the costs include: procurement of one and a half units ($225 million for procurement, about $100 million for 150 interceptors and about $475 million for R&D).

That is,

| Possible solution: active defense | Threat name<br>Threat target (km) | Grad rockets<br>40–70 | Zilzal rockets<br>70–200 | Scud (BM)<br>200–800 |
|---|---|---|---|---|
| David's Sling | | 375 | 200 | 800 |

### *A.5. Arrow Weapon Systems*

The Arrow 2 is already an operational system and Arrow 3 is under development.[29] While Arrow 2 interception altitudes are from a minimum of 10 km up to a maximum of 50 km and the maximum interception range is approximately 90 km, the Arrow 3 will feature interception capabilities at heights of more than 100 km (outside the atmosphere) in ranges which exceed 90 km. Based on public information which states that Israel already employs two batteries of Arrow 2,[30] we estimate that each unit (battery) of the Arrow is designed to defend an area equal to about half of the country, and this area serves as a benchmark for comparing all the systems designed in our model to contend with similar (long-range) threats. Thus, we assume in the computations that two batteries of the Arrow 3 will be purchased, should Israel choose to procure this system. The procurement cost of each unit, excluding interceptors, is $100 million. The R&D cost of the Arrow solution is estimated at $1600[31] million for intercepting Scud missiles (Arrow 2) and $2300[32] for intercepting Shihab missiles (Arrow 3), and we assume here that a battery will be equipped with 150 Arrow 2 (or Arrow 3) interceptors per unit at a cost of $3.5 million (Arrow 2) or $3 million (Arrow 3) per interceptor.[33] Therefore, the total cost of defending half of Israel with Arrow 2 against Scud missiles is $1425 million ($100 million per unit, about $525 million for 150 interceptors and $800 million for R&D). The total cost of defending with Arrow 3 against Scud and Shihab missiles is $1700 ($100 million per unit, about $450 million for 150 interceptors and about $1150 million for R&D). That is,

| Possible solution: active defense | Threat name<br>Threat target (km) | Scud (BM)<br>200–800 | Shihab (BM)<br>>800 |
|---|---|---|---|
| Arrow | | 1425 | 1700 |

[29]See http://www.israelnationalnews.com/News/News.aspx/152071#.T9NmVVJTYTA; http://www.israelnationalnews.com/News/News.aspx/146160#.T9NmpFJTYTA; http://www.army-technology.com/projects/arrow2 (accessed 8 June 2012).

[30]http://www.missilethreat.com/missiledefensesystems/id.10,page.2/system_detail.asp (accessed 2 June 2012).

[31]http://www.haaretz.com/misc/article-print-page/an-arrow-to-the-heart-1.28321?trailingPath=2.169%2C (accessed 29 April 2012).

[32]Assuming an evolution of Arrow 2 with additional development costs; http://www.ynetnews.com/articles/0,7340,L-3579000,00.html (accessed 29 April 2012).

[33]See Efrati (2011). Arrow 2 is intended to intercept threats like the Scud missile. Arrow 3 is intended to intercept threats like the Shihab missile.

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### *A.6. SM-3 and THAAD*

We assume here that each physical unit of the SM-3[34] and THAAD[35] systems is also designed, similarly to the Arrow system, to defend an area equal to about half of Israel (which is the benchmark for comparing all the systems designed to contend with long-range missiles – Arrow, SM-3 and THAAD). The areas to be covered by these systems are based on the systems' operational altitude and range interception. To date, the USA has invested about $3100 million in developing the SM-3 and $16,100 million in developing the THAAD (GAO, March 2012). One unit of the SM-3 interceptor is projected to cost $9-$24 million,[36] depending on the particular version that will be employed. The cost of the THAAD interceptor is estimated to be about $8 million.[37] We assume that the cost of radars, command and control unit and launchers of the THAAD and SM-3 will be similar to that for the Arrow 3 ($100 million). We also estimate that the US army will procure eight units of the THAAD, and equip them with 1422 missiles.[38] Should Israel choose to procure the SM-3 and/or the THAAD, we assume it will purchase two batteries of each system with 150 interceptors per battery. Thus, the total cost of the SM-3 will be $2300 million ($100 million for procurement, about $1800 million for 150 interceptors, at $12 million for each, and about $400[39] million for R&D). The cost of purchasing the THAAD system, equipped with 300 missiles, is $2900 million ($100 million for procurement, $1200 million for 150 interceptors, at $8 million each, and about $1600 million for R&D). That is,

| Possible solution: active defense | Threat name<br>Threat target (km) | Scud (BM)<br>200–800 | Shihab (BM)<br>>800 |
|---|---|---|---|
| SM-3 | | 2300 | 2300 |
| THAAD | | | 2900 |

[34]See O'Rourke (2012).

[35]http://www.lockheedmartin.com/products/thaad/index.html (accessed 14 November 2011).

[36]http://www.defenseindustrydaily.com/Land-Based-SM-3s-for-Israel-04986/ (accessed 26 April 2012).

[37]Assuming procurement of six batteries for the USA and two for Israel; http://www.missiledefenseadvocacy.org/web/page/930/sectionid/557/pagelevel/3/interior.aspx (accessed 26 April 2012).

[38]http://www.army-technology.com/projects/thaad (accessed 29 April 2012).

[39]http://www.army-technology.com/projects/thaad (accessed 29 April 2012).

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