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Engineered Resilient Systems Model Applied to Network Design

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Engineered Resilient Systems Model Applied to Network Design

A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelors of Science in Industrial Engineering

by

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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 resilient complex engineered systems throughout their lifecycle. There is growing literature with qualitative definitions of resilience and quantitative models for systems, but these focus typically on systems with one performance measure. In application, many systems have multiple functions and multiple performance measures. This research uses a quantitative resilience framework for ERS that includes system design options, reliability, external threats, vulnerabilities, responses, and consequences assessed on multiple system performance measures. This paper applies the ERS framework to designing resilient networks.

Keywords

Resilience, Engineering Resilient Systems, Network

1. Introduction

Andrew Zolli wrote in his 2012 book Resilience: Why Things Bounce Back; "Resilient systems fail gracefully. A perfect system is often most fragile" [Zolli]. In the current climate of system design, systems are continually designed to be more lean and efficient, however this can lead to direct tradeoffs with the ability of a system to cope with unexpected threats and environments. In operational use, many systems are subject to outside forces and influence in ways or at levels which are often unaccounted for during the design of the system. These outside forces and influences can cause the system to fail ungracefully in spectacular and challenging ways. The immediate aftermath of any system failure raises questions concerning the ability of the system tasks to be completed, how to recover the system, and the performance of the system moving forward. These questions are impossible to predict but the inclusion of resilient features in the design stage has the potential to provide solutions for how to handle the situation. One example from recent history of this scenario is the Fukashima Diiachi level 7 International Nuclear Event where, despite the high reliability of the nuclear power plant's system to perform safely despite a multitude of possible internal and external disruptions, the system failed due to an unexpected event. The unexpected event was the test of the system's resilience. The ability for the workers and government to handle the unforeseen situation was dependent on decisions made in the design stage.

Resilience is a current issue in many sectors of industry and government. The Department of Defense has sponsored a program titled "Engineered Resilient Systems" which focuses on the effective and efficient design and development of resilient complex engineered systems throughout the system's lifecycle. This paper will summarize the literature behind resilient systems. This paper will also discuss and describe ERS and its components. Next this paper will analyze a network through a decision tree matrix of ERS in an attempt to optimize the design tradeoff space of resilience versus cost. Finally, this paper will draw conclusions about the ERS framework applied to networks and provide additional areas of research and improvement for the ERS framework.

2. Literature Review

Resilience was originally defined in ecology to describe the persistence of nature [1]. From these ecological origins, two parallel definitions of resilience arose. The first is from Holling in 1973 which defines resilience as "the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist." Hollings definition emphasizes conditions far from stable steady-state, where instabilities can flip a system into different behavior but the system continues to exist. In this case, resilience is measured by the magnitude of changes that can be absorbed before the system moves to extinction in one or more of its state variables [2]. The second definition, due to Pimm in 1991, defines resilience as the length of time a system disturbed by outside forces takes to return to equilibrium. This definition of resilience could be measured by a return time for each of the system's state variables [3]. This definition is expanded upon and illustrated by the work of Barker et al in 2013 which can be seen in Figure 1. In the simplest form of Pimm's calculation of resilience, resilience is measure by the time between t_e and t_f. For the same event, the shorter the time between the event and recovery by single performance measure the more resilient the system is [3].

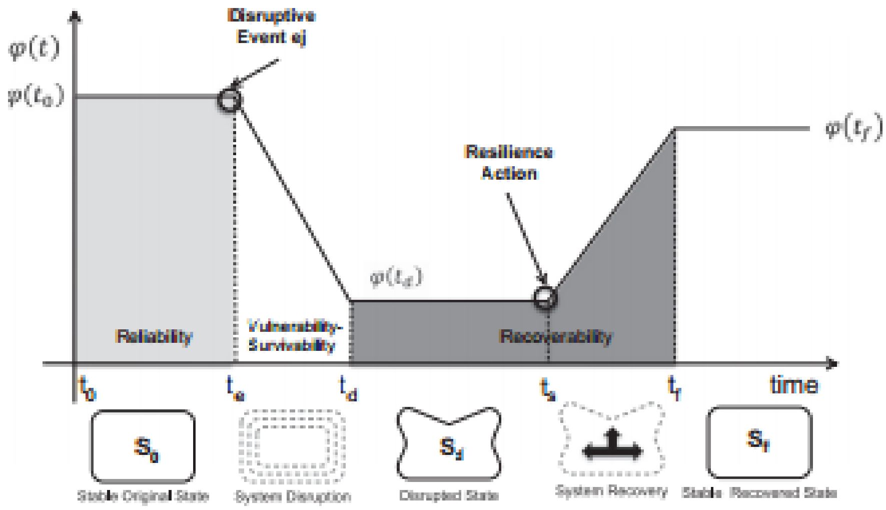

Figure 1: State transitions over time with respect to system performance [4]

These alternative meanings of resilience reflect different viewpoints about function of resilience and are often applied uniquely across separate domains. Pimm's resilience examines system behavior of one known stable state and focuses on maintaining efficiency of function. On the other hand, Holling's resilience examines alternative stable states and focuses on maintaining existence of function. The differences in viewpoints contribute to the difficulty of current literature in providing a unified and quantified definition of resilience and in general there is a lack of standard definition in the literature.

From a systems perspective, such as the domain of Engineered Resilient Systems, Neches and Madni in 2012 define a resilient system as "the ability of the system to adapt affordably and perform effectively across a wide range of operational contexts" [5]. Goerger in his 2014 paper cites this concept from Neches and Madni as "Broad Utility" and adds to the definition characteristics a system must have from a DoD perspective which includes, "ability to

Repel/Resist/Absorb; ability to Recover; and ability to Adapt." Goerger concludes his paper with the definition of resilience for the DoD as "A resilient system is trusted and effective out of the box, can be used in a wide range of contexts, is easily adapted to many others through reconfiguration and/or replacement, and has a graceful and detectable degradation of function" [6]. These definitions offer three useful perspectives.

As can be seen from this brief literature review, the field of resilience lacks a unified definition. In addition, the various definitions of resilience are lacking in several critical aspects. In the case of Holling's work multiple variables are considered insofar as they continue to exists and not as a measurement of performance or value. In Pimm's work as illustrated by Barker, only one variable is used as the performance measure and the only evaluation criteria is time while again value and performance is ignored. Finally in Goerger's paper there is yet to be a quantifiable definition of resilience. In most definitions, there is a lack of cost associated with resilience. Much of the remaining research which proposes quantified definitions, are based on a single variable which is most commonly time and rarely cost. Thus, there is a clear gap for a quantification method of resilience using multivariate performance models. This paper will discuss ERS, a system framework that allows for the use of multiple performance measures to ascertain the value of a system after a disturbance to function. This paper will discuss an example of ERS applied to evaluating and designing a real-world resilient network.

3. ERS Description

This paper was written in conjunction with Small et al. [7] to establish the foundation of the ERS framework and explore the literature gap in key interest fields. As such, Small identifies the framework of ERS as a cost-based multivariate probabilistic decision tree with the option to modify for an intelligent threat (attacker) or the threat from natural hazard [7]. The generic decision tree and influence diagram for this framework can be seen in **Figure 2** and **Figure 3** respectively.

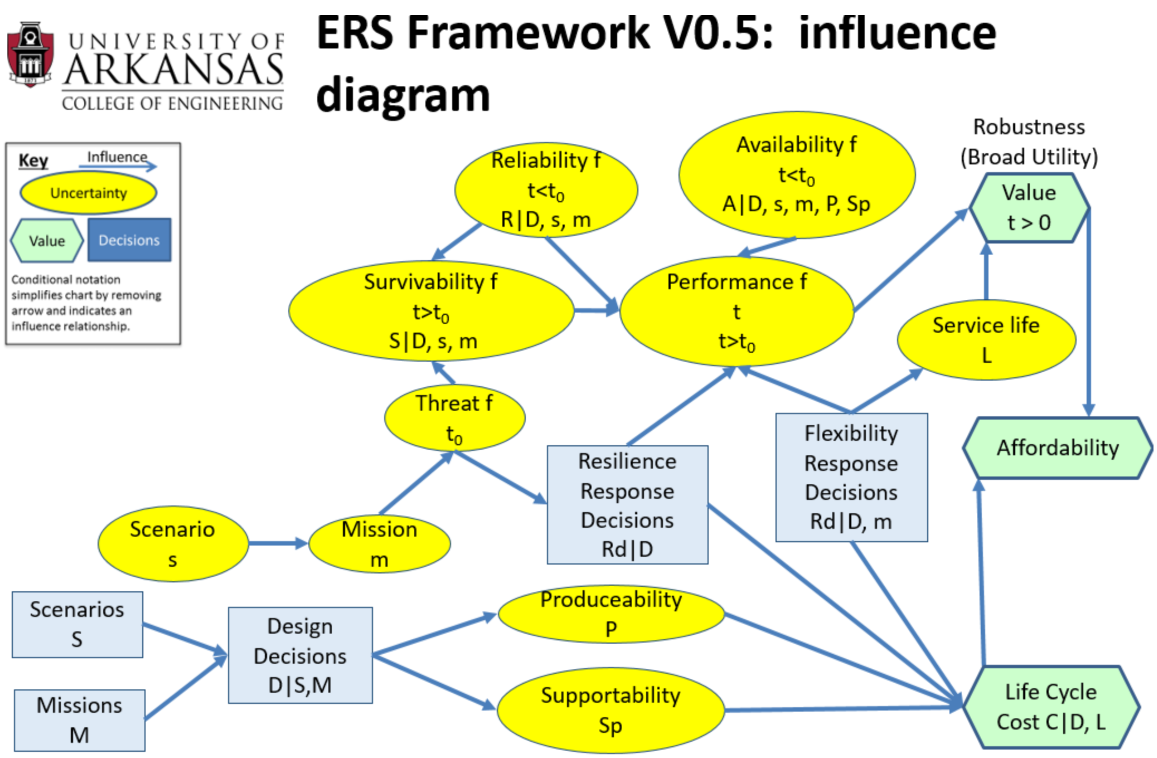

Figure 3: Influence diagram for the ERS framework [7]

The key terms for the ERS model are:

- Scenario: set of conditions of use for a given system.
- Missions: set of objectives of a system. A system may be designed to satisfy multiple missions or a single mission. In an intelligent attacker system an attack may attempt to cause failure to one or more of these missions.
- Design decision: options available for the system in the design stage. The decisions may be unique for different scenarios and missions.

- Produceability: the ability of the system to be produced or implemented given the associated costs or barriers.
- Supportability: the costs of maintenance and supply associated with the produced system.
- Reliability: the probability the system fails before the outside disturbance. Reliability may be dependent on the design decisions.
- Threat: the probability of an outside disruptive event acting on the system. In an intelligent attacker scenario this may be influenced by the mission and scenario in which the system operates.
- Survivability: the probability of the system to be functional or at a state which can be returned to previous performance levels.
- Resilience Response: the actions which are taken by the system or outside actors to return the system to previous performance levels for the original mission given the design options chosen.
- Flexibility Response: the actions which are taken by the system or outside actors to redefine the system to perform a new mission.
- Availability: the likelihood a system is able to perform its mission at a given time.
- Performance: how the system performs following a disturbance. This depends on the reliability, the survivability, and the response.
- Service life: the length of time the system can serve to fulfil its mission.
- Value: the return to scale across all performance measures, calculated with a value model.
- Life Cycle Cost: the monetary value of all costs throughout the service life of the system including the cost of design options to increase resilience.

- Affordability: the ability of the system to justify by value the life cycle cost for the options to be attractive.

The ERS modeling framework is an approach to resilience which directly compares alternatives in terms of value and cost in a way which is not being done currently. It incorporates elements of Holling's definition in its ability to survive. ERS encompasses Pimm's and Barker's definition of resilience in its measurement of recovery and goes a step further to relate it to value. ERS expands upon the idea of affordability discussed in the work of Neches and Madni. Finally, ERS explores the idea of "Broad Utility" with its relation to value as a system can change the direction of its performance vectors and still provide significant value. ERS is also unique in its ability to estimate the value of multiple decision interactions as alternatives could be compared individually or as separate configurations and each will return the same value versus cost perspective.

4. Network Case Study

4.1 Case Study Identification and Initialization

To apply the ERS framework to a network problem, several criteria for the case study network were determined. These criteria are; the case network must suffer from an external threat, must allow for design or redesign of the network or its systems in ways which could increase its resilience in respect to the definition of resilience, and must have at least one objective, quantifiable measure of performance. A network which fit these base criteria would be able to be optimized in a cost versus resilience design tradespace through the use of the ERS framework.

The identified criteria led to an examination of rail networks in Missouri. The Missouri rail networks match the criteria listed for an application of the ERS framework in the external threats the rail lines suffer such as weather, opportunities to design or redesign with increased resilience to these external threats such as weather hardening, and an objective, quantifiable performance measure in the amount of goods able to be successfully distributed by the rail network. The following rail network, **Figure 4**, from *The Association of American Railroads* provides the basis for the network in this case study.

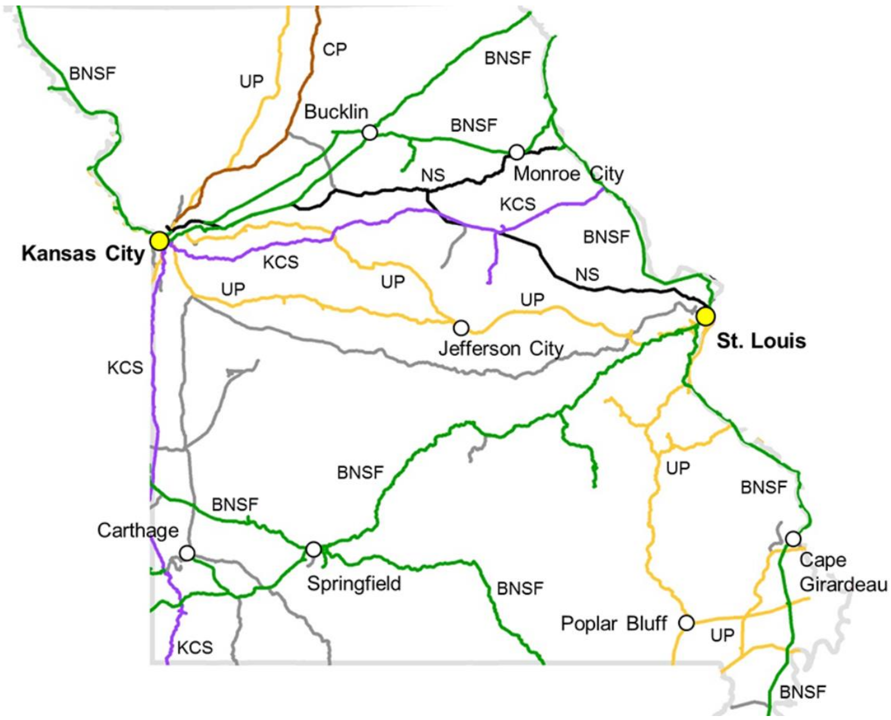

Figure 4: Missouri Rail Line Network [AAR]

While preserving all identified nodes identified in the Missouri rail line network model, a simplified network was determined the case study as seen in **Figure 5**.

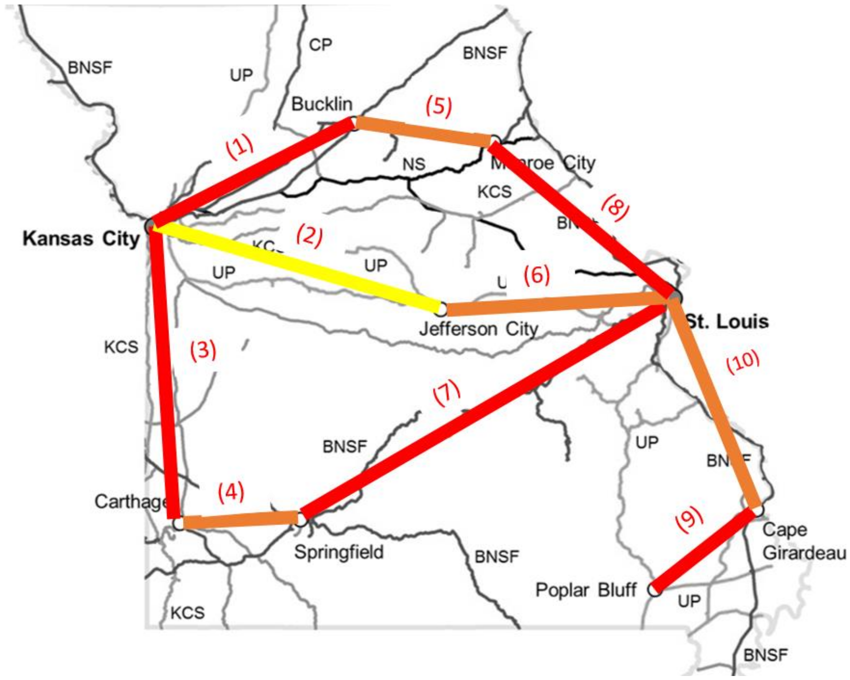

Figure 5: Simplified Rail Network Model

The model characterizes major rail lines connecting 9 listed nodes as a set of 10 edges where connections currently exist. In the case study, transportation of goods will occur along these lines.

For evaluation purposes, a type of good was needed to be measured in transfer between nodes. Again, the basis for the test data was drawn from the *Association of American Railroads* 2012 data which quantifies the amount of food products beginning in Missouri and leaving the state at 3,157,000 tons for the 2012 year [AAR]. This data led to a refined final version of the current network which can be seen in **Figure 6.**

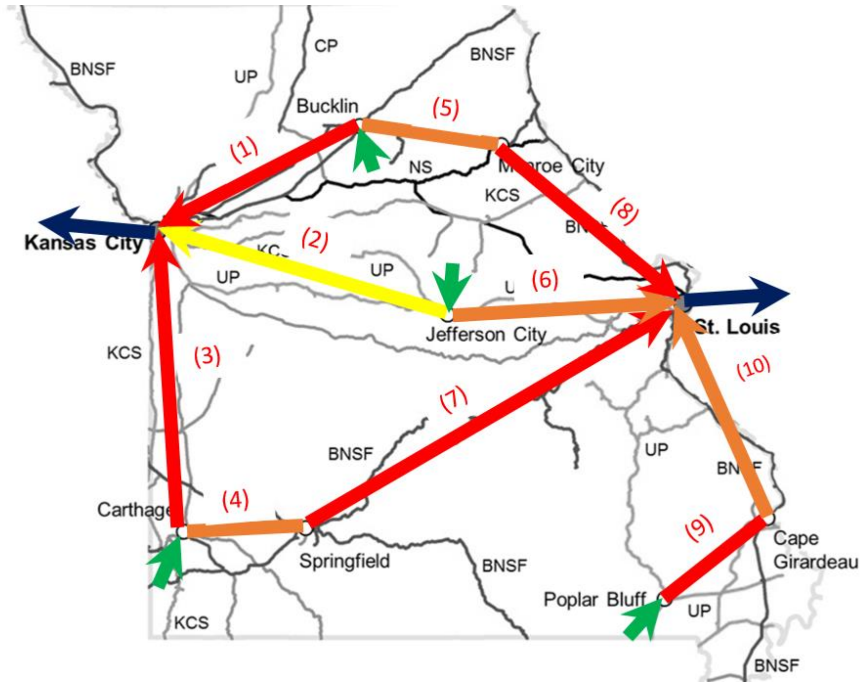

Figure 6: Current Network for Food Production and Transportation in Missouri

In this current network there are two demand nodes, St. Louis and Kansas City, and 4 input nodes; Bucklin, Jefferson City, Carthage, and Poplar Bluff. Links 1, 2, 3, 6, 7, 8, and 10 are classified as arcs as they end at one of the two demand nodes and links 4, 5, and 9 remain classified as edges. Total demand for this network is estimated at 3,150,000 tons per year or 8,569 tons per day between the two demand nodes. Max potential input for this network was notionally estimated at 5,000,000 tons per year or 13,699 tons per day allocated between the 4 input nodes. All edges and arcs were assumed to have sufficiently large capacity but each have varying cost of use per ton of food. It should be noted this data is notional for the purposes of this case study. Summary charts of this network initialization information can be found in **Table 1** and **Table 2**.

Node	Input (Tons/Day)	Demand (Tons/Day)
Bucklin	2,740	0
Jefferson City	4,110	0
Carthage	3,014	0
Springfield	0	0
Monroe City	0	0
Cape Giradeau	0	0
Poplar Bluff	3,836	0
Kansas City	0	3,090
St. Louis	0	5479
Totals:	13,699	8,569

Table 1: Node Input and Demand Summary Data

Arc/Edge	Cost ($/Ton)
1	34.25
2	43.01
3	38.63
4	15.62
5	17.81
6	36.16
7	58.90
8	35.07
9	22.47
10	32.33

Table 2: Arc/Edge Cost Summary Data

This data represents the initial parameters of the case study used for the evaluation of the ERS framework and remain constant throughout the evaluation.

4.2 Case Study Conditions and Methodology

Due to the limited scope of the case study, after analysis, only the following non-shaded nodes of the ERS influence diagram will be evaluated which can be seen in **Figure 7**.

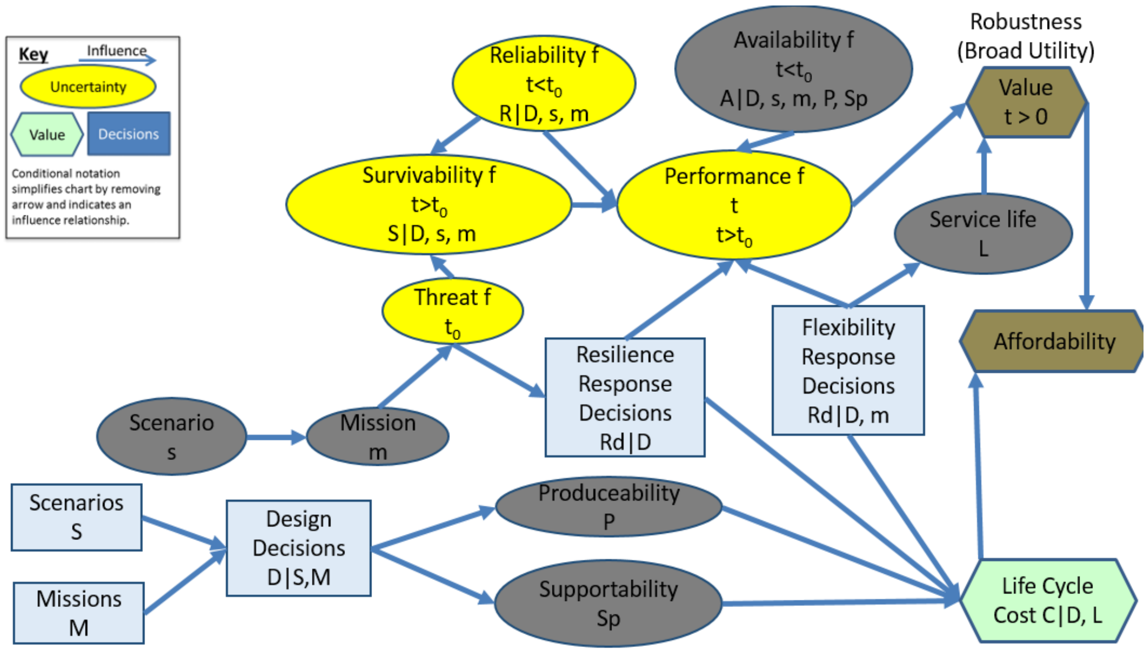

Figure 7: ERS Influence Diagram for Rail Line Case Study

The case study examined uses an unintelligent attacker model meaning the scenario and mission have no influence on the threat. This case study does not look at the supportability factor as a constraint was made which states all designs must be equally supportable. This constraint was added because the empirical data existed for a system already in place so any alternatives which could not be supported by the current system would not be acceptable. The assumption made for availability assumes that the rail lines are available if they have not failed. Finally, it was assumed the responses of the system would be focused solely on returning the functionality of the network to its original mission and flexible responses will not be considered. Values and scenarios used in this ERS case study are notional and based on empirical examples of threats to rail lines and actions taken to address these threats before or after a failure, unless specifically noted otherwise. The means of this testing was through the adapting of the ERS influence diagram and the case study constraints and assumptions into a decision tree. This adaptation can be seen in **Figure 8**.

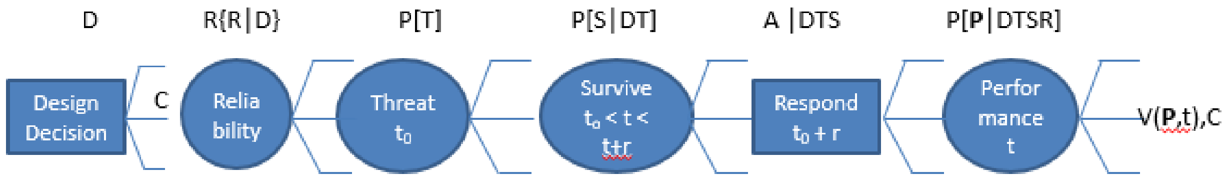

Figure 8: Modified ERS Decision Tree

This decision tree could then be expanded and solved, theoretically resulting in optimization of the design tradespace of the case study. Through the use of this technique, the performance of the ERS framework will be evaluated.

4.2.1 Identification of Case Study Threats

The method for evaluating ERS began with the identification of threats. It should be noted threat is not the starting node in the influence diagram however it is an independent node free from influence in an unintelligent attacker scenario. Threats identified directly influence the survivability of the network and the network's ability to respond. By identifying the threat potential first in an unintelligent attacker scenario design options can then be proposed which would directly mitigate the impact of the actualized threat. The first threat identified includes the loss of an edge or arc due to flooding, vandalism, or severe storm. The probability of the first threat to each edge and arc is 0.005 and is independent of any other failures. The duration of both threat one affecting arcs/edges and threat two affecting nodes was set at a constant 20 days given a normal response. The cost of a normal response action is $20,000 per day of failure. A simplification assumption was made which assumes no two edges or arcs may fail in the same year. Though a two edge or arc failing would be expected about once every 50,000 years, the additional complexity in the model and the corresponding multitude of decision tree branches for such a small probability would have had insignificant impact on the solving of the decision tree.

4.2.2 Identification of Case Study Options

The second step in the case study involved the identification of design options. With threats identified, the overarching purpose of the identified options focused on the mitigation in duration or likelihood of the threat, or the development of alternative paths for the network. The first design option identified is the hardening of edges and arcs against the previously identified threats. This first option may harden each arc or edge on an individual basis and there is no minimum to the amount of links which must be hardened if one link is hardened. The hardening of an edge reduces the probability of a failure from the unintelligent attacker by ten from 0.005 to 0.0005. An example of this hardening may be the addition of additional barricades along a rail line. This hardening is a one-time cost of $20,000. The second identified design option is the addition of emergency response teams. These teams reduce the duration of the effect of an actualized threat and allows for a rapid response which reduces the duration of effect by half of the normal 20 days. This emergency response team has a yearly cost of $2,000 but is unique in its ability to respond to any failure meaning the duration of actualized threat on any line is reduced by the one emergency response team. The cost of the emergency response team response is reduced to $12,000 per day of failure. The final identified design option is the addition of a new production node, Clinton, and the corresponding construction of an additional arc starting from Clinton and ending in Kansas City. The construction of this node and arc cost $1,074,126. Clinton has the notional capability to produce 1,370 tons of food per day. The arc has an associated use cost of $20.82/ton. As a final note in this evaluation only one design option may be selected. Though multiple selections could theoretically be evaluated using ERS, this overview is limiting one option selection for simplicity. In an application scenario the choosing of only one option could be required because of budget, labor, or other resource constraints. This also renders the influence node of produceability irrelevant as this assumption forces all options to be equally produceable.

4.2.3 Identification of Case Study Reliability and Survivability

The next step is to determine are the reliability of the network system and the survivability of the system given an assumed threat. For use in this deterministic case study, the network is assigned to be perfectly reliable or have reliability of one. In this case study, none of the options affect the reliability of the network therefore the reliability factor is constant for all branches of the decision tree. Conversely the network is assigned to totally fail under an actualized threat and survivability is zero in that no amount of food can be transported along that link. A survivability factor of zero or total failure was assumed as the most realistic as when track damage occurs trains cease all operations along the track.

4.2.4 Identification of Case Study Responses

The response of the system is the action taken after a failure has occurred. If a failure does not occur no response is taken. Because a failure can only occur due to an assumed threat of survivability zero, a response occurs to repair the failure. As described previously, the failure response of the system has a base duration of 20 days. It is assumed during the 20 days the functionality of the node or arc is zero and at the conclusion of the 20^{th} day is back to full operation. If the emergency response team has been chosen as described in the case study options, then it is assumed the functionality of the node or arc is zero for the duration of 10 days and after 10 days is fully operational. If a response is required, the cost per day of the response action is notionally set at $5000. This is true for both a normal or emergency response as the addition cost of an emergency response is built into its yearly cost listed in the case study options.

4.2.5 Identification of Case Study Performance and Value Measures

The final step in the method for evaluating the case study involves identifying the performance and value measures needed to draw conclusions about the solution. The performance of the network will be measured by the ability of the network to satisfy the demand at both of the demand nodes. Any failure to meet this demand would result in fractional performance. The value of the network is measured by the total cost to use and maintain the network.

4.2.6 Case Study Decision Tree

The notional constructs which have been described serve to create the conditions for the case study. The conditions serve to provide the calculations and branches of the decision tree which is the basis for this case study evaluation. The case study generic decision tree can be summarily seen in **Figure 9**.

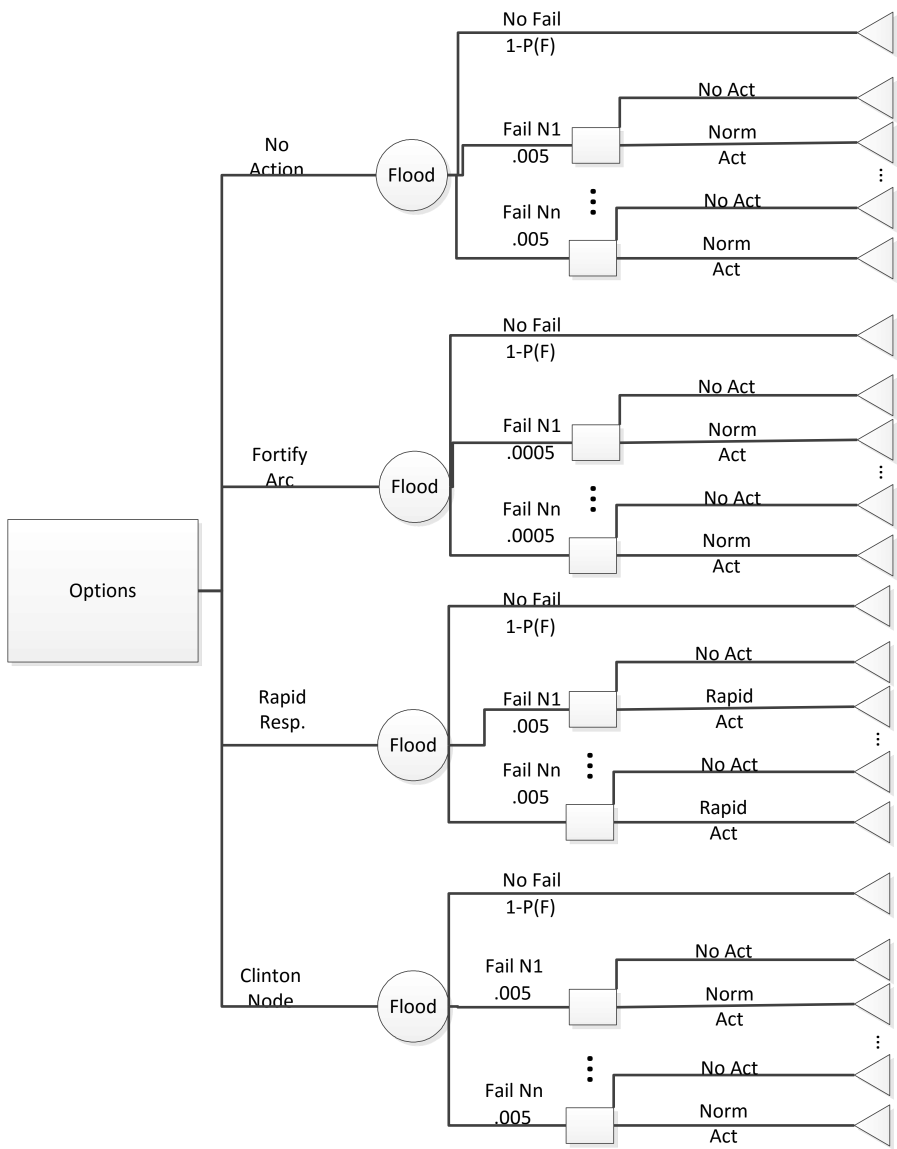

Figure 9: Case Study Decision Tree

4.2.7 Case Study Modeling

To solve this decision tree, a two-step Excel network model was built to be solved as a linear program using Microsoft Excel's Solver add-in. A two-stage model was selected as no input node was further away than two arcs from an output node and, as shown in **Figure 6**, there is no possible path for a good to travel a third consecutive time. The design of the two-stage model was such that each scenario of failure given the discussed options could be created and solved for the cost associated with each branch of the decision tree. **Figure 10** and **Figure 11** are a high level image of the two-hop network model built in Excel. Yellow shaded cells represent input parameters, shaded blue cells are the changeable variables of the model, and shaded green cells are calculations. The total cost was represented by the addition of Stage 1 and Stage 2 Costs.

					To						
From	Kansas City	Bucklin	Jefferson City	Carthage	Monroe City	Springfield	St. Louis	Cape Giradeau	Poplar Bluff		
Bucklin	34.25	NA	NA	NA	17.81	NA	NA	NA	NA		
Jefferson City	43.01	NA	NA	NA	NA	NA	36.16	NA	NA		
Carthage	38.63	NA	NA	NA	NA	15.62	NA	NA	NA		
Springfield	NA	NA	NA	15.62	NA	NA	58.90	NA	NA		
Monroe City	NA	17.81	NA	NA	NA	NA	35.07	NA	NA		
Cape Giradeau	NA	NA	NA	NA	NA	NA	32.33	NA	22.47		
Poplar Bluff	NA	NA	NA	NA	NA	NA	NA	22.47	NA		
From	Kansas City	Bucklin	Jefferson City	Carthage	Monroe City	Springfield	St. Louis	Cape Giradeau	Poplar Bluff	*Shipped From*	Production
Bucklin	0	0	0	0	0	0	0	0	0	0	2,740
Jefferson City	0	0	0	0	0	0	0	0	0	0	4,110
Carthage	0	0	0	0	0	0	0	0	0	0	3,014
Springfield	0	0	0	0	0	0	0	0	0	0	0
Monroe City	0	0	0	0	0	0	0	0	0	0	0
Cape Giradeau	0	0	0	0	0	0	0	0	0	0	0
Poplar Bluff	0	0	0	0	0	0	0	0	0	0	3,836
Shipped To	0	0	0	0	0	0	0	0	0		13,699
Required	3,090	0	0	0	0	0	5479	0	0	8,569	
Stage 1 Costs	$0.00										

Figure 10: Excel Network Model Step 1

					To						
From	Kansas City	Bucklin	Jefferson (	Carthage	Monroe C	Springfielc	St. Louis	Cape Gira(	Poplar Bluff		
Bucklin	34.25	NA	NA	NA	17.81	NA	NA	NA	NA		
Jefferson City	43.01	NA	NA	NA	NA	NA	36.16	NA	NA		
Carthage	38.63	NA	NA	NA	NA	15.62	NA	NA	NA		
Springfield	NA	NA	NA	15.62	NA	NA	58.90	NA	NA		
Monroe City	NA	17.81	NA	NA	NA	NA	35.07	NA	NA		
Cape Giradeau	NA	NA	NA	NA	NA	NA	32.33	NA	22.47		
Poplar Bluff	NA	NA	NA	NA	NA	NA	NA	22.47	NA		
From	Kansas City	Bucklin	Jefferson (	Carthage	Monroe C	Springfielc	St. Louis	Cape Gira(	Poplar Bluff	*Shipped Fr*	Productior
Bucklin	0	0	0	0	0	0	0	0	0	0	0
Jefferson City	0	0	0	0	0	0	0	0	0	0	0
Carthage	0	0	0	0	0	0	0	0	0	0	0
Springfield	0	0	0	0	0	0	0	0	0	0	0
Monroe City	0	0	0	0	0	0	0	0	0	0	0
Cape Giradeau	0	0	0	0	0	0	0	0	0	0	0
Poplar Bluff	0	0	0	0	0	0	0	0	0	0	0
Shipped To	0	0	0	0	0	0	0	0	0		0
Required	3,090	0	0	0	0	0	5479	0	0	8569	
Stage 2 Costs	$ -										

Figure 11: Excel Network Model Step 2

The mathematical model basis for what was entered into Excel Solver consisted of three sets: set N consisting of all nodes number {1,…,n} where $i, j \epsilon N$, set A consisting of all possible directed arcs where $(i, j) \epsilon A$, set b_i which consists of the set of constant supply or demand of each node where if $b_i > 0$ the node is a supply node, if $b_i < 0$ the node is a demand node, and if if $b_i = 0$ the node is a transshipment node, finally set c_{ij} which consists of the set of constant costs associated with the shipment of goods along each arc. The full list of members for each of these sets can be viewed in the appendix. The objective of this model was to minimize the cost of the shipment of food which can be seen in **Equation 1**.

$$Minimize: \sum_{(i,j)\in A} c_{ij}x_{ij}$$

Equation 1: Linear Program Objective Function

Where the variable x_{ij} represents the amount of flow which is shipped along arc (i, j). This objective function is subject to the following constraints, seen in **Equation 2,** and **Equation 3**.

$$\sum_{j=(i,j)\in A} x_{ij} - \sum_{j=(i,j)\in A} x_{ji} \leq b_i \quad \forall\, i \in N$$

Equation 2: Conservation of Flow Along Arcs

$$x_{ij} > 0; \;\; Integer$$

Equation 3: Constraints on Variable x

The second equation states the flow from one node to a second node must be conserved. By this, in a transshipment node, x_{ij} must equal x_{ji} as the demand and supply at this node is 0 so the flow in must equal the flow out. For $b_i > 0$ the flow out, x_{ij}, must be greater than the flow in. For $b_i < 0$ the flow in, x_{ji}, must be greater than the flow out to satisfy demand. The constraint in the second equation allows for the possibility that demand is over satisfied (e.g. receives -12 units when b_i is -10 units) however this circumstance will not happen in this model as the objective is to minimize cost and the flow of additional units would unnecessarily increase costs. The third equation constrains the variable x to be a positive integer. The mathematical model was converted into equations for the Solver tool which can be seen in the appendix. To quickly solve for each possible branch identified in the decision tree a Visual Basic macro was written to loop the Solver program with each arcs failed. It should be noted to simulate failure the cost of using the arc was made arbitrarily expensive at $1,000,000 per ton to force the cost minimization model to use another arc if such a solution could exist. The code for this Visual Basic macro can also be found in the appendix. In addition, for additional analysis a payback period analysis will be performed where applicable in accordance with **Equation 4.**

$$Payback\ Period = \frac{Initial\ Investment}{Cash\ Inflow\ Per\ Year}$$

Equation 4: Payback Period Equation

4.3 Case Study Results

The macro consisting of the Solver network model was run first with the unmodified two-step model and a second time with the new Clinton node added. The results of each of these solutions were output into a table which can be seen in the appendix. The case study decision tree was expanded to show the value of each branch in terms of total cost per day averaged over a 1-year time interval. The expanded decision tree for the No Action option in **Figure 12**. The expanded decision tree branches for the other three options can be seen in the appendix.

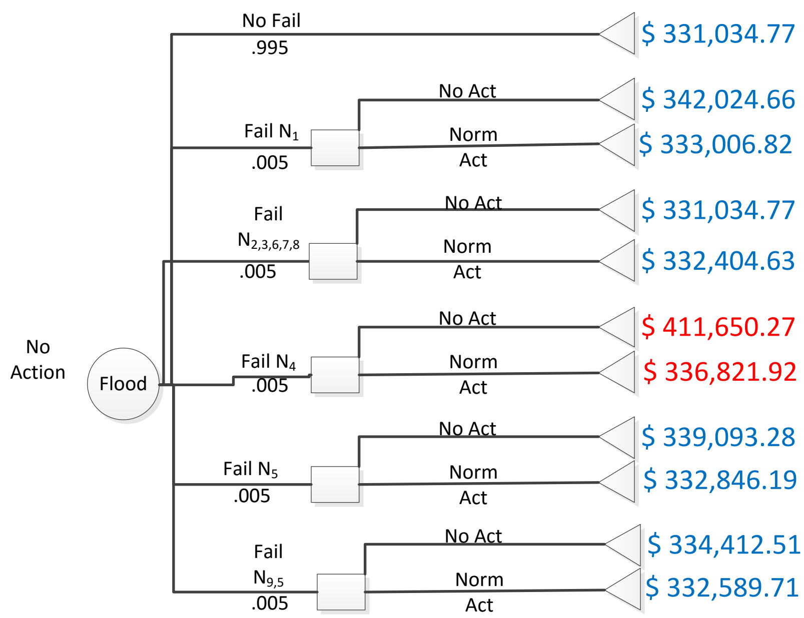

Figure12: No action option and associated branch costs

For each option, the network could be solved despite any single arc failure. In addition, the failure of arc 4 (Jef-KC) was the costliest. Given only one node could fail in a given year, each option value was calculated using a worst-case failure scenario of the arc 4 failure to assess which option would be the most resilient and least costly in this scenario. The summary calculations of the four options can be seen in **Figure 13.**

Figure 13: Decision Tree Option Calculations

4.4 Case Study Results Analysis

Based on the calculations of the decision tree, in this case study the addition of the Clinton node would be the option to be selected as it is significantly less expensive on a per day per year cost than all other alternatives. The decision tree has also provided the ability to rank alternatives by cost so that after the Clinton addition the next preferred option is No Action followed by Fortify Arc and Rapid Response. A closer examination reveals the reason the Clinton node is preferred is it reduces non-failure operating cost by over $20,000 dollars per day before accounting for purchase costs and $19,000 after accounting daily for the $1,000,000. The addition of the Clinton node increases the agility of the network and diversifies to protect from the impact of high-value arcs such as arc 4.

All other resilience options performed worse than the course of taking no action. The ERS decision tree reveals the cause of this to be the low probability of failure versus the impact. For the non-Clinton options the failure of arc 4 cost an additional $5,787 per day for the year but at a probability of failure at 0.005 the expected cost per day per year is $29.94 per day per year. This $29.94 per day per year is the breakeven point for any resilience alternative cost of normal operation per day. None of the non-Clinton alternatives was equal to or less than this value. Clinton, through significant investment, had an expected cost of $-18,945 per day per year and was thus the clearly preferred alternative.

Finally, payback period analysis was performed for all options. No Action used no investment and thus no relevant payback analysis. The Fortify Arc and Rapid Response option did not save any money for the investment made and thus hold an infinite payback period. Finally, the Clinton node's payback period can be calculated using **Equation 4** to show Payback Period = $1,075,126 / $6,915,019 which is approximately 0.16 years.

4.5 Case Study Conclusion

The ERS framework in a modified decision tree worked well in identifying the most attractive resilience option. In addition, the ERS framework encouraged well-rounded planning and consideration in the design phase in requiring the examination of influences on the network. The

ERS framework in the case study fit well with the definition of resilience as it examines the effect of outside forces and provides quantifiable context for each of the resilient options in terms of cost. In this case study, ERS identified an alternative which may not have been intuitive. The Clinton node required a significant amount of investment and without this analysis conducted the fear of the Clinton arc failure or overestimation of the time to fix may have driven the design team to a non-optimal conclusion. In this case study, ERS presented an encompassing picture of the costs of the problem and allowed for a clear recommendation to be made based on life cycle costs.

5. Conclusion

The ERS framework strives to fill the gap in current resilience literature. Current resilience literature ignores multivariate objectives, may confuse resilience with reliability, focuses solely on survivability, or fails to consider cost when evaluating decisions. ERS incorporates all of this into the framework and return results in an actionable value versus cost analysis to enable affordability analysis. ERS can additionally be modeled with natural hazards or intelligent adversaries. All of these features of ERS allow significant flexibility in the types of systems and availability of probabilistic estimates to quantify value. In this paper, a case study was used to explore the ability of the ERS framework to adapt and produce results with optimization. ERS includes a value model or multiple objective decisions. This flexibility allows the ERS framework to be applied to many areas in addition to network models such as supply-chains, weapon systems, and other multi-functional systems. The ERS framework as described in this paper is a useful (Railroads) approach for the purposes of engineering resilient systems.

6. Further Research

In future work relative to the case study however, multiple values could be used to provide context for the value of the system. Perhaps it is more valuable for Poplar Bluff to have production than Jefferson City and that texture to the problem was lost in this cost analysis. ERS provides the foundation for value to be measured and an excellent future use of this case study would be the calculation of the non-cost value of each option plotted with respect to the calculated cost done in this study to determine the affordability of each project.

One area for further research with ERS is the function of time in the model. The value of the design decisions between a network which fully recovers in 2 years is vastly different to the decisions which allow the network to fully recover in 2 weeks. This significance has the potential to be lost given the current framework as special care must be given to associate the value over time. Should an indefinite point of time *t* be chosen in the framework the value associated with a quick recovery would be lost. Thus one area of further research would be to establish methods for evaluating value over time for the various applications of the ERS framework.

7. References

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