SAND2015-2769C

A Framework for Guiding Homeland Security Programs from Risk to Resilience

Mark A. Ehlen,[1] Prabuddha Sanyal,[2] Mark A. Pepple[3]

Abstract

Many government agencies are currently moving from risk-based to resilience-based policies; a good example is the current transition in methodologies from community risk-based mitigation planning to resilience planning embodied in the draft NIST Disaster Resilience Framework. What's not obvious to this transition is whether the new resilience plans will still adequately address the existing risk needs, and whether the new resilience-based plans will be truly based on resilience and not just "resilience equals low risk." To help reconcile these two concepts, we present a basic mathematical framework that can be simultaneously achieve three important policy goals – minimized risks, ensured mission, and maximized resilience – by achieving any one of the three. Risk and resilience policies can be developed and promulgated in an internally consistent, effective, and efficient manner. Examples include the pharmaceuticals and community resilience arenas.

Keywords

Risk; resilience; homeland security policy; chemical sector, community resilience.

1 Introduction

1.1 The Need to Move from Risk to Resilience

days of U.S. homeland security, federal policies took a "guns, gates, and guards" risk-based approach, identifying threats, vulnerabilities, and potential impacts, first from terrorist attack and then after Hurricane Katrina, to natural disasters. Through DHS-sponsored RAMCAP and later other methods, the Department of Homeland Security (DHS) developed a consistent risk-based approach based on threats, vulnerabilities, and consequences. In the late 2000s, however, it was clear that there were too many threats and assets to protect, and the Department shifted focus away from risk management of individual assets to resilience planning of systems of assets. But while acknowledging the systematic interdependence of many of these assets was easy, developing resilience metrics and management processes has been more difficult. An overview of DHS chemical sector policy helps illustrate some of these difficulties.

The U.S. chemical sector provides significant value to the nation's way of life, purifying the water we drink, creating lifesaving medicines, protecting armed forces, and contributing $760 billion in annual economic activity (ACC, 2013). But chemicals present their own risks, to essential military, healthcare, and economic functions: in 2003 an acute shortage of para-aramid fibers, a chemical product commercially marketed as Kevlar and used in body armor, "reduced

---

[1] Sandia National Laboratories, 1515 Eubank Street, Albuquerque, NM 87123, 505 284-4568, maehlen@sandia.gov.
[2] Sandia National Laboratories, 1515 Eubank Street, Albuquerque, NM 87123, 505 503-6283, psanyal@sandia.gov.
[3] Sandia National Laboratories, 1515 Eubank Street, Albuquerque, NM 87123, 505 284-1517, mpepple@sandia.gov.

[military] operational capability and increased risk to troops in Iraq" (GAO 2005). In 2008, an acute disruption of acetonitrile supply, 70 percent of which is used as a key ingredient in pharmaceutical production, risked the effectiveness and safety of life-sustaining medicines. U.S. chemical facilities are at risk to attack and theft,[4] and the impacts of such attack could be significant to the chemical facilities themselves, to the products that use their chemicals, and to the broader nation and its government.

To mitigate these chemical-facility risks, the U.S. government enacted two pieces of legislation: the Maritime Transportation and Security Act (MTSA) (U.S. Public Law 107-295, 2002) and the Chemical Facility Anti-Terrorism and Security Act (DHS, 2007). MTSA, the U.S. implementation of the International Ship and Port Facility Security Code (IMO, 2003), authorizes the U.S. Coast Guard to regulate the security of all "… structure[s] or facilit[ies] of any kind located in, on, under, or adjacent to any waters subject to the jurisdiction of the United States." MTSA sites and assets must have security plans commensurate to their individual risks, and industry can proffer alternate security plans that provide an equal or greater level of security. CFATS, implemented through the U.S. Department of Homeland Security (DHS) Infrastructure Security Compliance Division (ISCD), defines risk-based performance standards for facilities that pose risks to public health and safety or could create "significant adverse consequences to national security and/or the ability of the government to deliver essential services." Both pieces of legislation focus on asset-based risks with few provisions for chemical sector-wide risks; the policies essentially reduce national risks one asset at a time.

DHS has broader policies for reducing sector-level risks and increasing sector-level resilience, ones that are potentially at odds with the chemical-sector asset-level regulations. The National Infrastructure Protection Plan (NIPP) (DHS, 2009) uses a risk approach that includes "resilience and response measures." The DHS Chemical Sector-Specific Plan (CSSP; DHS 2010b) states that the role of the NIPP "is to identify and take action to protect or improve the resilience of [critical infrastructure]" and "that resilient operations and effective loss prevention are a part of managing risk." The CSSP helps achieve "risk-based, cost-effective sector-wide protective programs that increase asset-specific resilience" and the broader goal of "a safe, secure, and resilient America through enhanced protection of [critical infrastructure]," all through a process that "ensures that resources are applied where they contribute the most to resilience and risk mitigation." Finally, the DHS National Critical Infrastructure Prioritization Program (NCIPP) helps "identify the Nation's lost critical, highly consequential domestic assets and systems ... to support the growing DHS role in incident response and recovery" (DHS, 2010b).

When combined, however, these risk and resilience policies create practical problems for risk analysis, management, and planning (it's fair to say that resilience analysis, management, and planning are in their infancy). DHS has provided guidance for measuring and reducing risk (threat, vulnerability, and consequence) – RAMCAP (ASME, 2009) is a good example – but uses disparate approaches across programs (GAO, 2014), and gives little guidance for measuring

---

[4] DOJ (2000): "[I]ndividuals have indeed attempted to use chemical releases from individual facilities as makeshift WMD both domestically and abroad. Some of these events have involved countries or factions hostile to the United Sates."

and increasing resilience. And there is little guidance for conducting combined risk and resilience analysis that ensures resources are applied where they contribute the most to both objectives. Chemical facilities-level risk models exist – for example, DOD (2000), NIJ (1997), Moran *et al* (2004), and FBI (2003) – but there are few facilities-level resilience-assessment models. A notable exception is the J100/RAMCAP model (AWWA, 2010) for water purification facilities; J100/RAMCAP does prescribe the measurement of both risk and resilience for individual assets, but does not provide clear guidance on how risk and resilience are related and can be simultaneously achieved.

Another problem is in using asset- and sector-based policies to increase resilience: reducing risks from acts of terrorism by regulating particular chemical facilities may actually reduce the resilience of the overall chemical sector. For example, one outcome of DHS chemical sector regulations is that chemical companies are reducing the production and stored amounts of hazardous chemicals, a reduction which does reduce risks to public health and safety, but also removes potentially important redundancies in chemical production capacity and where so, potentially lowers the resilience of the overall sector.

1.2 Community Disaster Risk and Resilience Management

As described in NIST (2015), an estimated 24,000 communities representing 80 percent of the U.S. population have conducted disaster mitigation plans in accordance with FEMA guidance. These mitigation plans are fundamentally risk based and while the NIST Disaster Resilience Framework notes that "expanding the scope to resilience is the next logical step" and "community resilience plans can be built around existing mitigation plans using the framework techniques related to the built environment," there is as of yet no clear distinction between risk management and resilience management, how to reconcile the two, and to ensure that a resilience management strategy correctly manages priority risks and vice versa. For example, our review of J100/RAMCAP water risk analyses has found that when given the opportunity to define the J100-required inclusion of a resilience measure, utilities define it as the economic impact itself, the implied notion being that high impact suggests low resilience.

1.3 The Need for a Common Framework

Identifying risks and resilience are potentially highly conflicted policy requirements. What is needed is a basic framework that ensures that risk and resilience policies are first understood and then implemented in a consistent, effective, and efficient manner. This article presents a preliminary framework for understanding these two concepts, side by side, in policy development that integrates risk, mission-assurance (shown herein to be closely related to risk), and resilience policy objectives. The framework, while initial in its constructs, is designed to inform government agencies as they move from risk-centric to resilience-centric policies. In support of the NIST Disaster Resilience Framework and the FEMA's Local Mitigation Planning Handbook, the framework provides constructs in which risk and resilience can be compared, and ultimately used together to ensure that a community plan both reduces community risks and increases community resilience. Section 2 describes the framework and a formulation that directly relates risk with resilience and highlights how the solutions for reducing asset-based risks to mission are sometimes sector-based. Section 3 summarizes and concludes.

2 Risk-Assurance-Resilience Framework

To develop effective risk and resilience policy, DSH needs a strong foundation of how their policies do three things: (i) reduce risks, (ii) ensure mission, and (iii) increase resilience. The following model articulates the fundamental relationships of the three in ways that can lead to internally consistent DHS policy. For clarity of exposition, it uses policy language and examples from DHS chemical sector policy, but is generalizable to any set of homeland security policies that have risk, assurance, and resilience objectives.

DHS chemical-sector policy states that "the loss of certain chemicals, materials, or facilities could create significant adverse consequences for national security or the ability of the government to deliver essential services," and seeks to identify and then (i) reduce risks to government mission by identifying at-risk chemicals and their facilities (DHS 2007). Mission is (ii) assured, through the minimization or transfer of these risks. Next, DHS defines resilience as "the ability of systems, infrastructures, government, business, communities, and individuals to resist, tolerate, absorb, recover from, prepare for, or adapt to an adverse occurrence that causes harm, destruction, or loss." (DHS 2010a) As discussed above, DHS has a number of policies designed to (iii) increase chemical-sector resilience. DHS then has all three requirements for the chemical sector.

The above risk-related "adverse consequence" and resilience-related "ability to adapt" statements are intuitively but not explicitly related; the former sets requirements on how to minimize disruptions to a given mission through identification of risks; the latter sets requirements on how to maximize the ability of systems to meet mission, through prevention or adaptation to disruptions. The solution to the first is apparently to identify and then remove the risks, while the second is to potentially recast the entire risk management. The first is at best a local optimum for the risk objective, while the second suggests but does not reveal a process for global optimum for risk management.

While the strategies for minimizing risks and its corollary, ensuring mission, are fairly well defined, the strategies for maximizing resilience are not. Our framework needs a definition of a strategy that maximizes resilience. Consider a government agency whose responsibility is to effectively plan and allocate resources to accomplish a mission. Missions could, for example, include federal policy actions and private-sector economic activities. This agency can allocate its mission-related resources using one of three alternate perspectives:

1. a risk perspective: minimize the use of resources for mitigating the risks to its particular mission;
2. a mission-assurance perspective: maximize the probability of mission outcome, given the risks and available resources to mitigate them; or
3. a resilience perspective: maximize the probability that mission will be achieved through planned ad-hoc adjustments to potential disruptions.

The agency has a number of alternate operational strategies to choose from, each with an associated cost and contribution toward reducing risks, assuring mission, and improving – if not maximizing – resilience. If the goal of this agency is to pick a particular set of strategies that optimizes these outcomes, we can define the resilience-maximizing strategy as follows:

The resilience-maximizing strategy is the one among alternate strategies that, for a given targeted mission and budgeted level of resources, maximizes the ability of the agency to prepare for, resist, tolerate, absorb, recover from, or adapt to disruptions that could cause significant loss of mission.

The definition harmonizes risk and mission-assurance concepts: it addresses the need to allocate resources that maximize the ability to meet mission, including selecting actions that reduce the potential for risk-related "significant loss of mission." It also addresses the need to find the strategy that maximizes the resilience of the agency's ability to carry out missions, specifically to adapt its actions so as to ensure the targeted level of mission at its given budgeted resources. Risk-resilience harmonization comes through formalizing a strategy that reduces potential disruption-based losses to mission through the abilities to adapt to these disruptions.

We illustrate this risk-assurance-resilience framework with a mathematical model that captures the relationships between risk, mission, and resilience; and shows how targeting one of these can achieve all three – reduced risk and increased mission and resilience for mission stakeholders. We illustrate this harmonization by first casting the risk-assurance-resilience problem as an example of the duality problem common in optimization theory.

Current definitions do not always lend themselves naturally and intuitively to measurement and the development of consistent metrics with clear relationships to metrics of other relevant abstract notions, such as reliability and risk (Ayyub 2013, Wu and Azarm, 2001, Farhang-Mehr and Azarm 2003). For example, Ayyub (2013) recently examined resilience definitions as they relate to quantification and metrics. Linking both sustainability and resilience metrics to system performance enhances decision making processes and resource allocation abilities. Wu and Azarm (2001) and Farhang-Mehr and Azarm (2003) devised metrics such as entropy for evaluating solutions to multi-objective optimization problems. Similar approaches can be undertaken for sustainability with a focus on construction and manufacturing.

2.1 The General Duality Approach

In many cases, a mathematical *constrained optimization* – "maximize or minimize an objective given a set of constraints" – can be viewed one of two ways, as a *primal* or *dual problem* (Mas-Collel *et al*, 1995). The true utility of this dual approach is that under the right conditions, the solution found for the primal is the same as that for the dual – solving one solves both. In microeconomic theory, the most common duality example is of an economic firm that has both maximize-production and minimize-cost objectives. The solution to the firm's problem of maximizing profits is the same as that found when minimizing costs. A quick review of this example lays the foundation for an analogous government risk, assurance, and resilience problem.

In microeconomics a firm's objective is to maximize output given inputs and their associated costs. Letting *l* and *k* be the labor and capital inputs to production q, *w* and *r* their respective unit costs, and $\bar{C}$ the budget the producer has to spend on purchasing input factors, the producer's problem is to select $\hat{l}$ and $\hat{k}$ that solve the (primal) problem of maximizing output while not spending more on input materials than $\bar{C}$:

$$\max \quad q(l, k) \text{ subject to } \quad wl + rk \leq \overline{C} . \tag{1}$$

The most commonly used function for *q(l,k)* is the Cobb-Douglas production function $q(l, k) = Al^{\alpha}k^{1-\alpha}$, where $0 < \alpha < 1$. Cobb-Douglas is not required for this example, but we do need *q(l,k)* to be monotonically increasing in *l* and *k,* concave, and twice-continuously differentiable. To solve this optimization, we first construct the mathematical Lagrangian

$$\Gamma = Al^{\alpha}k^{1-\alpha} + \lambda(\bar{C} - wl - rk), \tag{2}$$

where λ is the Lagrange multiplier. First-order conditions with respect to *k* and *l* result in the condition that the ratio of the marginal benefit of each input factor to its respective cost must be equal, for all factors of production:

$$\frac{A\alpha l^{\alpha-1}k^{1-\alpha}}{w} = \frac{Al^{\alpha}(1-\alpha)k^{-\alpha}}{r}; \tag{3}$$

that is, the marginal benefit-cost ratio of each input must be the same. Substituting in the constraint equation and then solving equation 3, we have the production-maximizing inputs $\hat{l}$ and $\hat{k}$:

$$\hat{l} = \frac{(1-\alpha)\overline{C}}{w}, \quad \hat{k} = \frac{\alpha\overline{C}}{r} . \tag{4}$$

Two insights from this are important to later sections: first, the inputs $\hat{l}$ and $\hat{k}$ are defined solely in terms of available budget ($\bar{C}$) and input costs (*w* and *r*). Second, the marginal increase in production of an additional unit of available budget resource $\bar{C}$ is equal to the Lagrangian multiplier, which itself is based solely on the technology coefficient *A*, resources, and costs:

$$\lambda = \frac{A\alpha l^{\alpha-1}k^{1-\alpha}}{w} = \frac{Al^{\alpha}(\alpha-1)k^{-\alpha}}{r} . \tag{5}$$

Finally, the optimal level of production can be described solely in terms of the parameters *A*, α, *w*, and *r*: letting γ be defined as

$$\gamma = \frac{A\alpha^{\alpha}(1-\alpha)^{1-\alpha}}{r^{\alpha}w^{1-\alpha}} \quad , \tag{6}$$

we have production defined in terms of the budget constraint: $\bar{q} = \gamma\bar{C}$.

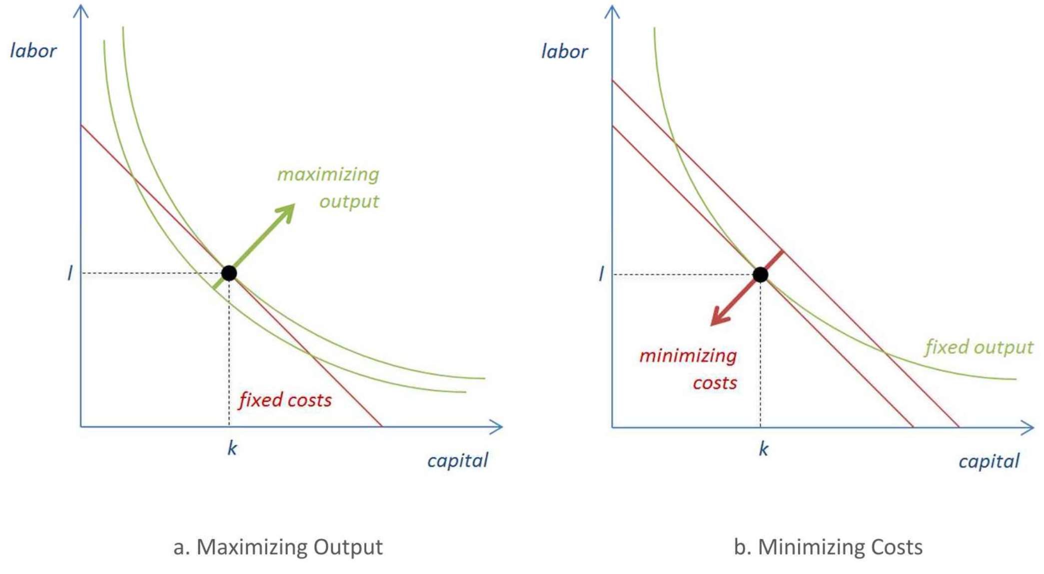
An important contribution from duality theory is that this producer could just as easily solve for $\hat{l}$ and $\hat{k}$ by minimizing the costs associated with producing output $\bar{q}$. To illustrate this, equation 1 can be re-cast as selecting $\hat{l}$ and $\hat{k}$ that solves

$$\min \ (wl + rk) \text{ subject to } q(l,k) = \bar{q} \ . \tag{7}$$

Using the same Cobb-Douglas function, the Lagrangian is

$$\Gamma = (wl + rk) + \lambda(\bar{q} - Al^{\alpha}k^{1-\alpha}) , \tag{8}$$

which is very similar in structure to equation 2. From first-order conditions, the solution to this dual problem is the same as in equation 3. Given that the respective production and budget constraints are related by $\bar{q} = \gamma\bar{C}$, the solutions for $\hat{l}$ and $\hat{k}$ from this dual problem are the same as those in the primal problem. Figure 1 summarizes the relationship between these two objectives.



a. Maximizing Output

b. Minimizing Costs

Figure 1. Primal and Dual Economics Problems

Each panel in the figure shows potential allocations of capital (horizontal axis) and labor (vertical axis). The red lines show the loci of *iso-budget* points that can be purchased for a given budget and input prices; the green lines show the loci of iso-production lines achievable with the different allocations of inputs. The left panel illustrates how output is maximized given a fixed level of costs: the agency can allocate its budget toward all labor (where it hits the vertical axis), to all capital (on the horizontal axis), or any combination of the two along the red line. Each green *iso-output* line indicates the amount of output that can be made from different combinations of labor and capital. The solution $\{\hat{l}, \hat{k}\}$ (the black dot) is that level of output that is on the (red) budget line. The right panel shows how this same allocation can be achieved by minimizing the costs $wl + rk$ given a fixed level of output. This dual understanding of output and costs is crucial to our risk and resilience approach for a government agency.

2.2 The Mission-Risk and Mission-Assurance Dual Problem

For a given government mission, there are two inherent but analogous opposing objectives: the first is to maximize the expected mission given the baseline costs of the mission and costs of preparing for or responding to the disruption of mission-related assets (Figure 2). For example, in the NIST Disaster Resilience Framework, the mission would embody the social needs of the community. We call this the *primal mission problem.* This same mission objective can be viewed as one of minimizing the total costs (operating and disruption-related costs) of conducting a given level of mission. A government agency typically has limited resources overall, and these resources need to be spent in ways that ensure that the agency's mandated missions are met. This same agency also attempts to minimize the costs associated with achieving the target mission. We call this the *dual mission problem*.

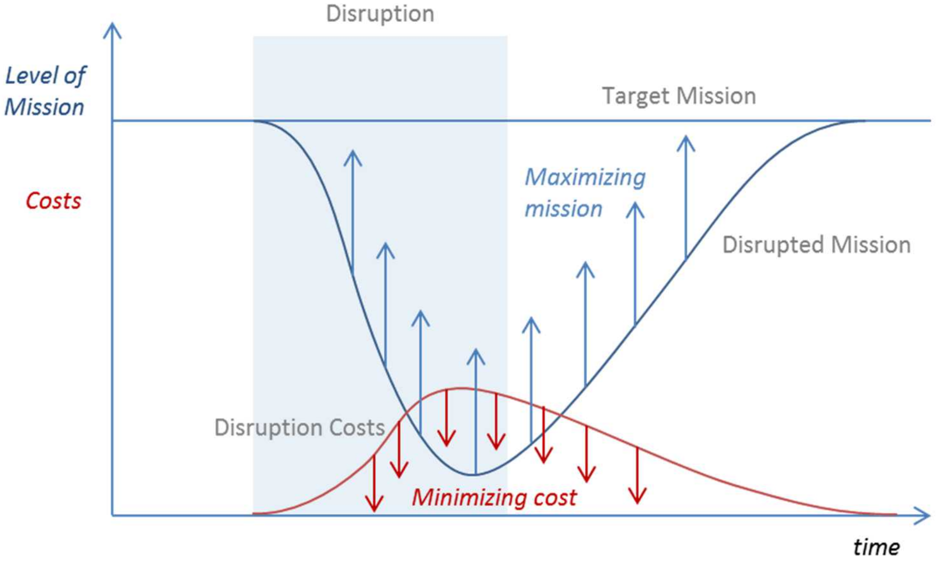


Figure 2. The Dual Objectives of Maximizing Mission and Minimizing Costs

The Model

We formulate the problem as that of an agency that must perform a mission that includes a set of assets $\{j\} \in J$, subject to potential disruptive events $\{i\} \in I$, each with probability p_i. Assets include individual facilities/built environment, supporting critical infrastructure systems, and social entities. Each disruption i, if it occurs, causes an associated consequence or in our case loss of mission, c_{ij}, to the associated asset j. The *a priori* expected loss in mission by asset, $\{c_i\}, i \in I$, can be expressed as

$$\begin{aligned}\text{Expected asset-}i\text{ loss} &= E[P \times C] \\ &= [p_1 \quad \cdots \quad p_i \quad \cdots \quad p_I] \times \begin{bmatrix} c_{11} & \cdots & c_{1j} & \cdots & c_{1J} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{i1} & \cdots & c_{ij} & \cdots & c_{iJ} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{I1} & \cdots & c_{Ij} & \cdots & c_{IJ} \end{bmatrix} \\ &= [c_1 \quad \cdots \quad c_i \quad \cdots \quad c_I].\end{aligned}$$

For each disruption i and associated consequence c_{ij} experienced by asset j, the agency has at its disposal a set of countermeasures or strategies $\{s_{ij}^m\}, m \in M$, measured in units of effort and an associated per-unit cost, r_{ij}^m. In initial planning and in response to a particular event, the agency must "produce" the loss of mission the disruption caused. Assuming *economies of scope* in these strategies – where conducting some of each alternate is better than conducting only a few – we can use a Cobb-Douglas production function for "producing lost mission" (the upper lost-mission area shown in Figure 2). We mathematically quantify the production for regaining this mission as:

$$\text{Regained mission} = A\prod\left(s_{ij}^m\right)^{\alpha_m},$$

where A is a technology constant and $0 < \propto_m < 1$ and $\sum_{m\in M} \propto_m = 1$. For example, to produce lost mission for a plan that has one asset and two strategies $\{m_1, m_2\}$, the restore-mission production function would be $A(s^1)^{\propto_1}(s^2)^{\propto_2}$.

Figure 2 illustrates this dual set of objectives. A government agency has a well-formed mission, with potential risks of disruption to this mission. The agency can assign a number and expected levels of disruption prevention and mitigation costs, which increase with their ability to reduce the resulting loss of mission. Given this relationship between disrupted mission and disruption costs, the graph can be used to articulate (disrupted) mission-maximizing strategies given a fixed budget for disruption costs, or to articulate a (disruption) cost-minimizing strategy given a target mission. (These mission and cost lines are actually "lumpy," or discrete, where the mission outcome and its costs jump from one discrete state to another.)

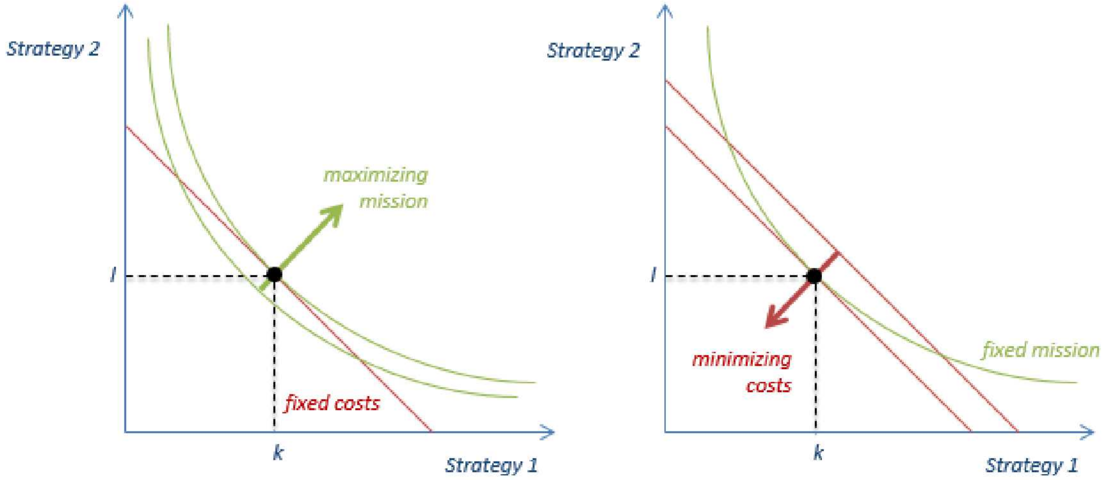


Figure 3. Primal and Dual Mission Problems

Using the definition above, the resilience-maximizing mission strategy is the one that maximizes the ability of government to resist, tolerate, absorb, recover from, or adapt to a disruption. Following the method in the previous section, either the primal or dual mission problem will maximize this ability. A government agency can achieve mission resilience by minimize the costs of disruptions for a given level of mission, since this is equivalent to maximizing the mission outcome. The following duality illustration helps make this point.

The Primal Mission Problem: Assuring Mission

Analogous to the economic firm above, consider a government agency that plans the resources and actions taken to conduct a particular mission, for example, the delivery of safe and effective pharmaceuticals (FDA, 2014). To "produce" a mission at level $\bar{q}$, the agency must spend operating costs c^{op} and carry out a strategy $\{s^m\}$ of potential actions for reducing the impacts of disruptions $\{i\}$ to the agency's assets $\{j\}$. (Since the operating costs are identical between strategies, they ignore them.) Figure 4 illustrates a set of such disruptions, organized by their probability of occurring and if they occur, their consequence to mission.

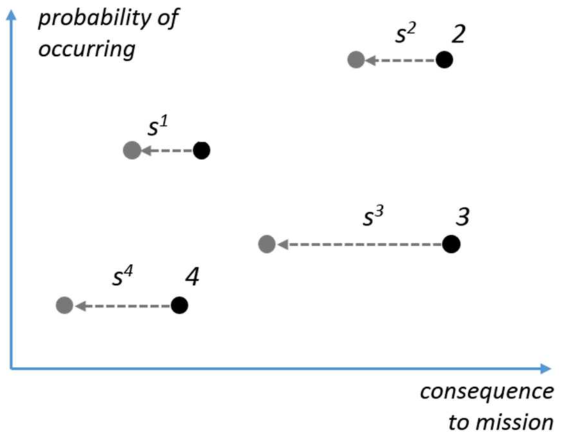


Figure 4. Mission Disruptions and Disruption-Response Strategies

In RAMCAP language, each disruption *i* is associated with a particular asset *j*, creating a {*i*,*j*} RAMCAP *threat-asset pair*.

Each of these actions, taken from a full set of potential strategies *S*, is designed to either prevent disruption of mission or to mitigate the losses to mission caused by the disruption. The strategies specify prevention/mitigation actions on, and associated costs, for (i) individual mission assets such as chemical facilities and manufacturers that use the chemicals and other materials to make mission products, and (ii) system-level assets such as transportation routes, ports, and other critical infrastructure that support these facilities and manufacturers. For simplicity of exposition, these response strategies do not change the probabilities of occurring; that condition is described in Section 2.3. The $\{s_{ij}^m\}$ can be thought of as *real options* in that they are paid for, in advance, so that action can be taken if and when the particular disruption occurs. For decisions in complex, high-resource-commitment, and high-uncertainty environments like government missions, risk management techniques such as *scenario planning with real options* (Varum, 2010; Alessandri *et al,* 2004; Miller & Waller*,* 2003; Cornelius *et al*, 2005; Raynor *et al*, 2004; Williams 2010) provide the means for identifying high risks to mission, identifying options for action given these events occur, and estimating the benefits and costs of keeping those options available. For example, a particular mission might potentially be disrupted by earthquake, flooding, or act of terrorism; the agency can build in low-cost options that allow it to effectively respond to all of these. The risk-assurance-resilience framework herein helps identify what the resilience actions can and should be.

Each disruption event *i* has a probability of occurring p_i, a level of effort to mitigate loss of mission s_{ij}^m, and a fixed cost r_{ij}^m of the action of addressing the event in a way that reduces the potentially lost mission.[5] Potential efforts to prevent, adapt, and recover lost mission include

---

[5] This cost breakdown could be considered a generalization of the FAA (2000) criticality approach, where total "impact of loss" is quantified as the sum of initial asset cost, temporary asset replacement, permanent replacement, and related costs such as flight delays and human life. It is also related to the RAMCAP (ASME, 2009) standard that identifies risk in terms of threat-asset pairs.

maintaining backup supplies of mission products, increasing security at the chemical and 'downstream' manufacturers, and increasing modes of available transportation of product.

Next, we assume that increases in these disruption-reduction efforts increase the mission outcome, but that there are decreasing returns from these efforts and costs (each additional dollar of effort gives a lower reduction in loss of mission):[6]

$$\frac{\partial q}{\partial s^{m}} > 0 \text{ and } \frac{\partial^2 q}{(\partial s^m)^2} \leq 0 \quad \forall \quad m. \tag{9}$$

Operating costs are taken as given and required for any mission, regardless of the particular $\{s^m\}$ risk strategy taken. Simplifying the problem by focusing on an agency formulation that has one asset, one event, and multiple strategies, we formalize this primal problem mathematically as selecting the set of $\{s^m\}$ that solves

$$\max q = q(\{s\}) \text{ subject to } \textstyle\sum_{m \in M} p_i s_i^m \, r_i^m \leq \bar{R}. \tag{10}$$

After forming the Lagrangian and solving for first-order conditions we have the condition (analogous to equation 3) that the marginal contribution of each mission producing/restoring activity per unit cost (or benefit-cost ratio) be the same:

$$\frac{{}^{\partial q}\!/_{\partial \hat{s}^m}}{p_i r_i^m} = \frac{{}^{\partial q}\!/_{\partial \hat{s}^n}}{p_i r_i^n} \; \forall \, m, n \in M \, . \tag{11}$$

This condition is shown in Figure 3 where the cost line touches the iso-production curve. As was the case in the previous economic-dual problem, this optimal allocation of efforts $\{s_{ij}^m\}$ is solely a function of the given parameters, in this case the effectiveness of mission-assuring activities, the probability of events and the cost per unit effort when responding to these events.

The Dual Mission Problem: Minimizing Resource Costs

Given the quasi-concavity of the mission-restoration function *q* and the linearity of restoration costs, the dual problem of minimizing disruption-related costs subject to a given level of mission is equivalent to the primal problem, that is, its solution is the same allocation of disruption-related resources:

$$\min R = \textstyle\sum_{m \in M} p_i s_i^m r_i^m \text{ subject to } q(\{s\}) \;\; \geq \; \bar{q}. \tag{12}$$

Note that the product $p_i s_i^m r_i^m$ can be the direct measure by which mission critical assets are identified, i.e., as the assets that have the highest combination of probability (p_i) of consequence – or effort (s^m) and cost (r^m) associated with maintaining mission. The implications of such a result are significant: the equations suggest that efficient government resilience policy occurs

---

[6] That is, *q* needs to be monotonically increasing in the efforts to increase mission, concave, and twice-continuously differentiable.

when the policy maximizes the mission outcome at lowest cost, where cost is measured by the cost of disruption; mission criticality assessment is a systematic measure of those high-cost sources of disruption. To determine the mission critical assets, we expand the Lagrangian

$$\Gamma = \left(\sum_{i \in I} p_i s_i^m r_i^m\right) + \lambda[q(\{s\}) - \bar{q}]. \tag{13}$$

and inspect first-order conditions the same way:

$$\frac{\partial q / \partial \hat{s}^m}{p_i r_i^m} = \frac{\partial q / \partial \hat{s}^n}{p_i r_i^n} \ \forall\, m, n \in M\ . \tag{14}$$

The equation ensures that the solution to the mission-cost minimization problem is the same as the solution to the mission-maximization problem, that this solution is the optimal solution.[7] Most importantly, given our definitions above, both of these solutions are also the resilience-maximizing solution, that is, they both maximize the probability of achieving mission given the ability to (and costs of) responding, adjusting, and adapting. This approach also ensures that the strategy selected identifies the mission-critical assets and ultimately maximizes chemical sector resilience to these security-related disruptions.

2.3 Important Extensions to the Framework

As constructed so far, though, the only means of maximizing resilience is to select the set of operational tasks and responses that support the potential states $\{s^m\}$ that occur over the analysis period. A number of logical extensions to this framework significantly increase its ability to maximize resilience while preserving the basic condition that one approach simultaneously achieves the risk, mission, and resilience objectives.

The first extension is *dynamic optimization*. Above, the decision maker optimizes the resource allocation only once, at the beginning of the time period. In an expanded dynamic optimization formulation, the decision maker makes an initial allocation and then re-optimizes, for example, when (i) a disruption occurs or ends, or (ii) there is a significant change in resources or mission. The decision maker uses the updated, realized information to ensure efficient use of resources and maximized mission from that point forward. Figure 5 illustrates how sequential optimizations are conducted, in particular when there is a disruption.

---

[7] That is, this solution $\{s^m\}$ is mathematically local and global optimum to the maximization and minimization problems.

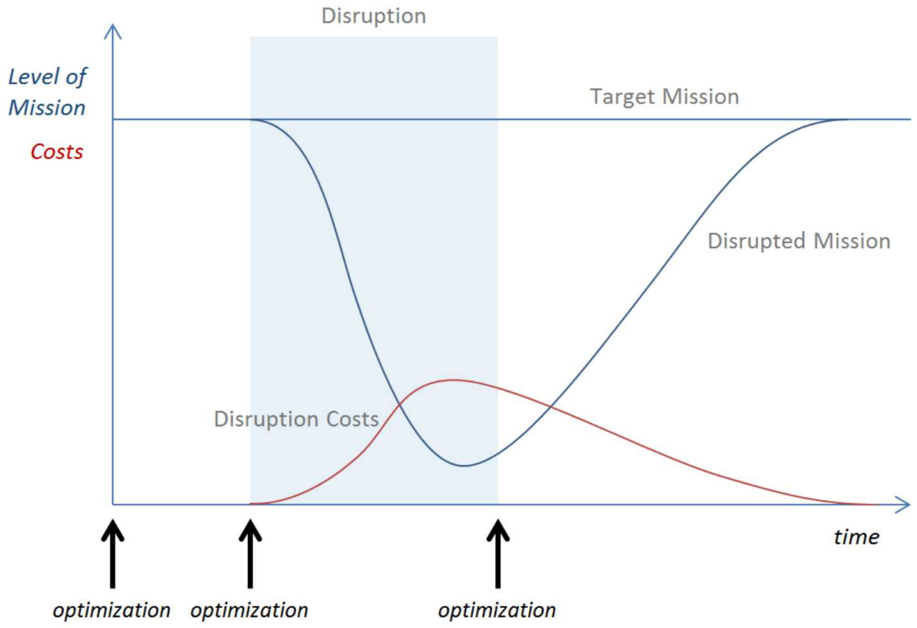


Figure 5. Resilience-Maximizing Dynamic Optimization

Assuming that there is a small cost to this optimization process, the decision maker will continually re-optimize in response to new information until the expected benefit of optimizing is less than its cost, similar to the *sequential search* rules found in, for example, Carlson & McAfee (1983). Optimal control techniques (Chiang, 2000) provide methods for ensuring that this piece-wise optimization over time is *a priori* equivalent to the overall temporal optimization, even under disruption uncertainties and particular outcomes. That is, this sequential optimization can provide a resilience-maximizing disruption strategy.

The second extension to this framework is the process of wholesale reconstruction of the overall set of circumstances that dictate operational and disruption actions. The initial mathematical construct above describes how an agency decision maker can optimize outcomes, resources, and resilience for a given set of alternative strategies. *Resilience design* is a process whereby the agency decision maker redesigns the mission itself, that is, reformulates the strategy, to further maximize resilience (and therefore minimize risks and maximize assurance). In the vernacular of the above agency problem, resilient design focuses more on developing a new mission and therefore new strategies *S* – for example, new capital investment over the long term – that categorically increase the ability of the agency to adapt to and recover from the disruptive events. When formulated correctly, the three-way optimization still holds.

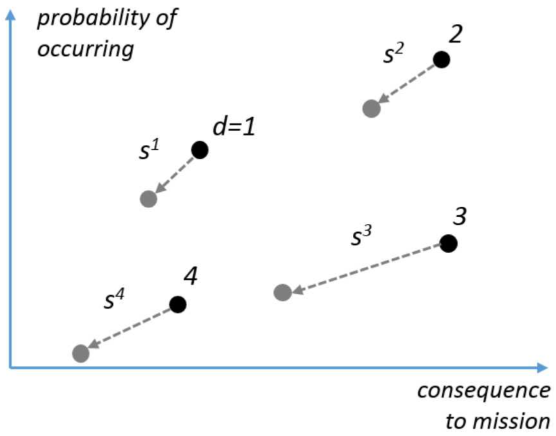


Figure 6. Effects of Resilient Design on Probability and Consequences of Events

As suggested by the figure, the agency can redesign the problem so as to transfer or remove certain risks.

2.4 Application Example: the Pharmaceutical Industry

U.S. pharmaceuticals facilities are regulated through a number of federal policies, including the U.S. Food and Drug Administration (FDA), which as an agency has a mandate to ensure the sufficient supply of safe pharmaceuticals. The FDA has direct control through regulations on pharmaceuticals facilities, and indirectly through DHS, EPA, and MTSA regulations, to name a few. If and when there is a disruption of an individual pharmaceutical facility, or asset within its mission, it has a number of responses in place to ensure mission, including (i) asset-level: increasing inventories of key pharmaceuticals (prophylaxis, anti-virals) and using secondary production facilities, and (ii) system-level: importing pharmaceuticals from overseas. Given the chronic shortages the FDA faces in over 100 medically necessary drugs, the framework provides a means for assessing the relative benefits and costs of these alternate response strategies, and also for assessing the overall ability of the strategy to maximize resilience.

Second, DHS/ISCD is part of a multi-agency mission for ensuring the safe production, use, storage, and transport of chemicals, given the threat of terrorism theft/release and destruction. ISCD policy, in its part, works to ensure that facilities have minimized the risk of attack, destruction, and theft/diversion, through site security plans that are based on risk-based performance standards. Other federal policies regulate the transport of chemicals to minimize the risk of terrorist threat, destruction, or diversion. Potential policy measures have included diverting if not halting the transport of particular chemical shipments until the threat was identified and removed. While such policies may be effective in reducing public safety impacts, they could have significant detrimental impacts to the economy and important government missions. With economic or mission as targeted performance, the framework makes clear what the disruptions are, the alternate potential responses, their comparative resilience benefits, and the overall risk-assurance-resilience strategy that can minimize terrorist risks and maximize sector resilience.

2.5 Application Example: Disaster Resilience Management

The current NIST Disaster Framework (Figure 7) illustrates how development of a disaster resilience strategy must include a clear statement of resilience and risk objectives. Table 1 maps our current framework with the NIST disaster framework (NIST, 2015) and the NIST economics framework (Gilbert and Butry, 2015).

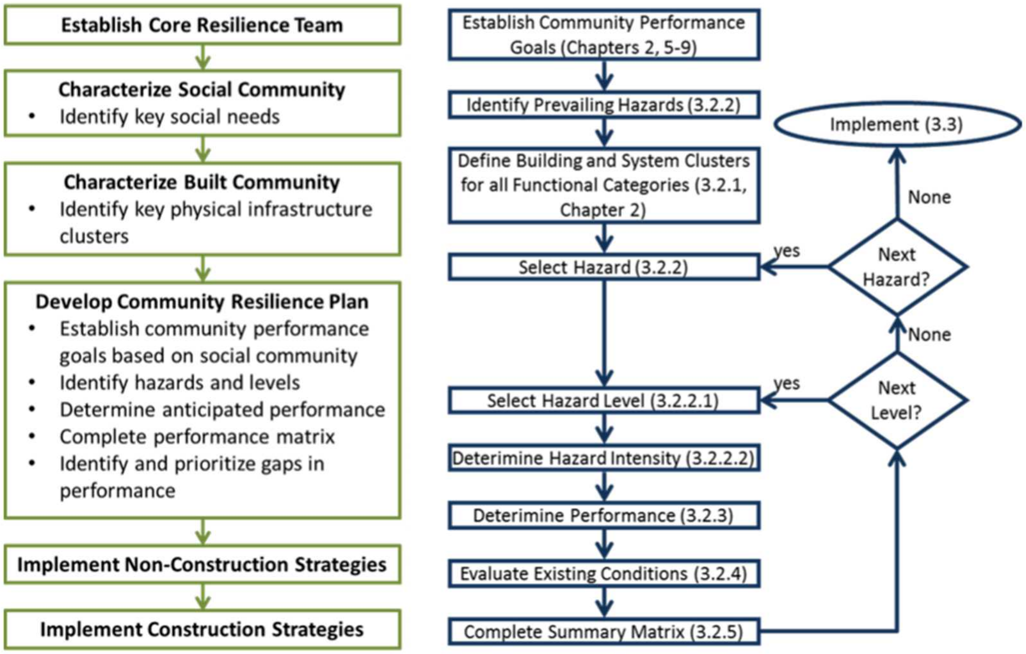


Figure 7. NIST Flow Chart for Developing Resilience Plan

Table 1. Mapping of Concepts Between Our Framework and NIST Framework

Framework	NIST Disaster Framework	NIST Economic Framework
Stated mission and constraints	"key social needs" "key community performance goals"	"Determine objective function" "Identify constraints"
Assets of concern	"key physical infrastructure clusters"	
Risks to mission	"identify hazards and levels"	
Consider alternate restorative strategies	"Implement non-construction /construction strategies"	"Select candidate plans" "Identify costs" "Identify benefits"

The selection of strategies in the NIST framework must include both "left of bang," preparedness strategies and "right of bang," restorative activities, the latter of which are broken down into short, medium and long term (Figure 8).

Figure 8. NIST Chart Describing Level of Recovery Efforts: Short, Medium, Long Terms

The figure illustrates how strategies and their ability can be compared based on their comparative abilities to use valuable resources and the most current information to dynamically optimize resources toward a low-risk, resilience outcome.

3 Summary and Conclusions

To address the lack of specific DHS guidance on how to simultaneously meet risk and resilience mandates, we present a risk-assurance-resilience framework that uses examples from the chemical sector. This appears to be the first approach that directly meets the combined requirement to “ensure that resources are applied where they contribute the most to resilience and risk mitigation” (DHS 2010b). The framework can be used, for example, to rank DHS assets by their ability to both (i) reduce asset and sector risks and (ii) increase sector-wide resilience. This can be used to identify resilience-maximizing strategies that involve the least-cost risk activities that do not involve individual facilities or assets.

The framework in its initial form herein is largely expository; more developed versions will need to take into account the ability to make changes in risk and resilience plans, and reallocate resources during and after a disruption, to ensure mission. More research is needed to fully develop the constructs that will allow chemical-sector policy analysts to evaluate the broader set of options for mitigating homeland security risks and ensure sector resilience.

Acknowledgements

The authors would like to acknowledge financial support from the U.S. Department of Homeland Security Infrastructure Security Compliance Division (for the risk components) and the DHS Science and Technology Directorate (for the resilience components).

References

Alessandri, Todd M., et al. (2004) Managing risk and uncertainty in complex capital projects. The Quarterly Review of Economics and Finance 44.5: pp. 751-767.

American Chemistry Council (ACC) (2013) The Business of Chemistry by the Numbers, June 2013, http://www.americanchemistry.com/chemistry-industry-facts, accessed March 2014.

ASME Innovative Technologies Institute. (2009) All-hazards risk and resilience: Prioritizing critical infrastructure using the RAMCAP PlusSM approach. New York: American Society of Mechanical Engineers.

American Water Works Association (AWWA). (2010) J100-10 (R13) Risk and Resilience Management of Water and Wastewater Systems (RAMCAP), 9781583217887. AWWA.

Carlson, J.A. and McAfee, R.P. (1983) Discrete Equilibrium Price Dispersion. Journal of Political Economy, Vol. 91, No. 3, pp. 480-93.

Chiang, A. C. (1992) Elements of dynamic optimization. New York: McGraw-Hill.

Cornelius, P., Van De Putte, A., and M. Romani. (2005) Three decades of scenario planning in Shell, California Management Review 48, pp. 92-109.

Federal Bureau of Investigation (FBI), Mueller, Robert S., III, Director. (2003) Testimony before the Senate Select Committee on Intelligence, Feb. 11, 2003, accessed at http://www.intelcenter.com/resource/2003/mueller.pdf on visited Feb. 4, 2005.

FAA (Federal Aviation Administration). (2000) "Security Risk Management Guide," accessed at http://fast.faa.gov/Riskmgmt/Secriskmgmt/secriskmgmt.htm on June 25, 2014.

Gilbert, S.W. (2010) "Disaster Resilience: A Guide to the Literature," National Institute of Standards and Technology, NIST Special Publication 1117, September.

Gilbert, S. and D. Butry (2015) Economic Framework for Community Disaster Resilience. Draft.

Government Accounting Office (GAO). (2014) DHS Action Needed to Enhance Integration and Coordination of Vulnerability Assessment Efforts [Reissued on September 17, 2014]. GAO-14-507: Published: Sep 15, 2014. Publicly Released: Sep 15, 2014

International Maritime Organization (IMO). (2003) ISPS Code: International Ship and Port Facility Security Code. December 2002. London: International Maritime Organization.

Mas-Colell, A., Whinston, M. D., and J.R. Green. (1995) Microeconomic theory. New York: Oxford University Press.

Miller, K.D. and H. G. Waller (2003) Scenarios, real options and integrated risk management, Long Range Planning 36, pp. 93-107.

Moran, K., Ackerman, G., and J. Bale. (2004) Assessing Terrorist Motivations for Attacking Critical "Chemical" Infrastructure. Washington, D.C: United States. Dept. of Energy.

National Infrastructure Advisory Council (NIAC) (2009). Critical Infrastructure Resilience: Final Report and Recommendations, September 8, p. 8.

National Institute of Justice (NIJ) (1997). A Method to Assess the Vulnerability of U.S. Chemical Facilities. Washington, DC: U.S. Dept. of Justice, Office of Justice Programs.

National Institute of Standards & Technology (NIST) (2015) Disaster Resilience Framework: 75% Draft. February.

Raynor, M.E. and X. Leroux (2004). Strategic flexibility in R&D, Research-Technology Management 47, pp. 27-32.

Sandia National Laboratories (2006). "A Risk Assessment Methodology (RAM) for Physical Security," white paper; accessed at http://www.sandia.gov/ram/RAM%20White%20Paper.pdf on June 25, 2014.

U.S. Department of Defense (DOD) (2000). Insider Threat Integrated Process team (2000). "DOD Insider Threat Mitigation: Final Report of the Insider Threat Integrated Process Team." April 24. Accessed at https://acc.dau.mil/GetAttachment.aspx?id=37478&pname=file&lang=en-US&aid=9018 on October 14, 2013.

U.S. Department of Homeland Security (DHS). (2007) Appendix to Chemical Facility Anti-Terrorism Standards; Final Rule, November 20.

U.S. Department of Homeland Security (DHS). (2009) National Infrastructure Protection Plan, Washington, D.C.

U.S. Department of Homeland Security (DHS), Risk Steering Committee. (2010a) DHS Risk Lexicon.

U.S. Department of Homeland Security (DHS). (2010b) Chemical Sector-Specific Plan: An Annex to the National Infrastructure Protection Plan.

U.S. Department of Justice (2000). "Assessment of the Increased Risk of Terrorist or Other Criminal Activity Associated with Posting Off-Site Consequence Analysis Information on the Internet." Washington, D.C. April 18, p. 24.

U.S. Food and Drug Administration (FDA). (2014) "Promoting Safe and Effective Drugs for 100 Years," website. Accessed at http://www.fda.gov/AboutFDA/WhatWeDo/History/ProductRegulation/PromotingSafeandEffectiveDrugsfor100Years/ on June 25, 2014.

U.S. Government Accountability Office (GAO). (2004) Aviation Security: Efforts to Measure Effectiveness and Address Challenge. GAO-04-232T. November 5, 2003

U.S. Government Accountability Office (GAO). (2005) Defense logistics: Actions needed to improve the availability of critical items during current and future operations: report to Congressional committees. Washington, D.C.: U.S. Government Accountability Office.

U.S. Public Law 107-295 (2002). Maritime Transportation Security Act of 2002.

Varum, C.A. & C. Melo. (2010). "Directions in scenario planning literature – a review of the past decades." Futures 42.4: 355-369.

The White House. (2013) Presidential Policy Directive 21 – Critical Infrastructure Security and Resilience, http://ww.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil, accessed June 13, 2013.

Williamson, Peter J (2012). Strategy as options on the future. Sloan Management Review 40.3.