Risk Quadruplet: Integrating Assessments Of Threat, Vulnerability, Consequence And Perception For Homeland Security

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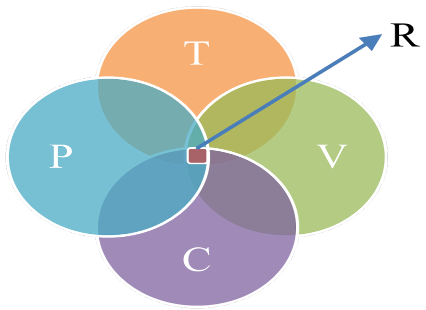
Abstract: Risk to a critical infrastructure, is considered to be a function of threat, vulnerability, and consequence. It has long been a challenge to integrate these three disparate assessments to establish an overall picture of risk to a given asset. There are many different types of risk assessments performed on assets and those different assessments explore risk from different perspectives. Is the asset a critical power plant, essential to electricity generation? Is it a large dam, critical to the water supply? Is it a major road, critical to transportation? Or is it a major tourist attraction, critical to national morale? Or, like the Hoover Dam, is it all of these things? Which risk assessment is "right"? How can all of these risk assessments be integrated? Are certain risk assessments more important than others? Obviously, risk is a function of our perceptions, which can influence our understanding of threat, vulnerability, and consequence. A risk quadruplet methodology is proposed to systematically integrate risk perceptions with assessments of threat, vulnerability, and consequence in a traceable, reproducible, and meaningful manner. The risk quadruplet model is explored by leveraging Evidential Reasoning technique (MCDA), along with simulated data for threat, vulnerability, consequence, and perception.

Keywords: Systems Engineering, Risk Management, Critical Infrastructures, Perception, Evidential Reasoning

1. INTRODUCTION

Many talk about risk as a function of threat, vulnerability, and consequence [4, 9]. Multiple risk assessments, which seek to assess threat, vulnerability, and consequence to a specific asset or facility, could vary widely [6]. Risk assessments could be based on risk data or perceptions. The data from one assessment could be drastically different from the data of another assessment; one assessment could incorporate factors such as whether the risk was voluntary or involuntary, while another might attempt to calculate risk using traditional risk equations [8].

Figure 1. Proposed Risk Quadruplet ©.



$$R = f(T, V, C, P)$$

There is also confusion about the definitions of threat, vulnerability, and consequence, let alone how to assess those nebulous concepts. The many different definitions of these concepts can drastically affect risk calculations. Threat could be viewed as a single scenario, or the likelihood of that scenario. Vulnerability could be seen as a probability, or it could be viewed as a state of the system, from which conditional probabilities of threat might be derived. And there are many types of consequences (economic, environmental, or in some cases loss of life), which must all be assessed in order to give the best possible overall risk picture. Most of this confusion arises from our inherent perceptions. There is, inevitably, an element of subjectivity to any risk assessment, and that subjectivity is currently missing from the risk assessment approach. It only makes sense to integrate our T, V, and C assessments with our perceptions into an overall, improved, risk assessment approach, thus defining a new risk paradigm. A risk quadruplet is proposed in this dissertation that incorporates threat (T), vulnerability (V), consequence (C), and perception (P) (Figure 1).

We must first define what we are trying to protect, which is the collection of critical infrastructure (CI), key resources (KR), and key assets (KA). Then we must define the way in which we shall protect those CIKRKA, which is to determine their overall risk as a function of T, V, C, and P, then rank them accordingly, such that risk mitigation actions can be prioritized and implemented. Figures 2-3 provide a list of terms and their intended meanings when used throughout this paper. Some of these definitions are pulled straight from the literature. Others are modified from definitions provided in official, government documents, such as the Department of Homeland Security (DHS) Risk Lexicon [7]. All of these definitions, as they are presented here, reflect the intents and purposes of this research.

Figure 2. CIKRKA Definitions.

CI	Government and private systems essential to the operation of our nation in any or all aspects of the lives of its citizens (health, safety, economy, etc.), such as utilities, facilities, pipelines, etc.
KR	Public or private resources essential to the operation of our nation's government and economy, such as fuel or goods.
KA	Those buildings, geographic regions, monuments, or icons, whose destruction would cause a crushing blow to our nation's ego, morale, and identity, but which are not essential to the operation of our nation, such as the Washington Monument or the Statue of Liberty.

The belief is that the currently accepted homeland security risk triplet (T, V, and C) is inadequate for characterizing risk to CIKRKA and that a risk quadruplet should be explored to incorporate perception into the current risk assessment approach. But exactly how those components of risk are integrated must be decided. The improved risk assessment integration methodology, based on T, V, C, and P assessments, will be developed and presented. This methodology will systematically integrate all four assessments in a meaningful, traceable, and reproducible approach using systems engineering techniques such as risk analysis and Multi Criteria Decision Analysis (MCDA). The end result will be a ranking of CIKRKA, based on the risk quadruplet methodology. This will allow for a more comprehensive ranking of these disparate entities along multiple risk scales. This ranking system will improve resource allocation for risk mitigation efforts in support of homeland security and homeland defence missions.

Figure 3. Risk Definitions.

Threat	Threat of a risk scenario to an asset; threat of an intentional risk scenario is generally estimated as the likelihood of an attack (that accounts for both the intent and capability of the adversary) being attempted by an adversary; for other risk scenarios, threat is estimated as the likelihood that the risk scenario will manifest; however, threat can also be estimated qualitatively as perceived likelihood
Vulnerability	Ability of an asset to endure a risk scenario despite physical features, operational attributes, characteristics of design, location, security posture, operation, or any combination thereof that renders an asset open to exploitation or susceptible to a given risk scenario; can be estimated qualitatively, or quantitatively, as the likelihood of a successful risk scenario given the risk scenario is identified, which implies that vulnerability is also related to resilience
Consequence	Effect of a successful risk scenario on an asset; consequence is commonly assessed along four factors: human, economic, mission, and psychological, but may also include other factors such as impact on the environment; consequence can be measured quantitatively if data exists, but can also be measured qualitatively either along a set of scales or along a single integrated consequence scale for which all consequence factors are considered as a whole

Perception	Subjective judgment about the severity of a risk scenario to an asset; may be driven by sense, emotion, or personal experience; generally measured qualitatively
Risk	Potential for an unwanted outcome resulting from a risk scenario, as determined by the T, V, C, and P of that risk scenario to an asset; often measured and used to compare different future situations, as well as to rank assets for the purposes of risk mitigation and budgeting for emergency preparedness, response, and recovery

2. RISK QUADRUPLET

Model. The risk quadruplet consists of three phases (Figure 4). The first phase is the perception assessment. The second phase consists of T, V, and C assessments. The final phase is the assessment integration phase, where the assessments of T, V, C, and P are all assimilated.

Figure 4. Risk Quadruplet Phases ©.

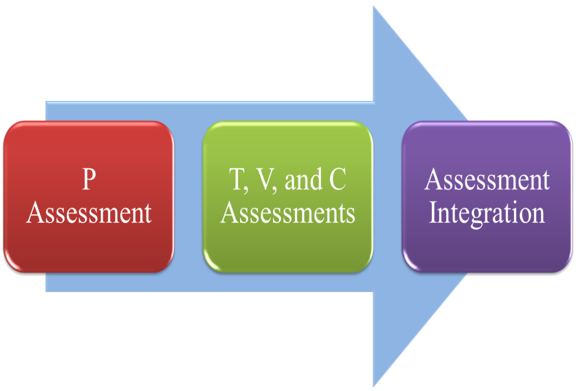
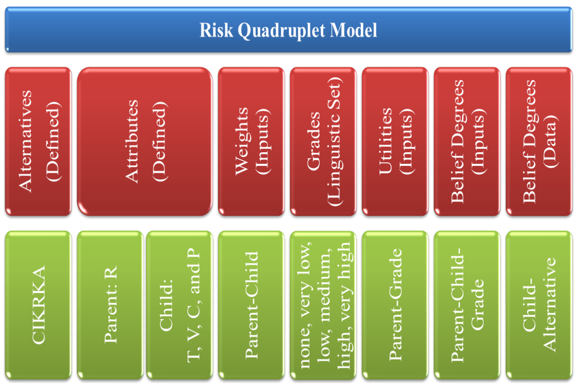


Figure 5. Risk Quadruplet Model.



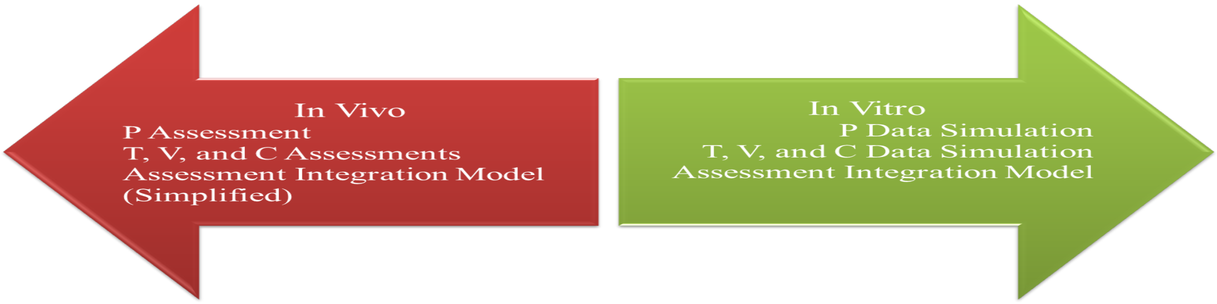
The risk quadruplet model to integrate the perception, T, V, and C assessments is given in Figure 5. It consists of alternatives, attributes, weights, grades, utilities, and belief degrees. The alternatives, in our case, are a set of CIKRKA assets. Further defining the model, we have a parent attribute denoted as risk (the overall value we are seeking to calculate), as well as child attributes (T, V, C, and P), all of which are part of the risk function. We also define grades for the child attributes, as they relate to the alternatives, using a linguistic set (none, very low, low, medium, high, very high). Weights are chosen to relate the child attributes to the parent attribute. Utilities are assigned to relate the grades to the parent attribute. The first set of belief degrees relates grades to the parent and child attributes. In other words, does the linguistic set choice of none for T, V, C, and P directly correlate to a linguistic set choice of none for the parent attribute of risk? What about the choice of very low? If so, the belief degrees assigned to relate those relationships would be higher than those relating a grade of none for a child attribute to a grade of high for the parent attribute.

The second set of belief degrees are derived from the assessment data and are used to relate grades to the alternatives within each child attribute. For the perception assessment, the belief degrees are the proportions calculated based on how many respondents selected each of the linguistic set choices in our adapted psychometric survey to collect risk perception data. For the T, V, and C assessments, the belief degrees would be translated to the linguistic set if the data was leveraged from historical assessments, or that data could be collected in a new set of assessments using the linguistic set.

Methodology. With the model defined, the next problem was how to test its viability. It would be ideal to validate the risk quadruplet methodology in vivo or in the real world, using real data, collected anew, with a full scale model of multiple CIKRKA to compare and rank. However, due to the constraints of scope, cost, and schedule, this type of model Verification, Validation, and Accreditation

(VV&A) is beyond the scope of our research. Instead, we intend to explore this model in vitro, literally in a petri dish, although in our case, the petri dish is a computer (Figure 6).

Figure 6. Risk Quadruplet Viability Testing Options: In Vivo versus In Vitro.



The proposed in vivo risk quadruplet methodology (Figure 7) would consist of the same three phases (assessment of perception; assessments of T, V, and C; and assessment integration) as previously defined (Figure 4). However, we have included additional details on the approach for deploying this methodology. The first phase would consist of a simplified psychometric survey, which would be deployed with a small group of subject matter experts and stakeholders. In order to conduct this survey, we chose Inquisite, a software package capable of deploying surveys online and collecting data [2]. We then designed a questionnaire, choosing a region, risk scenario, and a selection of CIKRKA assets to scope the survey. We also decided to limit the survey (and thus the overall in vivo model) to three CIKRKA assets, and we chose an example for each of the assets. Additionally, to further scope the survey and model, we selected a single risk scenario. We also chose a linguistic set for the survey responses (none, very low, low, medium, high, very high), which would be consistent with the Evidential Reasoning (ER) model we developed.

Figure 7. Risk Quadruplet Methodology (In Vivo).

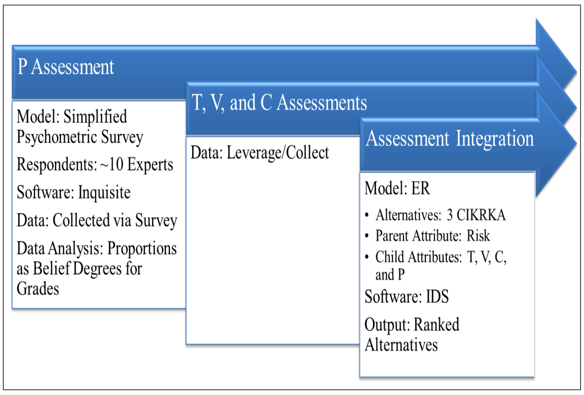
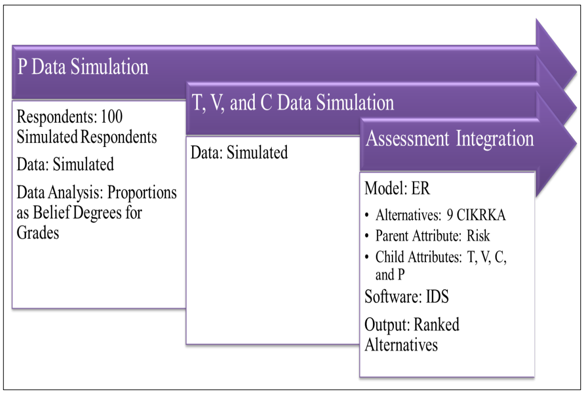


Figure 8. Risk Quadruplet Methodology (In Vitro).



The second phase assumes that the data for T, V, and C could be leveraged from previous assessments, or that those assessments could be conducted. The goal of the risk quadruplet is not to determine how to conduct these assessments, as they are already being conducted and many approaches already exist for doing so, such as the Infrastructure Vulnerability Assessment Model [1]. Rather, the point of the risk quadruplet is to determine how to integrate these assessments with the perception assessment we proposed for the first phase of the methodology. The final phase of the in vivo risk quadruplet methodology focuses on integrating these assessments. The ER model is defined with the three alternatives (CIKRKA assets) used in the Inquisite survey. The parent attribute and child attributes, weights, utilities, and belief degrees are also defined. And the final belief degrees would be input into the model based on the data collected from the perception, T, V, and C assessments. Finally, Intelligent Decision System (IDS) was the software selected for implementing the ER model, so the alternatives, attributes, weights, utilities, and belief degrees would be input into IDS for analysis [3].

The in vitro methodology is crafted to parallel the in vivo methodology (Figure 8) consisting of the same three phases as the in vivo risk quadruplet methodology; however, there are some obvious differences. The in vitro approach will rely on simulated data to emulate the real world, allowing us to explore the model without risking the exposure of sensitive (in vivo) information that might otherwise jeopardize the very CIKRKA we seek to protect. For the first phase of the in vitro approach, we simulated the perception assessment data using 100 virtual respondents. Rather than rely on leveraging or collecting data for T, V, and C data in the second phase, we simulated this data, as well. Lastly, the assessment integration phase remains similar to the in vivo approach. However, since we are not constrained to the limits of the survey respondents, we increase the number of CIKRKA alternatives. The same software, IDS, would be used to input the data and analyze the results [5]. The resulting analysis would provide a ranked output of CIKRKA assets (alternatives) based on their parent attribute scores (risk). The generalized risk quadruplet methodology (whether in vivo or in vitro) is given in Figure 9.

Figure 9. Risk Quadruplet Methodology.

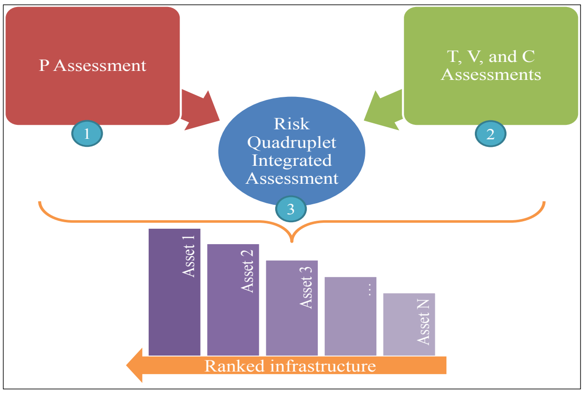
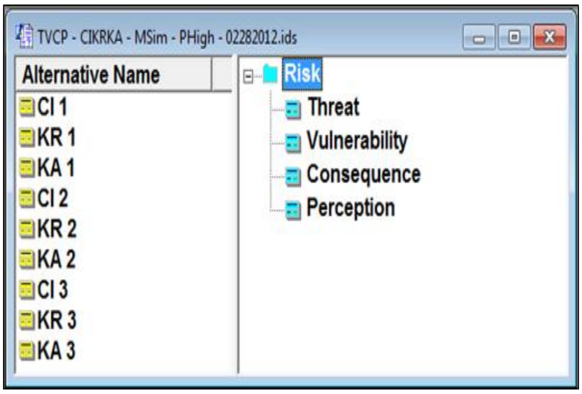


Figure 10. Risk Quadruplet Model (In Vitro).



Risk Quadruplet Viability Testing (In Vitro). The in vitro approach for testing the viability of the risk quadruplet methodology relies on simulated data. However, this research is still informative and allows us to explore how the model behaves prior to an in vivo deployment of the methodology. With IDS we are able to build an ER model for the risk quadruplet using a combination of collected perception data and simulated T, V, and C data [2, 3].

An example of how this model appears in IDS is shown in Figure 10. Each of the attributes (T, V, C, and P) were defined and graded using the same linguistic scale. Utilities for the overall or parent attribute (risk) were assigned to these grades (from our linguistic set of none, very low, low, medium, high, and very high) as shown in Figure 11. For our purposes, a risk grade of none would be ideal and thus would receive a Utility of 1. The remaining grades were ranked accordingly. Utilities, unlike probabilities, need not sum to 1.

Figure 11. Grades and Utilities

Grade	*Utility [0,1]*
None	1
Very Low	.9
Low	.7
Medium	.5
High	.3
Very High	.1

In the interest of keeping this model simple, belief degrees to relate parent and child attributes were assigned using the identity matrix (Figure 12). These belief degrees are not the same belief degrees that are selected by respondents during data collection when they chose the grade they deem appropriate for a given combination of alternative and attribute (collected using the simplified psychometric survey).

Figure 12. Belief Degrees for Relating Parent and Child Grades

Parent Grade/ Child Grade	None	Very Low	Low	Medium	High	Very High
None	1	0	0	0	0	0
Very Low	0	1	0	0	0	0
Low	0	0	1	0	0	0
Medium	0	0	0	1	0	0
High	0	0	0	0	1	0
Very High	0	0	0	0	0	1

Weights are then used to relate the child attributes to the parent attribute. This can be done using visual scoring or using a pairwise comparison of attributes. For the in vitro viability testing, we used the visual scoring approach. Visual scoring is an ad hoc approach, which allows us to visually compare the weights of the different attributes against each other. IDS, initially presents the attribute weights as equal across all attributes. Perception might not be considered equally important by the stakeholders, as the other attributes. We adjusted the weights to create a low perception version of the model for which the perception attribute weight was set to be approximately half as important as the other attributes (where the other attributes were weighted equally and the sum of the weights were constrained to sum to 1) as shown in Figure 13. Other versions of the model will be explored later.

Figure 13. Attribute Weights Using Visual Scoring Attribute (Low Perception)

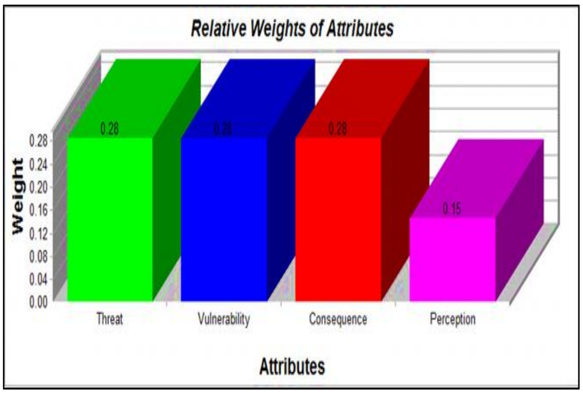


Figure 14. Ranking of Alternatives on Risk (Low Perception)

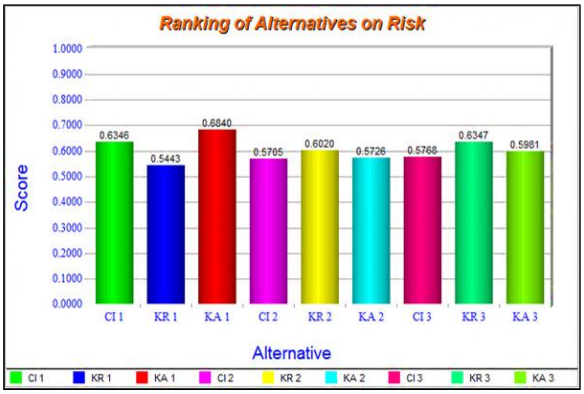


Figure 15. Alternative Performances Across Child Attributes (Low Perception)

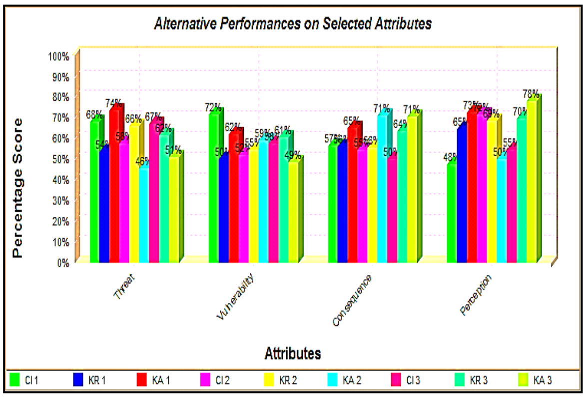
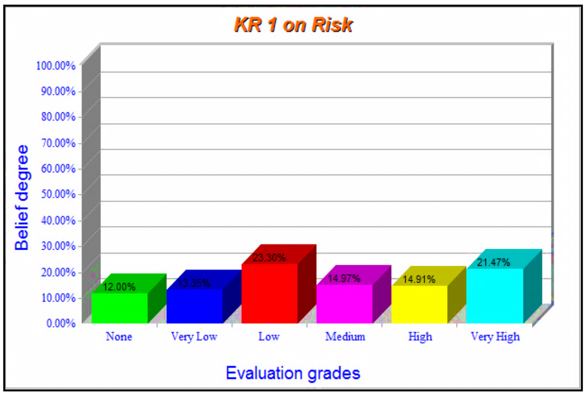


Figure 16. KR 1 Grades for Risk Attribute (Low Perception)



Using simulated data for T, V, C, and P, the IDS model can now rank the nine alternatives (CIKRKA) based on the attributes, grades, and associated utilities, belief degrees, and weights. Figure 14 shows a comparison of the nine CIKRKA alternatives based on their respective overall risk scores. But Figure 15 shows this comparison broken down by the attributes of risk (T, V, C, and P).

Figure 16 shows the breakdown of grades for KR 1 (with the lowest overall risk in the model for which perception was weighted lower than the other attributes) at the parent attribute level (risk). This gives an overall distribution of the calculated grades and belief degrees for risk, based on the grades and belief degrees for the child attributes (T, V, C, and P). Charts can be created by respondents to explore the, degree of belief, indicator.

Model Validation. A preliminary validation of the assessment integration model selected for the risk quadruplet was conducted to determine the impact of selected values, such as weights, utilities, and belief degrees on the ER model. Validation ensures that the model is useful [3]. In other words, the model should address the correct problem and provide accurate information about the system or phenomenon being modeled. Validation of complex models involves demonstrating that the model has the appropriate underlying relationships to permit an acceptable representation of the real world, often exploring the range of inputs under which the risk quadruplet model results are useful.

Figure 17. Risk and Attributes Radar Plots by Alternative (Low Perception)

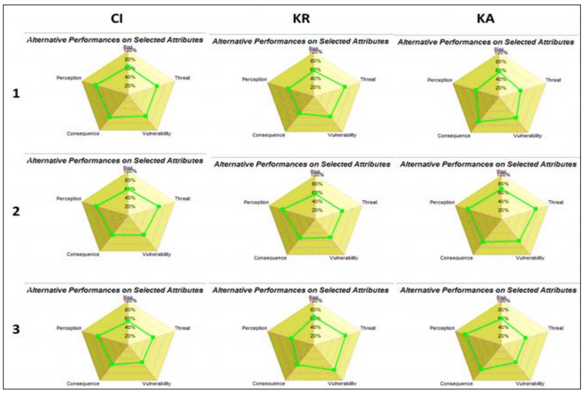
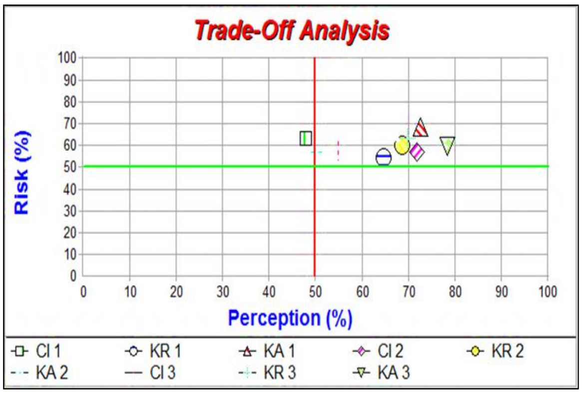


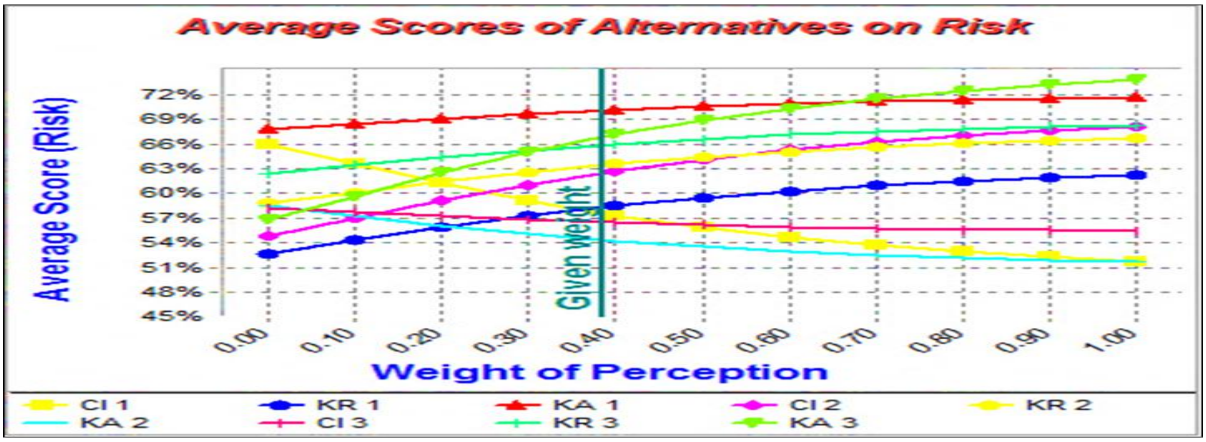
Figure 18. Risk and Perception Trade-Off Analysis (Low Perception)



IDS offers some built-in sensitivity analyses and even though this data is simulated, it is still interesting to explore the results as it is obvious how they could be invaluable to the in vivo risk quadruplet methodology [2, 3]. The radar plot shows the values of all of the child attributes, alongside the parent attribute, so it is easy to see which of the child attributes is driving the overall risk score (Figure 17). We can see, for example, that consequence shows some influence on KA 1, while perception affects KR 2 for the low perception model. Figure 18 displays a trade-off analysis chart, which shows the overall risk scores for the nine CIKRKA alternatives, as well as the perceived scores for the low perception model. We see that the overall risk score for KA 3 was 60% even though it was perceived to be 78%, whereas the overall risk score for CI 1 was approximately 63% while it was only perceived to be 48%.

More formally, IDS can produce sensitivity analyses based on the individual child attributes [2, 3]. The graphic given in Figure 19 displays the overall risk scores for each alternative as the weight of the perception attribute is varied from 0 through 1 (we adjusted the y-axis scale, used for the overall risk score, in order to better see the relationship between the weight for perception and the risk rankings). Since we conducted this sensitivity analysis from the high perception model, that value is displayed as a vertical line, denoted as “Given weight”, on the chart so that users can compare their current alternative risk scores and rankings to those that would be produced by adjusting the weight for perception. It is interesting to note that the overall risk score for each asset varies with the weight of the perception attribute, but it is not a linear relationship. And while the majority of the alternative risk scores increase as the weight of perception increases, three of the assets show a negative correlation (CI 1, KA 2, and CI 3).

Figure 19. Sensitivity Analysis of Perception



IDS can also produce sensitivity analyses of belief degrees based on adjusting the child attribute weights [2, 3]. We explored only two alternatives from the high perception model: CI 1 and KA 3, ranked lowest and highest on their overall risk scores, respectively (Figure 20). This shows the belief degrees (our simulated data) for the perception attribute related to the grades (our linguistic set) based on the weights input for the child attributes of T, V, C, and P. However, even as we adjust the child attribute weights, the belief degrees do not change, and with good reason. If we recall the belief degree values we chose for relating child attributes to parent attributes (Figure 15), we used the identity matrix; the belief degrees input from our simulated data for the perception attribute would not be impacted by adjusting the child attribute weights. IDS can also produce sensitivity analyses based on the data, itself (Figure 22). The first graph displays the belief degrees input for each grade (from our simulated data) for a selected alternative. We selected KA 3, which received the highest perception score (in the model for which perception received a higher weight). The second graph displays the perception score for all of the alternatives (other attributes, such as T, V, and C can also be explored as desired). Although we did not drastically alter the belief degrees from the original values, we still see a marked change in the overall perception score for KA 3, which dropped from 78% to 68% (Figure 23).

Figure 20. Child Attributes on Belief Degrees (Original)

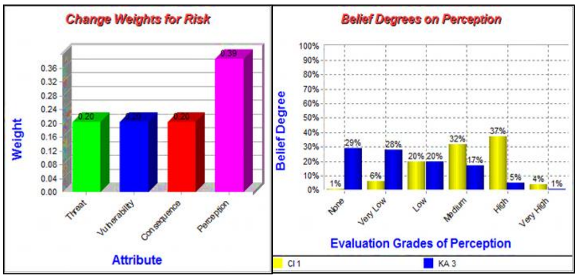


Figure 21. Child Attributes on Belief Degrees (Adjusted)

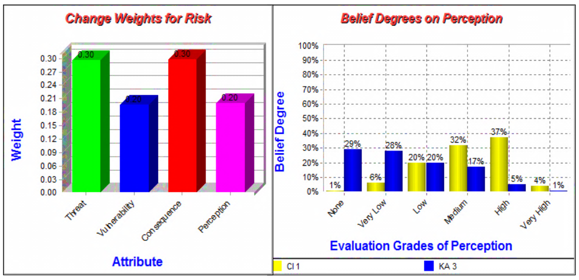


Figure 22. Input Data (Original)

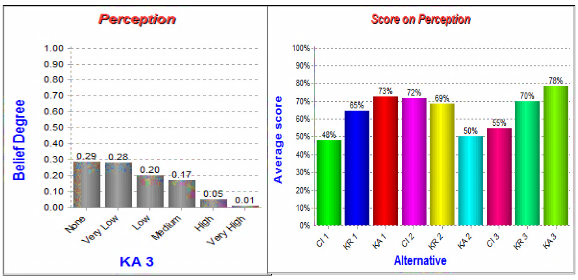


Figure 23. Input Data (Adjusted)

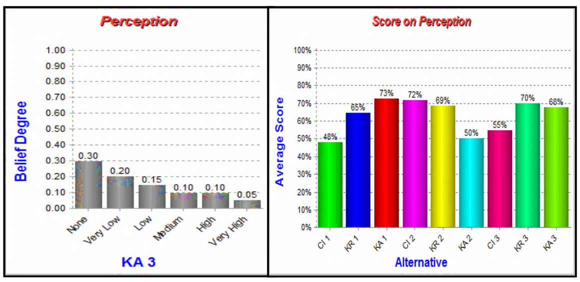
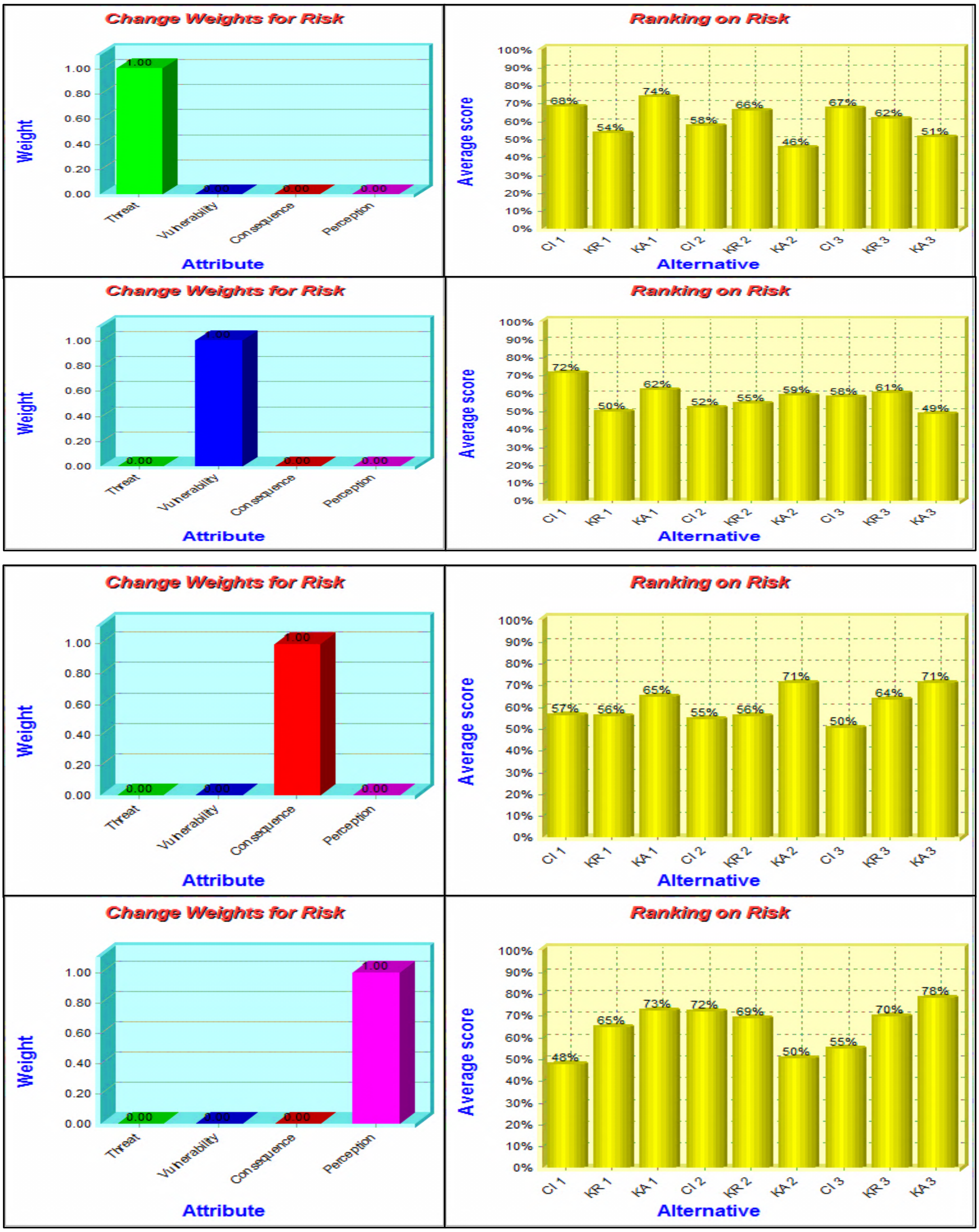


Figure 24. Max Attribute Models



The output of the risk quadruplet model (the ranked CIKRKA) should change depending on the weights selected for the child attributes, so we will explore some extreme weighting cases to test the validity of the model by ensuring that the results align with our intuitions. From Figure15, we know that KA 1 received the highest threat score, CI 1 received the highest vulnerability score, and KA 2 and KA 3 jointly received the highest consequence score, whereas KA 3 received the highest perception score. We will now systematically explore four max attribute - weighting schemes (for example, the Max Threat Model has a threat weight of 1, with vulnerability, consequence, and perception weights of 0 (Figure 24). We condensed the results of these different models in Exhibit 25 and the highlighted values were the assets, which received the highest overall risk score for that model. For the Max T Model, we would expect KA 1 to be ranked highest as it received the highest threat score, and that is exactly what we see. Since CI 1 received the highest vulnerability score, we expect to see it ranked the highest for risk in the Max V Model and that is again what we see. KA 2 and KA 3 jointly received the highest consequence score, so it is no surprise that we see both of them tied for the overall risk score in the Max C Model. And because KA 3 received the highest perception score, it only makes sense that KA 3 received the highest overall risk score for the Max P Model [10].

Figure 25. Model Validation Comparison of Weighting Schemes

	Risk (Max T)	*Risk (Max V)*	*Risk (Max C)*	*Risk (Max P)*
CI 1	68%	72%	57%	48%
KR 1	54%	50%	56%	65%
KA 1	74%	62%	65%	73%
CI 2	58%	52%	55%	72%
KR 2	66%	55%	56%	69%
KA 2	46%	59%	71%	50%
CI 3	67%	58%	50%	55%
KR 3	62%	61%	64%	70%
KA 3	51%	49%	71%	78%

3. CONCLUSIONS

This research challenges the existing paradigm for risk, not just as it is defined in homeland security (as a function of T, V, and C) but as it is typically defined in risk analysis, in general (as a function of probability and consequence). We assert that risk is inherently related to our perceptions and that we construct risk methodologies and models based on those perceptions. The risk quadruplet methodology proposed is capable of integrating T, V, C, and P assessments. While the risk quadruplet methodology was not deployed in vivo, it has been subjected to preliminary testing and analysis, in vitro, and has proven to be a viable approach for ranking CIKRKA in order to improve decision making for homeland security and homeland defense.

References

[1] Ezell, B. C. (2007). Infrastructure Vulnerability Assessment Model (I-VAM), Risk Analysis, 27(3), 571-583.

[2] IDS Multicriteria Assessor Quick Guide (2010), www.eids.co.uk
Inquisite, (2011), from http://www.inquisite.com/

[3] Intelligent Decision System (2010), http://www.e-ids.co.uk/

[4] National Infrastructure Protection Plan (2009), http://www.dhs.gov/xlibrary/assets/NIPP_Plan.pdf

[5] Norman Hill, K., & Ezell, B. C. (2011) - A Risk Quadruplet for Homeland Security. Paper presented at the INFORMS Annual Meeting, Charlotte, NC.

[6] Norman Hill, Kara, Gheorghe, A. V., (2012). Old Dominion University, Dept. of Engineering Management and Systems Engineering Risk Quadruplet: Integrating Assessments of Threat, Vulnerability, Consequence, and Perception for Homeland Security and Homeland Defense. Thesis (PhD), Old Dominion University.

[7] Risk Steering Committee: DHS Risk Lexicon (2010), Retrieved from http://www.dhs.gov/xlibrary/assets/dhs-risk-lexicon-2010.pdf

[8] Turner, B. A. (1994), The Future for Risk Research, Journal of Contingencies and Crisis Management, 2(3), 146-156. doi: 10.1111/j.1468-5973.1994.tb00037.x

[9] Willis, H. H. (2007), Guiding Resource Allocations Based on Terrorism Risk. Risk Analysis, 27(3), 597-606. doi: 10.1111/j.1539-6924.2007.00909.x

[10] Macal, C. M. (2005), Model Verification and Validation. Paper presented at the Threat Anticipation: Social Science Methods and Models, The University of Chicago and Argonne National Laboratory.

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