Modeling Supply Chain Resiliency

Jeff A. Hazel

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Modeling Supply Chain Resiliency

An Undergraduate Honors College Thesis

in the

Department of Industrial Engineering

College of Engineering

University of Arkansas

Fayetteville, AR

by

Jeff Hazel
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Abstract

Engineered Resilient Systems (ERS) is a Department of Defense (DoD) program focusing on the effective and efficient design and development of complex engineered systems throughout their life cycle. There is a growing literature with qualitative definitions of resilience and quantitative models for systems with one performance measure. This paper uses a quantitative resilience framework (the Framework for ERS) that includes system design options, reliability, threats, vulnerabilities, responses, and consequences assessed in multiple system performance measures. The framework assists in establishing a model for any system to evaluate resiliency. This paper applies this framework using Multiple Objective Decision Analysis (MODA) to evaluate resiliency tradeoffs in designing supply chain and logistics networks to help decision makers increase the resilience of their supply chain networks. By using the MODA framework, decision makers can identify and evaluate multiple design options for a supply chain network.

Keywords

Resilience; Decision support; Supply chain management; Multiple objective decision analysis
Introduction

In numerous domains, there is a growing need for more resilient systems in today’s society. Over the past decade, resilience has become a buzz word; there have been many attempts at defining or quantifying resilience, with more qualitative approaches than quantitative. Much of the existing quantitative literature is very specific to one type of system or maybe a class of systems. This has resulted in many ways to assess systems resiliency. In the context of Engineering Resiliency, resiliency can be defined as the ‘ability of a system to return to its original (or desired) state after being disturbed’ (Christopher & Rutherford, 2004) or put another way, the system “must develop the ability to react to an unforeseen disturbance and to return quickly to its original state or move to a new, more advantageous one after suffering the disturbance” (Carvalho, Barroso, Machado, Susana, & Cruz-Machado, 2011). The INCOSE Systems Engineering Handbook defines resilience as “the ability to prepare and plan for, absorb or mitigate, recover from, or more successfully adapt to actual or potential adverse events” (International Council on Systems Engineering, 2015).

It is useful to compare resiliency versus robustness and resiliency versus reliability. “A robust process might reasonably be expected to produce consistent results with very little variation in output” but a resilient process must be adaptable (Christopher & Rutherford, 2004). This idea of adaptability is right in line with the idea that ‘an unforeseen disturbance’ might result in a ‘new, more advantageous’ state for the resilient process. The underlying difference between reliability and resiliency is the environment that generates ‘threats’ or disturbances. A reliable system accounts for threats within the system, whereas a resilient system accounts for threats outside the system. The difference being that failures in the system can more easily to be predicted, where
disruptive failures outside the system are less predictable. Thus, we have increased complexity when defining resiliency; one must design the system so that the system can withstand failures, threats, or disruptive events. Systems that successfully do this, maintaining or returning to the expected, desired, or necessary performance can be considered resilient.

As noted, previous studies have attempted to quantify resilience in a specific domain or application. In this paper, we will use a framework for developing a model to quantify resiliency. The idea is that the framework is general and applicable to a wide variety of systems and therefore applicable in many necessary contexts (Small & Parnell, 2016). The application within the supply chain management domain will be the focus of discussion and modeling in this paper, where the various components of the framework model are evaluated against previous research in this field.

**Literature Review**

Circa 2009, Figure 1 illustrates the landscape of literature that exists for Supply Chain Resilience (Bakshi & Kleindorfer, 2009). A variety of topics have been studied regarding supply chain resilience. However, what is lacking is a unified framework to encompass and address all parts of supply chain and all possible levels of threat and complexity.
As demonstrated by Figure 1, there is an opportunity for a unifying framework for modeling system resilience. As the INCOSE Handbook discusses, resilience is “an emergent and nondeterministic property of a system … because it cannot be determined by the examination of individual elements of the system” (International Council on Systems Engineering, 2015). Therefore, a framework is necessary to help model and evaluate resiliency.
Engineered Resilient Systems Framework

The Engineered Resilient Systems Framework or ERS Framework is a framework developed to apply and assess resiliency to systems with the following aspects included:

- Design Decisions (or Options)
- Reliability
- Survivability
- Threat(s)
- Responses
- Availability
- Produce-ability
- Supportability
- Performance measure(s)
- Service Life
- Value
- Cost
- Affordability

The relationships of these aspects can be seen in the influence diagram shown in Figure 2 below (Small & Parnell, 2016).

Figure 2: ERS Framework Influence Diagram (Small & Parnell, 2016)

This model allows systems with multiple functions and multiple performance measures to be evaluated, as well as dynamic systems. A key piece in this framework model is the options or
design decisions. In many systems, decisions are made in the design process to increase reliability, but decisions to increase resiliency of the system can also be made. In this framework, options influence cost, reliability, survivability and what responses are available to a threat or failure. There are advantages to designing for resiliency from the conception of a system, anticipating potential outside threats. Natural hazards and actions of intelligent adversaries can be anticipated and responses developed. This addition could be made by adding a line between the options node and the threats node. In any system where a ‘failure’ could be the difference in life or death for an individual, a resilient design is paramount. How reliable the system is influences the survivability and the performance. Before the time that a threat occurs ($t_0$), the system is just reliable. After $t_0$, the system is survivable if inherently resilient. There is also the possibility of an action to be taken to return the system to expected level of performance. Both survivability and this response influence the performance of the system, and performance influences the value. Whatever decisions are made in the design or response to the threat increase the cost. In the following section, existing studies and models with be evaluated and compared to the ERS Framework.

**Framework Application to Supply Chain Management**

Due to the continual competition in Supply Chain Management, there has been a growing need for lean networks that are lower cost. As a result, supply chain networks have become more vulnerable to threats, as there are more critical links and nodes due to the reduction of complexity. This balance of efficiency and resiliency is apparent in this context, as it is in many others as well. This concept can be referred to as the “price of resilience” because “many actions that can increase resilience conflict with “traditional” business goals such as reducing costs and
increasing operational efficiency” (Falasca, Zobel, & Cook, 2008). The vulnerability of the global supply chain has also increased due to the vast amount of outsourcing by companies. As the supply chain becomes more spread out with more ‘moving parts’ from end to end, the more vulnerable it will be, and the necessity of designing resiliency into the supply chains will be even more important.

While collaboratively working with Parnell and Small, the following figure (Figure 3) was developed to determine if the ERS Framework could capture the essence of all the terms discovered in our literature review.

![Figure 3: Framework—Generic Decision Tree (Small & Parnell, 2016)](image)

The nodes represent the elements of the framework that was developed, and the words listed below are the words found in the literature review for different domains. Each word is listed
beneath its corresponding term or most closely related term. We did not find any supply chain words that could not be placed under one of the nodes, thus we determined the framework to be encompassing for the literature we have reviewed. Words are either supply chain specific or words that are just general words pertaining to systems.

Using this framework, the literature for Supply Chain Resiliency was assessed. Supply Chain Resiliency is defined as “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function (Ponomarov & Holcomb, 2009). The following table, Table 1, displays the literature that was used in this evaluation, again, determining how well the framework applies to these various supply chain resilience articles and one general network resilience article that is applicable (Barker, Ramirez-Marquez, & Rocco, 2013).
As displayed in Table 1, the framework is applicable to the four papers reviewed, displaying its ability to effectively model Supply Chain systems as they pertain to resilience. All four papers reviewed were based on a single performance function and that function was related to reliability or robustness. They all discussed vulnerability as a key aspect, and the first used survivability interchangeably with vulnerability. Three of the four discussed recoverability as the performance measure for resiliency, meaning that how well the system returns to its desired state on its own,
or after triggered by some built-in response. Several authors note that the most desired state post-disruption may in fact be different from the originally most desired state, pre-disruption. Ponomarov says that “a resilient supply chain must be adaptable as the desired state in many cases is different from the original one; the dynamic nature of this adaptive capability allows the supply chain to recover after being disrupted, returning to its original state or achieving a more desirable state of supply chain operations” (Falasca, Zobel, & Cook, 2008). Three of the four papers reviewed discuss options or design decisions as being a major piece in the achievement of a resilient supply chain. The literature refers to them as strategic considerations, decisions factoring in risk considerations, and decisions to reduce vulnerabilities.

**Multiple Objective Decision Analysis**

The use of Multiple Objective Decision Analysis (MODA) allows one to quantitatively evaluate several alternatives on the basis of many objectives (Parnell, Driscoll, & Henderson, 2011). Specifically, this can be especially useful when evaluating the trade-off of competing objectives. The model uses an “additive value model to calculate how well candidate solutions” satisfy the intended value (Parnell, Driscoll, & Henderson, 2011). Each objective is assigned a weight based on the level of impact or importance it carries. Swing weight sensitivity analysis can then be done to see how the overall score for each alternative is affected based on an adjustment of the swing weight.

**Developing the Value Hierarchy**

Using the framework to consider assessing resiliency in the supply chain, a functional hierarchy was developed to define the main functions as planning for suppliers, sourcing goods and
materials, producing goods and materials, delivering goods, and finally integrating goods and services (Gunasekaran, Patel, & Tirtiroglu, 2001). These functions encompass the entire supply chain of a manufacturer who must source materials, produce in house, and deliver the finished product to the end customers, whether that is a wholesaler, store, etc. Then, using the functions, objectives were selected and a value hierarchy was developed. This hierarchy is shown in Table 2 below. Each objective has an appropriate value for performing an analysis of alternatives using MODA.

Table 2: Functional Hierarchy (Gunasekaran, Patel, & Tirtiroglu, 2001)

<table>
<thead>
<tr>
<th>Function</th>
<th>Objective</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning for Suppliers</td>
<td>Maximize range of product/services</td>
<td>Scale (1-5)</td>
</tr>
<tr>
<td></td>
<td>Maximize total cycle time</td>
<td>Total Cycle Time (weeks)</td>
</tr>
<tr>
<td></td>
<td>Maximize accuracy of forecast techniques</td>
<td>MAPE (%)</td>
</tr>
<tr>
<td>Sourcing Goods and Materials</td>
<td>Maximize supplier delivery performance</td>
<td>On time delivery (%)</td>
</tr>
<tr>
<td></td>
<td>Minimize supplier lead time</td>
<td>Lead time for sourcing (days)</td>
</tr>
<tr>
<td></td>
<td>Maximize responsiveness to expedited delivery</td>
<td># days decreased in sourcing time</td>
</tr>
<tr>
<td>Producing Goods and Materials</td>
<td>Minimize Product Cycle Time</td>
<td>Product Cycle Time (hours)</td>
</tr>
<tr>
<td></td>
<td>Maximize capacity utilization</td>
<td>Utilization (%)</td>
</tr>
<tr>
<td></td>
<td>Maximize labor efficiency</td>
<td>Productivity (%)</td>
</tr>
<tr>
<td></td>
<td>Maximize quality by minimized defects</td>
<td>Number of defects</td>
</tr>
<tr>
<td>Delivering Products</td>
<td>Minimize delivery lead time</td>
<td>Lead time for delivery (days)</td>
</tr>
<tr>
<td></td>
<td>Maximize delivery performance</td>
<td>On time delivery (%)</td>
</tr>
<tr>
<td></td>
<td>Maximize responsiveness to expedited delivery</td>
<td># days decreased in delivery time</td>
</tr>
<tr>
<td>Integrating Goods and Services</td>
<td>Maximize quality of delivered goods</td>
<td>% of non-defects</td>
</tr>
<tr>
<td></td>
<td>Maximize level of perceived value of product</td>
<td>Quality 5 star rating</td>
</tr>
<tr>
<td></td>
<td>Minimize customer complaints</td>
<td>Number of complaints</td>
</tr>
</tbody>
</table>
Value Curves

A key step in MODA analysis is creating value curves for each value measure. Using these value curves and the input values for each alternative, a Microsoft Excel macro calculates a scaled value. Figures 4a-4e show the value curves for each objective and value. Each figure is separated by the main supply chain function (i.e. Figure 4a is the value curves associated with the planning for suppliers objectives). Under the objective, there is a row indicating whether the object pertains to or influences resilience, flexibility, both, or neither directly.

Maximizing the range of product in services has a increasing linear value curve based on the constructed scale. Minimizing the cycle time has essentially a decreasing linear value curve until after 4 weeks. The highest value in this analysis was 6 weeks, which was awarded a value of 0. Maximizing the accuracy of forecasts (or minimizing the MAPE or mean absolute percent error) has negative diminishing returns because under 10% is going to be good accuracy, but over 10% and the values significantly become worse.
Maximizing the supplier delivery performance has a value curve as shown in Figure 4b because there is separation between a supplier good performance (above 90%) and anything below.

Minimizing supplier lead time has a negative diminishing returns value curve due to the fact that a week of lead time is expected and reasonable, but beyond that, there is not much value.

Maximizing the responsiveness to expedited delivery has a positive and diminishing return due to the fact that if no decrease can be made, there is no value, but if anywhere around a week is reduced, there is high value.
Minimizing product cycle time and maximizing labor efficiency ended up not being relevant to this analysis, as all the alternatives maintained the same cycle time. Maximizing capacity has one of the more interesting value curves. In terms of resiliency, the best value for utilization would not be 100%, as it gives no flexibility or resiliency in the scenario of getting behind. Instead, the best value would be 90% (or something around there depending on the manufacturer).

Minimizing the number of defects has a negative diminishing returns value curve for similar reasons as comparable value curves; low defects have high value, with no value given to a lot.
Minimizing deliver lead time has a negative diminishing returns value curve due to the fact that a week of lead time is expected and reasonable, but beyond that, there is not much value.

Maximizing the delivery performance has a value curve as shown in Figure 4d because there is separation between a good delivery performance (above 90%) and anything below. Maximizing the responsiveness to expedited delivery has a positive and diminishing return due to the fact that if no decrease can be made, there is no value, but if anywhere around a week is reduced, there is high value.
Maximizing the quality of delivered goods is considering any damages that may occur during delivery. The value curve is positive and diminishing because a high percentage of non-defects is essentially the same. Maximizing the level of perceived value nearly has a positive linear value curve, however, the 2 star rating has a slightly lower value (20) than what would be linear (25) due to the fact that a 2 star rating is never considered a proficient or good rating. Minimizing the number of customer complaints has a negative diminishing returns value curve because no complaints is the best value, but a lot of complaints results in a significant drop in value, eventually to a value of 0.
Swing Weights

The next step in performing MODA is to define swing weights (Parnell, Driscoll, & Henderson, 2011). These weights are used to take the values from the different alternatives and proportion them into a final weighted value. The weight matrix depicted in Figure 5 shows the rationale and the allocation of the. Value measures that have significant customer impact were assigned the most weight due to the fact that most companies will have a “customer first” focus. The value measures were still given relatively high weight if they impact the customer at all, even if the opportunity to improve would be considered ‘some’ or ‘minor’. The next category used to assign weights was whether or not the objective value had major cost impact, and the final category used was minor cost impact. The degree of “Opportunity to Improve” was used to assign the weights for each column after the columns were assigned. Using swing weight analysis, the effect that the weights have on the outcome can be evaluated; this is to be discussed in the following section.

![Figure 5: Swing Weight Matrix](image)

The additive value model used to compute the total value for each alternative is defined as

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i)$$
where \( v(x) \) represents the total value, \( n \) is the number of value measures, \( x_i \) is the score of the alternative on the \( i \)th value measure, \( v_i(x_i) \) is the single-dimensional value of the alternative on the \( i \)th value measure, \( w_i \) is the normalized swing measure weight of the \( i \)th value measure, where the sum of all \( w_i \) is equal to one (\( \sum_{i=1}^{n} w_i \)) (Parnell, Driscoll, & Henderson, 2011). As shown in Figure 5, \( f_i \) is the non-normalized swing weight value to the \( i \)th value measure, and

\[
\omega_i = \frac{f_i}{\sum_{i=1}^{n} f_i}.
\]

**Alternative Generation**

The application of the model was intended to assess the tradeoffs in supplier selection and its impact on the entirety of the supply chain. To demonstrate the range of application of this model, two baselines are used, with specific additions or changes for each one. Table 2 lists the considered alternatives.

<table>
<thead>
<tr>
<th>Baseline A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop second source for A</td>
</tr>
<tr>
<td>Expedite transportation A</td>
</tr>
<tr>
<td>Baseline B</td>
</tr>
<tr>
<td>Partner with a source B</td>
</tr>
<tr>
<td>Increase source capacity B</td>
</tr>
<tr>
<td>Hypothetical Best</td>
</tr>
<tr>
<td>Ideal</td>
</tr>
</tbody>
</table>

Baseline A, in this scenario, is assumed to be a problem supplier that is resulting in delays, defects, and customer complaints. Developing a second source would be considered a long term solution in transitioning to a new source to ultimately replace A. Expediting transportation would be considered a short term solution to help eliminate the delays with source A. Baseline B, in this scenario, is assumed to be a good supplier that has low capacity and therefore low impact on the overall supply network and supply chain for the company. Partnering with source B could result
in several benefits, and increasing the source’s capacity has a clear intent and benefit. ‘Hypothetical Best’ and ‘Ideal’ are included for analysis purposes, where hypothetical best is taking the best value for value measure combined into one alternative, and ideal being what would be the maximum value possible on the scale (100). Including these two ‘alternatives’ helps show how far from ideal the candidate solutions really are. The hypothetical best option shows the potential for a new alternative to be developed to include the best components of all six alternatives. It is called hypothetical since it may not be a feasible alternative.

Value Scoring

Once the alternatives were generated, notional data was determined for each alternative. The scores are displayed in Table 3.

<table>
<thead>
<tr>
<th>Table 3: Scores for Each Alternative and Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Scale (%</td>
</tr>
<tr>
<td>Baseline A</td>
</tr>
<tr>
<td>Develop second source for A</td>
</tr>
<tr>
<td>Expedite transportation A</td>
</tr>
<tr>
<td>Baseline B</td>
</tr>
<tr>
<td>Partner with a source B</td>
</tr>
<tr>
<td>Increase source capacity B</td>
</tr>
<tr>
<td>Hypothetical Best</td>
</tr>
<tr>
<td>Ideal</td>
</tr>
</tbody>
</table>

As mentioned previously, an Excel macro function evaluates uses the alternative data and the value curve to obtain value of each alternative on each value measure. The values are displayed in Table 4. Inherent to the value calculation, the value will be between 0 and 100.
Using the additive model for value scoring as discussed previously, we multiply each value shown in Table 4 by the weights ($w_i$) shown in Figure 6 and listed, sorted by weight in Table 5.

**Table 5: Sorted Normalized Weights**

<table>
<thead>
<tr>
<th>Objective Value</th>
<th>$w_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of complaints</td>
<td>0.14</td>
</tr>
<tr>
<td>5 star rating</td>
<td>0.13</td>
</tr>
<tr>
<td>Lead time for delivering (days)</td>
<td>0.12</td>
</tr>
<tr>
<td>Product cycle time (hours)</td>
<td>0.12</td>
</tr>
<tr>
<td>On time delivery for delivering(%)</td>
<td>0.12</td>
</tr>
<tr>
<td>Time (weeks)</td>
<td>0.09</td>
</tr>
<tr>
<td># of days decreased in delivery time</td>
<td>0.07</td>
</tr>
<tr>
<td>Lead time for sourcing (days)</td>
<td>0.06</td>
</tr>
<tr>
<td>Number of defects (parts per 1000)</td>
<td>0.06</td>
</tr>
<tr>
<td>On time delivery for sourcing (%)</td>
<td>0.04</td>
</tr>
<tr>
<td># of days decreased in delivery time</td>
<td>0.03</td>
</tr>
<tr>
<td>% of non-defects</td>
<td>0.01</td>
</tr>
<tr>
<td>Range Scale (1-5)</td>
<td>0.01</td>
</tr>
<tr>
<td>MAPE (%)</td>
<td>0.001</td>
</tr>
<tr>
<td>Utilization (%)</td>
<td>0.001</td>
</tr>
<tr>
<td>Productivity (%)</td>
<td>0.001</td>
</tr>
</tbody>
</table>

The final normalized, weighted value for each value is calculated by multiply the respective normalized weight by the value. This final value matrix is shown in Table 6.
Table 6: Weighted Value for Each Alternative on Each Value Measure

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Range Scale (1-5)</th>
<th>Time (weeks)</th>
<th>MAPE (%)</th>
<th>On time delivery for sourcing (%)</th>
<th>Lead time for sourcing (days)</th>
<th># of days decreased in delivery time</th>
<th>Product cycle time (hours)</th>
<th>Utilization (%)</th>
<th>Productivity (%)</th>
<th>Number of defects (parts per 1000)</th>
<th>Lead time for delivering (days)</th>
<th>On time delivery for delivering (%)</th>
<th># of days decreased in delivery time</th>
<th>% of non-defects</th>
<th>5 star rating</th>
<th>Number of complaints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline A</td>
<td>0.4</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.9</td>
<td>0.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Develop second source for A</td>
<td>0.7</td>
<td>2.2</td>
<td>0.1</td>
<td>2.5</td>
<td>4.6</td>
<td>0.7</td>
<td>2.9</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
<td>6.1</td>
<td>1.7</td>
<td>3.6</td>
<td>1.2</td>
<td>6.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Expedite transportation A</td>
<td>0.4</td>
<td>1.1</td>
<td>0.1</td>
<td>1.6</td>
<td>2.9</td>
<td>2.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>4.0</td>
<td>6.1</td>
<td>0.0</td>
<td>6.5</td>
<td>5.1</td>
</tr>
<tr>
<td>Baseline B</td>
<td>0.2</td>
<td>2.2</td>
<td>0.1</td>
<td>3.9</td>
<td>4.9</td>
<td>0.7</td>
<td>2.9</td>
<td>0.0</td>
<td>0.0</td>
<td>4.6</td>
<td>8.1</td>
<td>9.2</td>
<td>0.0</td>
<td>1.3</td>
<td>9.7</td>
<td>13.0</td>
</tr>
<tr>
<td>Partner with a source B</td>
<td>0.5</td>
<td>6.5</td>
<td>0.1</td>
<td>4.1</td>
<td>5.2</td>
<td>0.7</td>
<td>4.3</td>
<td>0.0</td>
<td>0.0</td>
<td>5.2</td>
<td>9.2</td>
<td>10.3</td>
<td>0.0</td>
<td>1.4</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Increase source capacity B</td>
<td>0.5</td>
<td>4.3</td>
<td>0.1</td>
<td>3.9</td>
<td>4.9</td>
<td>0.7</td>
<td>2.9</td>
<td>0.1</td>
<td>0.0</td>
<td>4.0</td>
<td>6.1</td>
<td>9.2</td>
<td>3.6</td>
<td>1.2</td>
<td>9.7</td>
<td>13.0</td>
</tr>
<tr>
<td>Hypothetical Best</td>
<td>0.7</td>
<td>6.5</td>
<td>0.1</td>
<td>4.1</td>
<td>5.2</td>
<td>2.2</td>
<td>4.3</td>
<td>0.1</td>
<td>0.0</td>
<td>5.2</td>
<td>9.2</td>
<td>10.3</td>
<td>6.5</td>
<td>1.4</td>
<td>13.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Ideal</td>
<td>0.7</td>
<td>8.7</td>
<td>0.1</td>
<td>4.3</td>
<td>5.8</td>
<td>2.8</td>
<td>11.5</td>
<td>0.1</td>
<td>0.1</td>
<td>5.8</td>
<td>12.3</td>
<td>11.5</td>
<td>7.2</td>
<td>1.4</td>
<td>13.0</td>
<td>13.0</td>
</tr>
</tbody>
</table>

The benefit that this method of analysis is that it provides the weight value of each alternative.

The value measure weights can be revised as the market fluctuates or the business changes.

Moving forward with the current weights, we can easily compare the value of each alternative and even shed light to the value measures that contribute significantly to the overall value score by creating a value components chart as included in Figure 6.

![Figure 6: Value Components Chart](image)

As observable in Figure 6, the alternative of developing a second source to replace source A is the best alternative for supply chain A, and partnering with source B provides the greatest value.
for supply chain B. An interesting observation to point out is that the hypothetical best is not far from the alternative for partnering with source B in this supply chain.

Alternative Costs

When performing Multiple Objective Decision Analysis, you must not stop at the Value Component Chart (Figure 6) and simply choose the alternative to pursue based on the highest value alone. Nearly inevitably, value comes with a cost, and this tradeoff should be fully assessed and evaluated when making a final decision. In order to do this, we must first start with the cost of each alternative. In this supply chain, the main five functions are also suitable for cost categories, meaning that our breakdown of cost will consist of planning cost, sourcing cost, production cost, delivery cost, and integration cost. Again, notional cost data was created for analysis purposes where the baseline was given a $1,000,000 expenditure. Costs for each of the alternatives were then estimated based on expected impact of the implementation of each. For example, the extra planning and coordinating associated with developing a second source would result in an increased planning cost and sourcing cost. The cost components are displayed in Table 7 numerically and Figure 7 graphically.

**Table 7: Cost Breakdown of Each Alternative**

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Planning cost ($)</th>
<th>Sourcing cost ($)</th>
<th>Production cost ($)</th>
<th>Delivery cost ($)</th>
<th>Integration cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline A</td>
<td>$250,000</td>
<td>$200,000</td>
<td>$300,000</td>
<td>$150,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Develop second source for A</td>
<td>$350,000</td>
<td>$250,000</td>
<td>$300,000</td>
<td>$150,000</td>
<td>$150,000</td>
</tr>
<tr>
<td>Expedite transportation A</td>
<td>$250,000</td>
<td>$200,000</td>
<td>$250,000</td>
<td>$250,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Baseline B</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Partner with a source B</td>
<td>$250,000</td>
<td>$300,000</td>
<td>$150,000</td>
<td>$150,000</td>
<td>$50,000</td>
</tr>
<tr>
<td>Increase source capacity B</td>
<td>$250,000</td>
<td>$250,000</td>
<td>$200,000</td>
<td>$150,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Hypothetical Best</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$50,000</td>
</tr>
<tr>
<td>Ideal</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
</tbody>
</table>
Cost vs. Value

A side by side comparison of cost and value is shown in Table 8 but the most effective way to evaluate the tradeoff of value and cost is a Cost vs. Value chart (Figure 8).

Table 8: Cost and Value of Each Alternative

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Cost</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline A</td>
<td>$1,000,000</td>
<td>7</td>
</tr>
<tr>
<td>Develop second source for A</td>
<td>$1,200,000</td>
<td>49</td>
</tr>
<tr>
<td>Expedite transportation A</td>
<td>$1,050,000</td>
<td>30</td>
</tr>
<tr>
<td>Baseline B</td>
<td>$600,000</td>
<td>59</td>
</tr>
<tr>
<td>Partner with a source B</td>
<td>$900,000</td>
<td>74</td>
</tr>
<tr>
<td>Increase source capacity B</td>
<td>$950,000</td>
<td>64</td>
</tr>
<tr>
<td>Hypothetical Best</td>
<td>$550,000</td>
<td>82</td>
</tr>
<tr>
<td>Ideal</td>
<td>$0</td>
<td>100</td>
</tr>
</tbody>
</table>
Figure 8: Cost vs. Value Chart

When using a chart as such, we first want to eliminate the alternatives that are dominated (Parnell, Driscoll, & Henderson, 2011). An alternative is dominated when another alternative achieves the same value for less than or equal to its cost. For example, partnering with source B dominates increasing the capacity of B because partnering with source B achieves a higher value for less cost. In fact, this is the only alternative that is dominated. Baseline B would dominate all of the A alternatives in terms of what is represented on this chart, but we know that A alternatives and B alternatives are to be compared independently. Therefore, we are left with only one improvement alternative that is acceptable for source B, at that is to partner with source B. It is then up to the decision maker to decide if they want to leave the relationship with source B as it is currently (Baseline B), or to implement the alternative of partnership. For the
improvement alternatives for source A, Figure 8 shows us that either option is acceptable, and it will be up to the decision maker to decide which course of action to take. Both require additional cost to achieve additional value, and as you would expect, to achieve higher value, more must be invested.

**Discussion**

The framework provides the elements to evaluate system resiliency. As demonstrated by the Supply Chain literature, the framework successfully addresses many aspects necessary to create a model that can assess the level of resiliency achieved by a supply chain. With the ability to model supply chain resiliency, the end result can be a more resilient supply chain network and processes. Currently, many optimized supply chains are focusing on reducing operating costs, but do not consider the additional cost of disruptive events on the supply chain. Assessing this balance of operating cost efficiency and increasing resiliency is the next major step. This can allow the supply chain manager and decision maker to establish the level of resiliency that is financially justified. MODA provides a useful tool for this analysis. This paper demonstrates the use of MODA with notional data, but a decision maker in industry could input actual values and measures to evaluate real-world tradeoffs and alternatives.

**Future Research and Improvements**

Where the current supply chain resiliency literature is lacking includes a measure of value or utility other than just cost, how to account for an intelligent adversary, and dynamic threats. These all present opportunities for improvements. The major opportunity for research is to model a supply chain exposed to outside threats that will result in some level of disruption in the supply
chain. To what extent will depend on the design parameters used. If modeled well, use of simulation software could allow the testing of multiple scenarios and analyzing the results to determine the best design under various probabilities of threats. It could even be possible to optimize the design based on the simulated performance. AnyLogic software seems to provide the necessary tools and functionality to perform this simulation with the desired inputs and evaluation (AnyLogic Company, 2016). Another approach could be to use Monte Carlo simulation and assign probabilities to the supplier’s performance alternatives.

This MODA framework addresses the opportunity of evaluating a multi-function system for tradeoffs in resilience by quantifying the value added for resilience added. Once resilience is in fact awarded with value in the model, the additional cost associated with the more resilient alternative(s) can then be assessed whether or not the additional resilience is worth the additional up-front cost. Investing in resilience can be economically beneficial in the long run. For sake of this paper, the evaluation of alternatives focused on the supplier selection and planning process, while still giving value to the other functions, as the decision impacts and influences them all. Additional MODA models could be used to evaluate similar alternatives for other components of the supply chain (i.e. different production alternatives with varying levels of automation or different distribution networks). This could be done by adapting some of the objectives, their value curves, adjusting the swing weights, and generating appropriate alternatives. Ultimately, a higher up approach could be used to assess the entirety of the supply chain in one MODA model.
References


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This thesis is approved.

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