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Visual Analytics for Risk-based Decision Making, Long-Term Planning, and Assessment Process

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Abstract

Risk-based decision making is a data-driven process used to gather data about outcomes, analyze different scenarios, and deliver informed decisions to mitigate risk. We describe the design and application of integrated visual analytics techniques and components to support risk-based decision making following a structured risk management process in the US Coast Guard domain. The components proposed perform the following interactive tasks: the identification of risk priority areas, the distribution of pre-computed risk values, and the analysis of coverage versus risk, all of which equip analysts with the tools to examine the different decision factors and assist course of action development in the long-term planning and assessment process.

1. Introduction

Risk-based decision making is a growing operational and business trend that currently lacks interactive tools to aid the decision makers. The term risk is defined as the "potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences" [Com10]. Therefore, risk-based decision making can be defined as a process that collects and organizes information about different possible outcomes in an ordered structure that helps analysts make informed choices [MMGW04]. Risk-based decision making provides a framework for making decisions and helps identify the greatest risk so the decision maker can prioritize efforts in order to minimize risk and support long-term planning.

However, performing risk analysis and long-term planning is a complex and challenging analytical task, in which the decision maker must set up the problem and determine inputs, outputs, and other factors that might influence the decisions. Research in other areas has shown that individuals often make sub-optimal decisions due to cognitive limitations [SLFE11] and information overload [EM08]. Moreover, the analyst could base his/her decisions on subjective, rather than objective, perception of the risk at hand.

Therefore, we have developed several visual analytics components that can facilitate and improve the process of risk-based decision making. These components, developed through a collaborative user-centered process with the U.S. Coast Guard, use graphical depictions to assist the cognitive process of quantifying and comparing lines of evidence [LCG*12]. Our interactive components facilitate thinking, thereby improving the analyst's understanding of the data and speeding the overall decision making process. The components include feedback and exploratory abilities to examine, filter, and modify certain parameters.

During development, we followed a procedure similar to Sedlmair et al.'s [SMM12] nine-stage framework for conducting design studies. The new components were added to the framework described by Malik et al. [MMME11] because the end users have an understanding and working knowledge of the system.

The new risk-based visual analytics components being applied to visualize and compare risk include the following:

- The use of interactive graphics and choropleth maps to visualize operational risk profiles.
- A method to visualize and identify areas of high risk and compare the changes in risk priority areas over time.
- A method to spatially evaluate and distribute precomputed risk values based on the underlying distribution of cases over time.

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2. Related Work

In this section, we review previous works that describe the use of visual analytics in communicating risk, some existing models for risk analysis, and different tools to address risk in the maritime security domain.

In risk communication, Lipkus and Hollands [LH99] demonstrated that static images displaying risk characteristics such as risk magnitude and cumulative risk communicate the risk values more effectively than a display of numbers. Savikhin et al. [SME08] demonstrate the benefits of applying visual analytics techniques to aid users in their economic decision making. In contrast, our components provide not only visualizations, but also integrated techniques to analyze the changes of risk values both spatially and temporally.

For risk analysis and modeling, Bonafede and Marmo [BM08] demonstrate that the use of graphs can reduce search times for solutions and for identification of data. They propose four sub-plots with bar graphs and parallel coordinates to compare clients. Feather et al. [FCKM06] describe a risk based decision process with a model that takes into account requirements, risks, and mitigation strategies using bar charts and treemaps. Both papers emphasize that no single visualization technique serves all purposes and instead it is better to use a mix of several. One limitation in their systems is the lack of support of spatiotemporal data. Migut and Worring [MW10] developed a framework that integrates interactive visual exploration with machine learning techniques to support the risk assessment and decision making process. Their visualizations include scatterplots and mosaic plots as tools to build classification models.

Willems et al. [WvdWvW09] presented a geographical visualization using density estimated heatmaps to display vessel movements and support coastal surveillance systems. Pelot et al. [PP08] created a grid colored map representing vessel traffic where they model and identify vulnerable areas. Marven et al. [MCK07] analyzed Search and Rescue operations for the Canadian Coast Guard, exploring the clustering of incident areas with two different models: a Spatial and Temporal Analysis of Crime (STAC) and kernel density estimation (KDE). Abi-Zeid et al. [AZF05] developed SARPlan, a geographic decision support system for planning search and rescue missions, originally developed for aeronautical incidents. Orosz et al. [OSB*10] developed PortSec for decision-making and planning of port resources to address security needs to outside threats and hypothetical scenarios.

3. Visual Analytics in the Risk Management Process

We used the risk management process originally specified in ISO 31000:2009 [ISO09] to provide the initial principles and generic guidelines for risk management. Based on this process, we developed specific goals that our new visual analytics components should achieve:

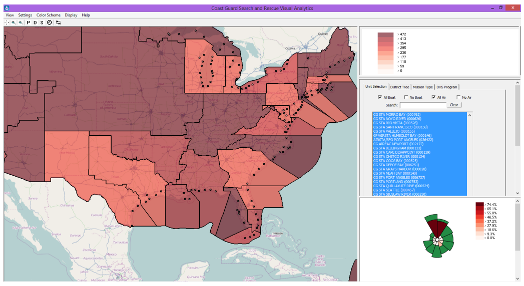

Figure 1: *View of the overall Visual Analytics System*

- Understand areas and missions driving the risk values.
- Identify risk priority areas and how they evolve over time.
- Visualize the geographical distribution of operations.
- Visualize the spatial distribution of the risk.
- Obtain details on demand about the operations.
- Provide a feedback loop if certain parameters change.

Malik et al. [MMME11] focused on the consequences of station closures, but the new additions to the system focus on Risk at the operational level. Such risk is assessed by the USCG Operational Risk Assessment Model (ORAM) [USC12]. Analysts at the Coast Guard Atlantic Area's Operations Analysis Division created this model to support mission planning and analysis of the Coast Guard's mission set. The model combines quantitative and qualitative theoretical frameworks to calculate and compare risk between the eleven Coast Guard statutory missions and geographical areas by providing the Risk Index Numbers (RIN) [USC12]. The RIN is a numerical value that characterizes and quantifies the qualities of risk. RIN values provided include both total risk and residual risk values as shown in Equation 1 [Com10].

$$\text{Total RIN} = \text{Residual RIN} + \text{Mitigated RIN} \quad (1)$$

3.1. Operational Risk Profiles

The first step is to acquire an understanding on how the risk numbers behave for each district as well as how much risk was mitigated. Therefore, there are two main goals in visualizing the Operational Risk Profiles:

- Compare the RIN values between the districts for any given mission or combination of missions.
- Compare the RIN values between missions for any given district.

When performing total versus residual risk analysis, the ratio between the RIN values is more critical than the raw numbers; therefore, we choose a radial layout to focus on ratios and relative values since such layouts inhibit the analysts innate tendency to focus on these numerical details.

We went through several design iterations and presented different alternatives to our end users to gain feedback in terms of which design was the most effective in conveying the information and comparing the distribution of risk. A risk

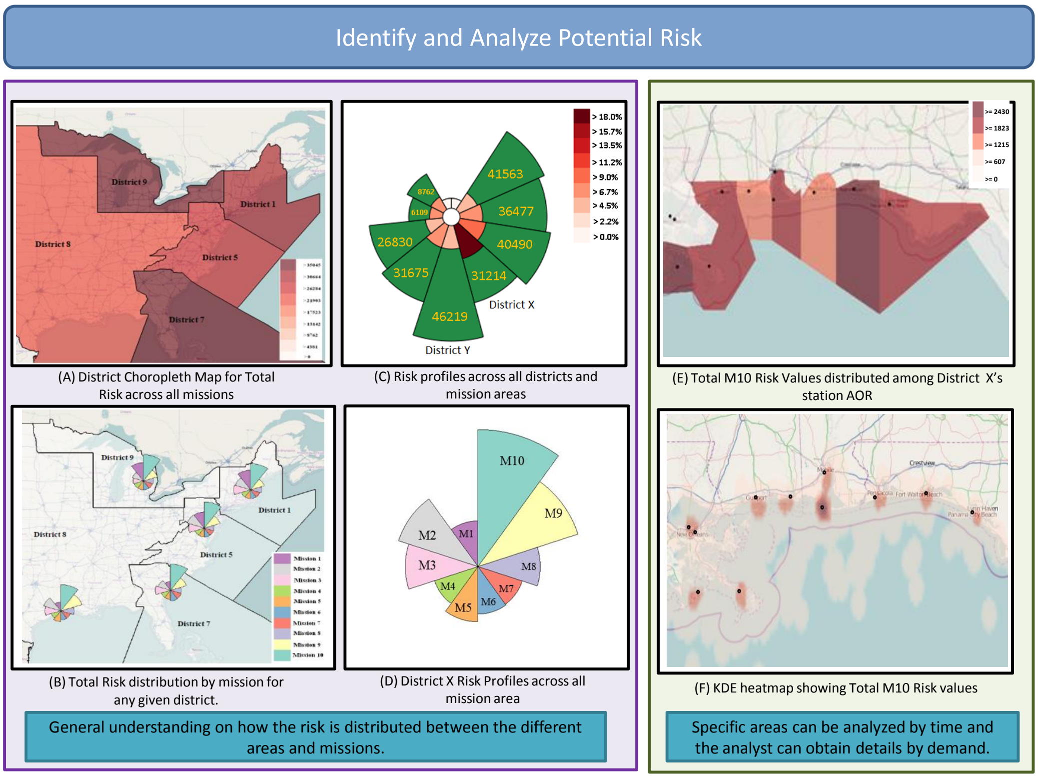

Figure 2: *General process for identifying and analyzing potential risk.*

pie graph was created with eleven fixed pie slices each representing a Coast Guard district as shown in Figure 2-C. The area of each outer pie slice is used to encode the comparison of total risk across districts, with larger pie slice corresponding to higher total risk. The area of inner pie slices represent the comparison of residual risk across districts. Each inner pie slice is also colored on a sequential red scale indicating the ratio of residual versus total risk for a given district. The choice of color (green indicates mitigated risk and red indicates residual risk) is consistent with the Coast Guard's Green-Amber-Red model. We allow interactive filtering by missions to analyze and compare the spatial distribution of risk across districts for any given mission or combination.

3.2. Risk Visualization Using Heatmaps

Next, we need to analyze risk priority areas and how they evolve over time. To quickly identify hotspots, a modified variable kernel density estimation technique (KDE) is employed on the map. Risk at the strategic level is not assigned to a specific unit or station, instead the analyst is able to observe areas with a high density of incidents independent of station location. The heatmap can display the RIN values for total, residual, and mitigated risk. The analyst can switch between the total risk and the residual risk to find hotspots where the risk has not been mitigated and examine the incident details in these zones. Analyzing the incident helps the analyst develop new strategies and courses of action to mitigate the risk.

3.3. Risk Distribution using Choropleth Maps

We utilize choropleth maps in two different ways to help visualize risk. The first option is to visualize any of the Risk values for any given mission or combination of missions by district (Figure 2-A), providing an effective way to present and share the information about risk levels within the U.S.

The second use of choropleth maps (Figure 2-E) highlights the risk distribution of the RIN values per district. During the process it is useful to visualize risk at the station level by using each individual station's Area of Responsibility (AOR). Certain mission's RIN numbers are computed at a district level rather than the station level. Therefore, in order to distribute the RIN values across the stations' AORs, we analyze the underlying incident distributions for a given time period. We use the incidents distribution as a basis to assign risk values across stations given the pre-computed total RIN values by district. The mathematical formula used to compute distributed RIN value for a particular station X that belongs to district Y is:

$$\text{station X RIN} = \frac{\text{Incidents in X}}{\text{Incidents } \forall \text{ stations in Y}} \times \text{district Y RIN} \qquad (2)$$

The risk distribution choropleth map provides an easy way to visualize the variations in risk values for individual station's AOR and help identify stations that will potentially require allocation of more resources.

3.4. Visual Analytics System

The overall system provides multiple linked windows and advanced filtering techniques to perform spatio-temporal analysis on the risk data as shown in Figure 1. The system allows the user to visualize historical Coast Guard Data, such as the number and location of incidents that occurred during a certain period of time. It can analyze incidents occurring on specific date ranges to explore seasonal trends and it can filter incidents relevant to the analyst's hypothesis. The addition of the new components enables the Coast Guard analyst to perform risk-based analysis of the operation as well as long term planning by providing new visualization along with feedback loops that control resource allocation.

4. Case Study: Identify and Analyze Potential Risks

To illustrate the use of our system, we present an example use scenario using notional data. In decision making, several questions will drive the analyst in developing the planning strategy: What risks exist in the region and where they are distributed? Where are our resources allocated? What constraints exist in the system that will require a prioritization of resource use?

In a resource constrained environment, we want to use resources in the mission area that provides the greatest return on investment (large amount of total risk but very little residual risk). The first step in the risk management process is to identify potential risks; therefore the analyst begins by looking at the operational risk profile and the district risk choropleth map to observe the risk values at the district level across all mission areas.

Figure 2-C displays the total and residual risk and the ratio between them for all the districts across all mission areas. In this case, we can observe that although District Y has the largest total risk values, it mitigated most of the risk effectively. On the other hand, District X shows less total risk, but the amount of residual risk as well as residual to total risk ratio is the highest as encoded by the darkest red shade. District X can be seen as more problematic than District Y; thus, the analyst will focus more attention on analyzing this particular district. This visualization provides a starting point in understanding how risk is distributed among the different districts and focusing on districts with high risk concentration.

After identifying that District X has the greatest residual risk and the highest risk concentration, the next step is determining the key drivers of risk within a district. This leads the analyst to leverage other components of the risk visual analytics tool to specifically evaluate District X. For instance, the analyst can examine the distribution of risk across different missions in District X as shown in Figure 2-D to identify which mission type has the greatest risk in this district. The analyst can observe that most of the operational risk emerges from one of the missions, in this case M10.

New questions emerge at this stage: Are there several big events that drive the risk, or are there many small events with smaller consequences accumulated to affect the operation? So now we examine the spatial distribution of M10 risk within District X to analyze specific areas of high residual risk. Depending on the data quality regarding spatial location, the analyst has two options for drilling down into specific areas within District X. The first option is to use the risk heatmap described in Section 3.2 to locate risk priority areas, as seen in Figure 2-F. If the spatial location is not available, then we re-distribute the risk to station AORs as described in Section 3.3 and as seen in Figure 2-E.

5. Domain Expert Feedback

The prototype components went through an iterative design refinement process with the collaboration of four Coast Guard personnel: an operation research analyst, a former Coast Guard officer, one in-field officer, and a high level officer. Informal feedback is given below:

"These components aid the analyst in answering the questions that come from developing the planning strategy, often with a speed that was previously unattainable with the Coast Guard's usual brute force processing of thousands of lines of data to calculate summary statistics."

"This system provides a risk informed process for building a defensible planning baseline for the long-term planning process. Understanding the risk profiles provides analytic justification for resource use, and can aid in demonstrating effective application of resource use based on risk."

6. Conclusions

We have demonstrated how our interactive visual analytics components can facilitate the risk management process and evaluate courses of action. Within the maritime context, our interactive visual analytics environment utilizes KDE heatmaps to help identify risk priority areas, multiple designs to visualize risk profiles, a risk distribution choropleth map to visualize the spatial distribution of pre-computed risk values, and the coverage map overlaid with risk distribution for analysis of coverage capability/efficiency as well as potential need for resource reallocation or assets upgrade. Finally, we included a case study that examines the efficiency of Coast Guard operations and provides useful visual reference that can communicate recommendations based on risk management. The described risk-based decision making process serves as a blueprint for future systems dealing with risk values and resource planning.

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