Making Sense of the Operational Environment Through Interactive, Exploratory Visual Analysis

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ABSTRACT

The success of defense and security operations depends on the ability to make sense the operational environment and to anticipate those factors that influence operations both negatively and positively. In this paper, we present a framework for interactive, exploratory visual analysis as a means for making sense of the operational environment. This framework is grounded in the sensemaking process and characterized by three essential dimensions: information retrieval/fusion, interactive visualizations and modeling and simulation. The framework reveals several important research gaps that must be filled to provide full benefit to the task of understanding the operational environment. The paper highlights two such gaps: identifying emerging topics and trends, and making sense of integrated modeling and simulation.

1.0 INTRODUCTION

It is widely recognized that effective interaction with local populations is essential to the success of defense and security operations. Effective interaction, however, depends on the ability to make sense the operational environment and to anticipate those factors that influence defense and security operations both negatively and positively. Unfortunately, the structure and behavior of the systems that commonly comprise these factors suggest that making sense of operational environments is a "wicked problem" [1].

Wicked problems are high-stakes, complex problems that are without definitive formulations; they are problems with open solution spaces where solutions have relative quality; and they are problems that are arguably unique in each instance. Given these characteristics, managing wicked problems presents both a difficult and daunting challenge. Fortunately, exploratory capabilities offer a promising approach to managing wicked problems as they provide the foundation for competitive analyses and the study of alternative hypotheses [2].

In this paper, we present a framework for interactive, exploratory visual analysis as a means for making sense of the operational environment. This framework is grounded in the sensemaking process [3] and characterized by three essential dimensions: information retrieval/fusion, interactive visualizations and modeling and simulation. While connecting these three dimensions, the framework reveals several important research gaps that must be filled in order to provide full benefit to the task of understanding the operational environment and those factors that influence the outcomes of defense and security operations. In this paper we describe two of these research gaps and illustrate two applications where sensemaking is enabled by interactive, exploratory visual analysis. We conclude this paper by connecting these applications to the framework and decision cycle by illustrating: i) how the identification of emerging topics and trends can inform modeling and simulation; and ii) how these same techniques can build further understanding when applied to data farming enabled by through modeling and simulation.

2.0 SENSEMAKING AND THE OPERATIONAL ENVIRONMENT

In order to appreciate the "wickedness" associated with the challenge of making sense of the operational environment, it is useful to highlight the characteristics that commonly comprise the operational environment and explore how those characteristics are aligned with military doctrine.

Within U.S. military doctrine, the operational environment is define to be "[a] composite of the conditions, circumstances, and influences that affect the employment of military forces and bear on the decisions of the unit commander" ([4], p. xi). Examining this definition more closely reveals several important insights. First, the operational environment exists in the context of a mission – i.e., the employment (or potential employment) of military forces. In other words, mission requirements are integral to defining the bounds of the operational environment. Second, the operational environment is both situated and dynamic. The operational environment is situated along multiple dimensions – e.g., temporal, geospatial, cultural, etc. – and these dimensions are what give meaning to actions or events within the environment. The operational environment is dynamic as a reflection of changes in conditions, circumstances and influences within the environment. Third, the operational environment is relational, suggesting that there are meaningful patterns and causalities that underlie and explain observable behaviors and changes within the environment.

Under recent U.S. military doctrine, the operational environment is frequently characterized as a combination of the political, military, economic, social, infrastructure, information, physical environment and time (PMESII-PT) factors (identified as operational variables), and their interdependencies, that affect military operations [5]. Each of these factors itself is a complex system exhibiting emergent, nonlinear behavior. In fact, understanding the structure and behavior of any one of these factors is arguably a wicked problem in its own right. Collectively, these dimensions challenge analysts and decision makers, and further stretch analytical thought.

Characterization of the operational environment is often a key element of military doctrine. The Joint Intelligence Preparation of the Operational Environment (JIPOE) [4] is a prime example. JIPOE is a four-step process designed to provide analytical support to decision-making in a joint operational context (see Figure 1). Table 1 summarizes the tasks associated with each step. It is easily observed that central to each step is the construction and maintenance of an understanding of the operational environment, initiated in Step 1 and explored in subsequent steps.

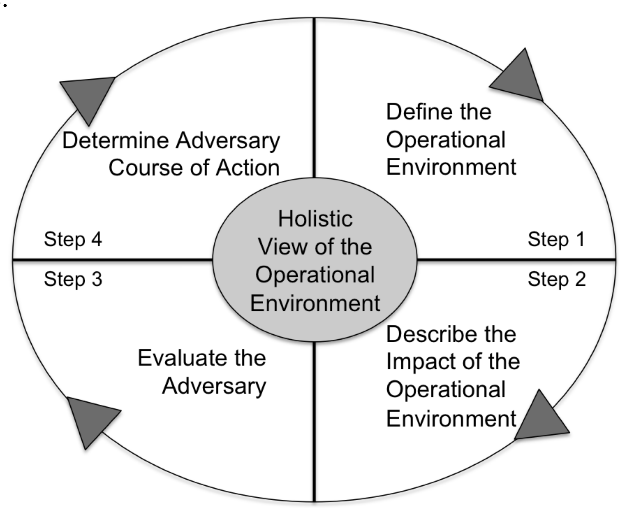

Figure 1 - Joint Intelligence Preparation for the Operational Environment [4]

Table 1 - JIPOE Tasks [4]

Step 1	Step 2
• Identify the joint force's operational area • Analyze the mission and joint force commander's intent • Determine the significant characteristics of the operational environment • Establish the limits of the joint force's areas of interest • Determine the level of detail required and feasible within the time available • Determine intelligence and information gaps, shortfalls, and priorities • Collect material and submit requests for information to support further analysis	• Develop a geospatial perspective of the operational environment • Develop a systems perspective of the operational environment • Describe the impact of the operational environment on adversary and friendly capabilities and broad courses of action
Step 3	**Step 4**
• Update or create adversary models • Determine the current adversary situation • Identify adversary capabilities and vulnerabilities • Identify adversary centers of gravity	• Identify the adversary's likely objectives and desired end states • Identify the full set of adversary courses of action • Evaluate and prioritize each course of action • Develop each course of action in the amount of detail time allows • Identify initial collection requirements

We argue that the process of building a proper understanding of the operational environment as characterized by the complex PMESII-PT variables and described in military doctrine such as JIPOE is largely a sensemaking process. Sensemaking has been described in numerous ways. Duffy [6] states that sensemaking is "how people make sense out of their experience in the world." The final report from the *2001 Sensemaking Symposium* [7] describes sensemaking "as the process of creating situation awareness in situations of uncertainty." Klein et al. [8] describe sensemaking as, "a motivated, continuous effort to understand connections…in order to anticipate their trajectories and act effectively."

Collectively, these descriptions of sensemaking share many common characteristics. First, each characterizes sensemaking as an iterative process with numerous feedback loops – c.f., [3]. Second, each argues that sensemaking involves several activities including foraging, encoding and reasoning. Central to these activities is the iterative construction and refinement of representations, i.e., models – a process that Klein et al. refer to as the framing process [8]. Russell et al. capture this characteristic in their notion of the Learning Loop Complex [9]. In the Learning Loop Complex, people search for a good representation; and, then, instantiate the representation – i.e., encode the data – based of the data available – i.e., data that have been foraged. Those data, called residual data, that do not "fit" the representation lead to the selection, construction or refinement of the representation – i.e., reframing. Third, sensemaking is largely a human-centric activity where judgment and critical thinking play essential roles. This suggests one must abandon the notion that outcomes (e.g., decisions or courses of action) are the output of computational tools; rather, tools should enable the exploration possible outcomes, facilitate human judgment and help to evaluate plausible futures.

Figure 2 is the sensemaking representation that we adopt for the work reported here. In this representation, the progression of data to information, information to knowledge and knowledge to understanding is clearly visible. Information, foraged from data and placed in analytical context, provides the foundational evidences to the analytical question(s). Knowledge, as representations encoded from information, emerges from relationships among concepts [10]. Understanding is synthesized from knowledge through reasoning and critical thought. This progression, however, is not necessary linear and often highly iterative.

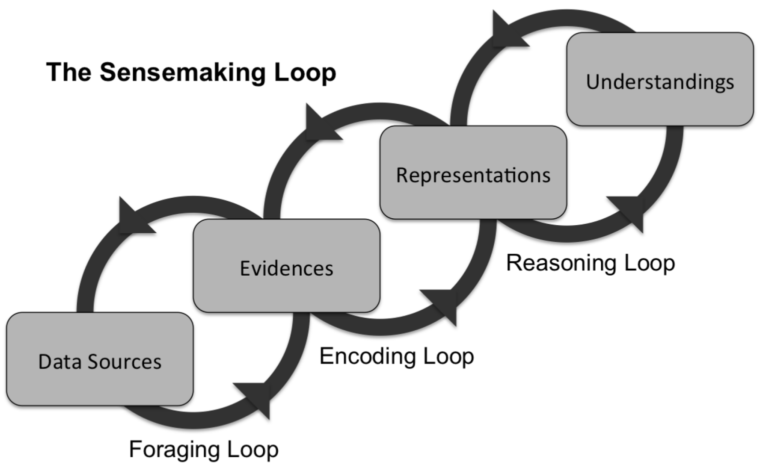

Figure 2 – The Sensemaking Loop

3.0 A FRAMEWORK FOR INTERACTIVE, EXPLORATORY VISUAL ANALYSIS

We contend that exploratory visual analysis offers important affordances to the sensemaking process. In support of this contention, we have developed a framework for interactive, exploratory visual analysis as a means for making sense of the operational environment. The sensemaking process is central to our framework (see Figure 3) with its foraging, encoding and reasoning loops serving as the core analytical activities. The utility of the framework is found in the direction it offers to tool and method research and development in relation to the ability to characterize operational environments quickly and accurately – relative to mission requirements. We believe that the volume, velocity and variety of data that describe the operational environment – e.g., political, economic, military, social, infrastructure, environmental systems, etc. – as well as the complexity of the systems they represent necessitate both knowledge-driven and data-driven approaches to analysis. This accounts for the trifold dimensions of information retrieval/fusion, interactive visualizations and modeling and simulation forming the foundation of the framework.

Knowledge-driven approaches emphasize the application and adaption of existing representations, both cognitive and digital, in support of the sensemaking process by enabling the ongoing reframing of representation as a reflection of current understanding. Modeling and simulation, particularly integrated modeling and simulation (i.e., coupling models representing the various PMESII-PT variables), offer an especially promising research direction as applied to the challenge of making sense of the operational environment,. Data-driven approaches, on the other hand, emphasize the construction of new representations from raw data and the situating of those representations within current understanding – revealing as new frames the hidden structure in large corpora of data. Here, techniques such as automated topic-modeling offer a promising research direction in support of the sensemaking challenge.

A further contribution of this framework, however, is its emphasis on the essential role of exploratory visual analysis in relation to both knowledge and data-driven approaches (as well as the dynamic interplay between them) as interactive visualizations provide the vocabulary for analytical dialogue between the human and the computer when facing wicked problems, in this case giving the human access: i) to enhance and direct information retrieval/fusion as well as modeling and simulation; and ii) to explore their results and other relevant data.

Unifying all three dimensions of the framework are the processes associated with operational planning. The embedded representation of operational planning in our framework suggests that the analytical methods and tools be applied not only to mission data and knowledge, but also to data and knowledge that are both a representation and product of the planning process (indicated by thickening red arrows). In other words, operational planning is an exploratory process that produces both data and knowledge. We contend that there is hidden structure and meaning in these products that can offer valuable insights to the decision making process. For example, these products can reveal: i) the limitations of the employed tools and methods; ii) the provenance of the underlying inputs to the characterization of the operational environment; and iii) the processes (and their embedded intuitions as well as biases) that led to the constructed understanding of the operational environment.

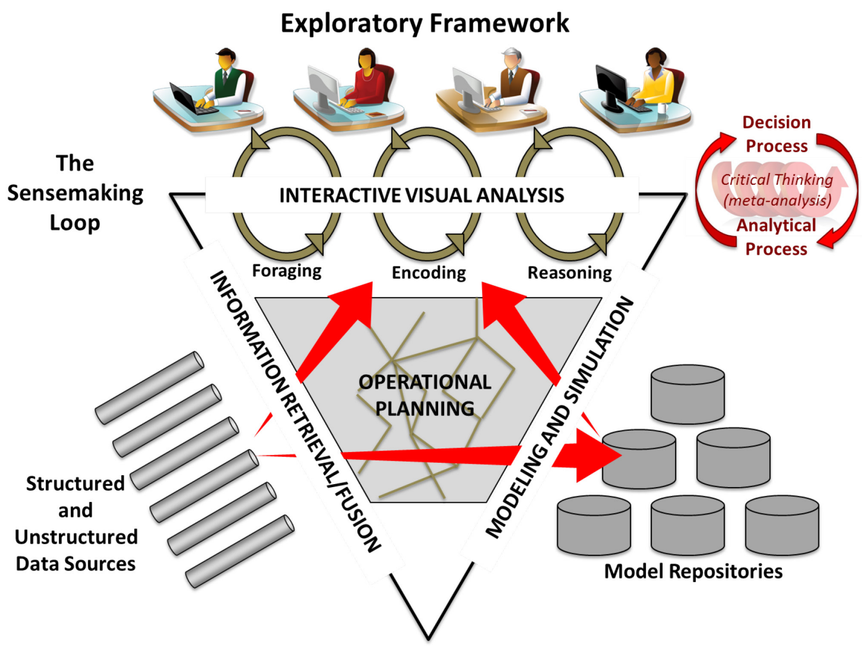

Figure 3 – Exploratory Framework for Interactive Visual Analysis

There are several research gaps suggested by our framework that must be filled in order to provide full benefit to exploratory analysis of wicked problems – in particular, to the process of making sense of operational environments and the factors that influence the outcomes of defense and security operations. The first research gap highlights the challenge of revealing and leveraging hidden structure within large corpora of data as a means of making sense of those data. The second research gap highlights the challenge of understanding the structure and behavior of integrated models, and simulations they produce, as reflections of the systems they represent. With both gaps, we emphasize the value of exploratory visual analysis as an essential affordance to meeting these challenges.

4.0 GAP 1: IDENTIFYING EMERGING TOPICS AND TRENDS

The first gap and application illustrates data-driven methods for identifying emerging topics and trends from structured and unstructured data sources. Digital textual content is being generated at a daunting scale, much larger than we can ever comprehend. Vast amounts of content are accumulated from various sources, diverse populations, and different times and locations. For example, 1.35 million scholarly articles were published in 2006 alone. With an average annual growth rate of 2.5%, research articles are currently being published at the pace of approximately 4400 titles per day. In the social media world, people are contributing to the accumulation at an even faster pace. By June 2012, Twitter is seeing 400 million tweets per day. Meanwhile, 900 million active Facebook users have been busy sending 1 million messages every 20 minutes. It is generally agreed in government and industry that valuable but latent information is hidden in the vast amount of digital textual content, information that can provide insights into proper characterization of operational environments. For instance for emergency response agencies, sifting through massive amount of social media data could help them monitor and track the development of and response to natural disasters, as illustrated in the use of Twitter to reach victims from hurricanes.

With all this activity, a large and growing problem is how analysts and decision makers can gain an understanding of the ideas and connections being expressed in media, and the trends, relationships, events, and social connections indicated or implied in this activity. Once a particular event or activity is identified, one can use search and organizational capabilities to gain more information about it, but this leaves out the majority of events that may be of interest but have not fully bloomed yet and, thus, are not known. In this case, one is overwhelmed with the noise of unrelated events and activity; even in the situation where analysts have an idea what they are looking for, they still are faced with actually examining too large a corpus of data messages in order to get a good understanding of how topics develop, intertwine and change.

To meet these challenges, we have developed interactive visual analytics system that aims to provide sophisticated visual interfaces and verifiable analytics results to augment the analytics capability to detect and validate events from heterogeneous, unstructured data sources. We illustrate our research results through its application to the detection and validation of social events from heterogeneous social media sources. Though a specific example, one can easily see how these results can benefit sensemaking process focused on the operational environment.

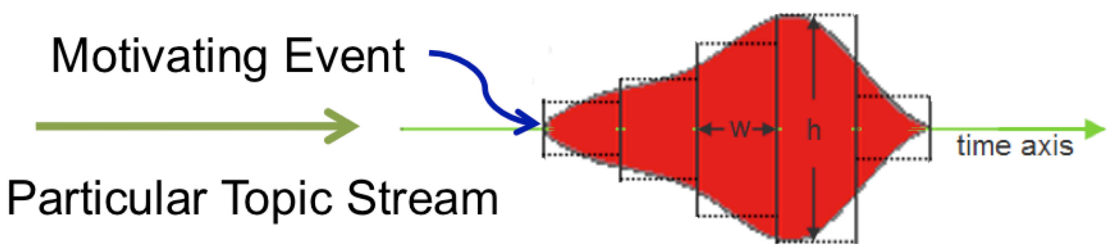

Figure 4--- Bursty Event Structure.
H indicates the volume of documents (e.g., tweets) associated in this event. W suggests the duration of the event.

The fundamental component of our visual analytics system is the **Event**, which we define as a “meaningful occurrence in space and time.” Events are bursts of activity over a relatively short time period, the time scale depending on the category of the temporal data. For example, with streaming Twitter data, a typical single event burst lasts one to two days; major events can be longer lasting, but they usually can be divided into sub-events. In this paper, events are associated with a particular topic (as shown in **Figure 4**) so that an event occurs for a particular topic, time, and set of extracted entities (e.g., location, indicated past or future times, names of people, etc. extracted from the social media texts). Thus, in the case of the interactive interface we have developed for Twitter data, a selection of an event chooses only those tweets for the given topic and for the part of the event burst time range selected. As discussed below, events provide a great focus and together make up an interpretable narrative; thus this selection is a powerful filtering tool.

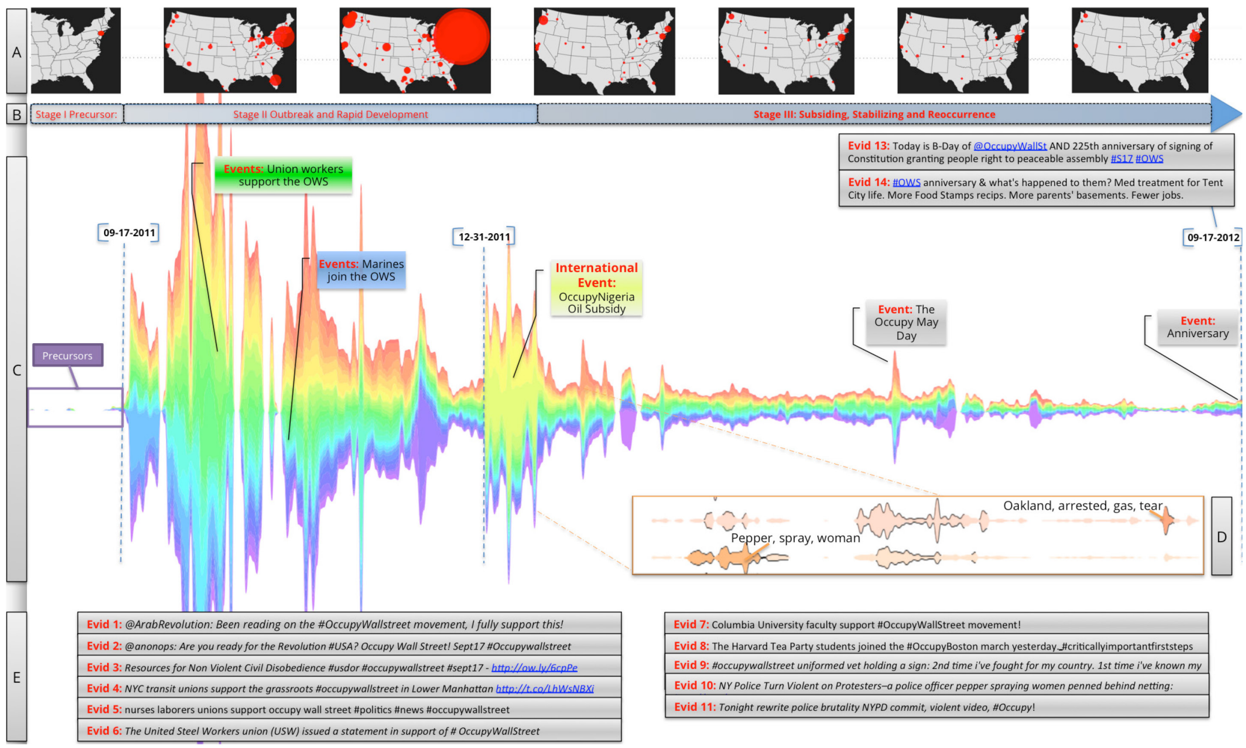

Figure 5 --- Overview of the Occupy Wallstreet Movement (OWM) in our VA System.
A: Occupy hotspots over time. *B*: Three stages of the OWM divided based on the rise and fall of the overall activities. *C*: Visual summary of the Occupy activities. The x-axis represents time; each color-coded ribbon represents a topic extracted from the tweets. Event detection is performed on individual topic to identify bursts as indicators of events. *D*: Sample events labeled with corresponding keywords. *E*: Evidence [Evid.X] mentioned in the paper. For more detail refer to [11].

To identify emerging topics and trends, we perform one more analysis step on our event structure. We label as events only those bursty structures that have a motivating event (see **Figure 4**). A motivating event is an occurrence, either described in the event burst tweets themselves (usually at the beginning) or external to this set of tweets that has motivated the bursty response. Most if not all event bursts of this type are responses to the initial motivating event. For example, the main topical events on September 17, 2011 were clearly associated with the launch of Occupy Wall Street (OWS) on that date at Zucotti Park in New York City, but most of the associated tweets, from individuals and from online news, were in response to this event. In fact, OWS was large enough that there were several topics with their associated events on that date.

We have found that by just analyzing the shape, size, and duration of the burst, we can automatically identify events that will have clear motivating events. Thus, we have a mechanism for automatically identifying meaningful events that we have tested successfully on multiple categories of data, not just streaming social media. This is not to say that there are no other, unmarked bursts that are meaningful. Nor is it to say that the meaning is immediately clear from this analysis. Input from a human-in-the-loop is necessary to resolve these questions. But this identification of meaningful events is still a boon for exploratory analysis since we have found it identifies most of the major events and also directs the user's attention. We have applied our visual analytics system to tell the complete story of OWS from precursor discussion before the launch till now. As shown in **Figure 5**, this shows how a comprehensive, rich narrative can be built efficiently [11].

5.0 GAP 2: MAKING SENSE OF INTEGRATED MODELING AND SIMULATION

The second research gap highlights the challenge of understanding the structure and behavior of integrated models, and the simulations they produce, as a means for making sense of the operational environment. As defined by U.S. military doctrine, the operational environment is a "composite of the conditions, circumstances, and influences that affect the employment of military forces and bear on the decisions of the unit commander" [4]. These "conditions, circumstances, and influences" are understood in terms of operational variables (e.g., PMESII-PT) that characterize the operational environment. Integrated modeling and simulation offers a promising approach to this sensemaking challenge as models representing each of the operational variables are composed, or coupled, to represent an interdependent system of systems within the operational environment.

To illustrate, consider the *Vu* architecture depicted in Figure 6. A product of our previous research results [12],[13],[15], *Vu* is a knowledge-driven approach to integrated modeling and simulation of complex systems of systems. As a knowledge-driven approach, the architecture supports the adaptation, or reframing, of models to produce an integrated representation of specified operational environment. It also enables the exploration of alternative hypotheses, a useful strategy to managing wicked problems (c.f., Roberts [2]).

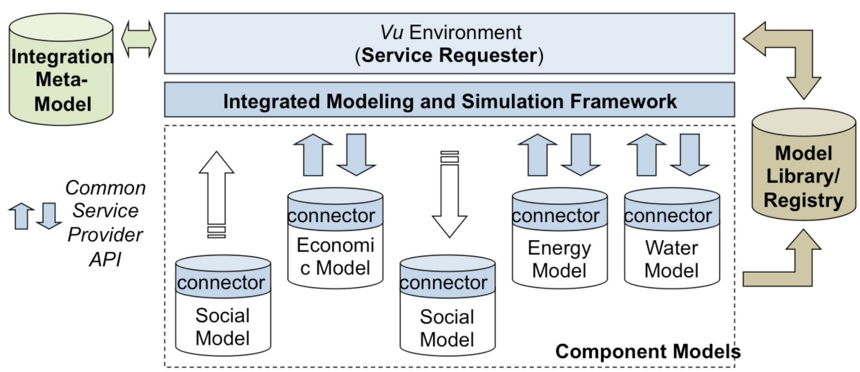

Figure 6 – Architecture for Integrated Modeling and Simulation

While the architecture [14] presents a novel approach to integrated modeling and simulation, its utility depends directly on the essential role of exploratory visual analysis. The *Vu* user experience (see Figure 7) consists of temporally situated, geospatially-oriented, interactive visualizations of interdependent models as they respond to disruption or reconstitution events with cascading effects. More specifically, the *Vu* environment provides numerous interactive visualizations that enable users to identify and understand quickly: i) emerging, cascading effects; ii) chains of causality and their underlying interdependencies; and iii) plausible futures of potential courses of action. Furthermore, the exploratory interfaces help users to identify key events in sequence in order to turn these identified events, their behaviors and relationships, into actionable plans or courses of action, augmented with alternative scenarios. The interactive visualizations also play an essential function in model verification and validation by increasing transparency of model projections.

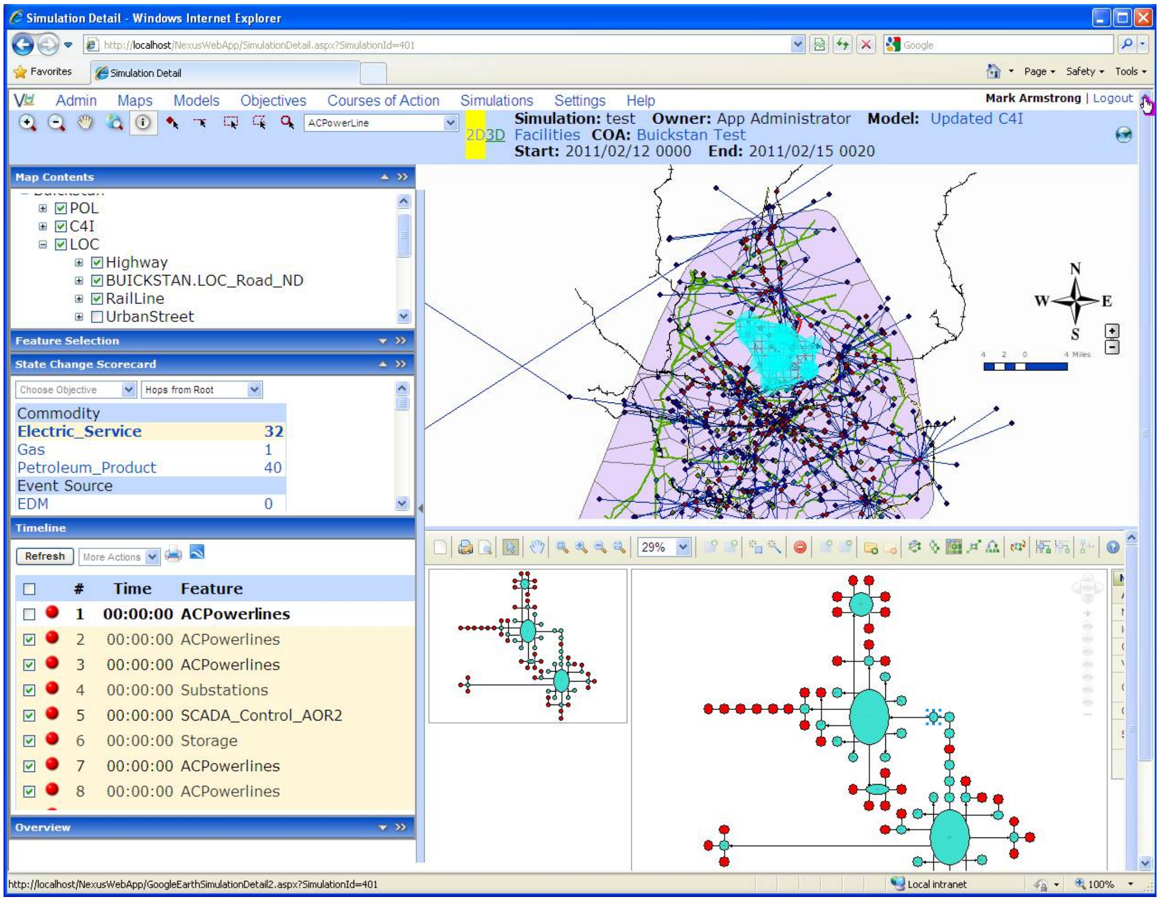

Figure 7 – The *Vu* User Experience

The second gap and application also illustrate data-driven and knowledge-driven methods working in concert to understand better the properties of knowledge representations. More specifically, the planning process produces numerous knowledge artifacts including models of the operational environment, potential courses of action and simulation traces representing plausible futures. The application of data-driven methods supported by exploratory interfaces to these knowledge artifacts can reveal important insights about the representations themselves and the complex space of simulations they produce. Figure 8 offers two illustrations of this affordance. Both allow visual exploration of a suite of *Vu* simulations produced using data farming techniques. The visualization on the left is aggregate sustainability analysis of simulation outcomes for an integrated urban model. The visualization on the right is aggregate temporal analysis of integrated infrastructure resiliency in the face of majorly disruptive weather events (e.g., hurricanes). Each visualization reveals hidden structure within the integrated modeling and simulation data – thus, providing further insight about the respective operational environment.

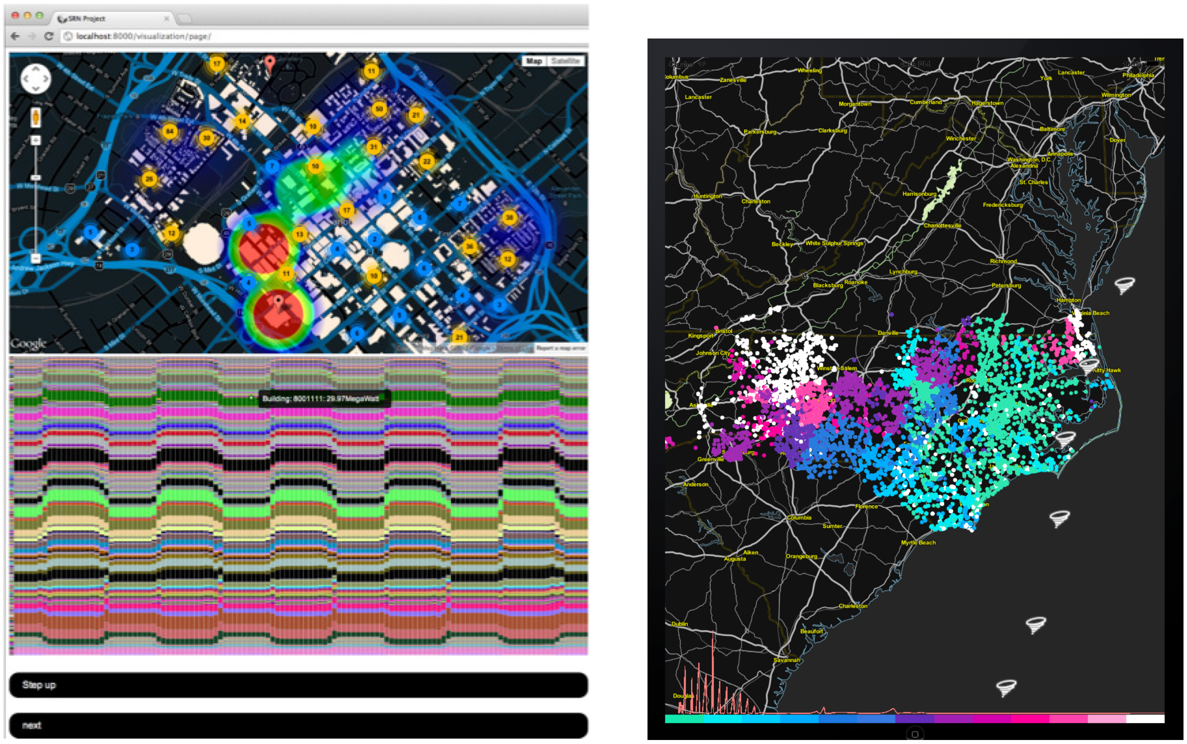

Figure 8 – Visual Analysis of the Space of Simulations.

6.0 CLOSING THE LOOP

We conclude this paper by connecting framework dimensions – i.e., information retrieval/fusion, interactive visualizations and modeling and simulation – to the sensemaking process in general, and the process of making sense of the operational environment more specifically.

As demonstrated by our discussion of the illustrative gaps, exploratory visual analysis can benefit all aspects of the sensemaking process – i.e., foraging, encoding and reasoning. In particular, exploratory visual analysis can facilitate the efficiency and efficacy of the foraging loop, including the organization of collected data and the identifications of key evidence. As illustrated by Gap 1, data-driven tools and methods offer important utility to this process, as there is often hidden structure and meaning within collected data. Connecting exploratory visual analysis capabilities to these data-driven tools and methods also enables the encoding loop as evidences are organized into relevant representations. These activities become the initial, though powerful, forays into the reasoning loop.

As illustrated by Gap 2, extending exploratory visual analysis capabilities to knowledge-driven tools and methods can further facilitate the reasoning loop. Exploratory visual analysis enables users not only to understand better the modeled phenomenon, but also the limitations of the models as reflected in identified uncertainties, biases, inaccuracies and/or missing evidences. Exploratory visual analysis also can help users understand better the range of potential representations and plausible futures in the face of recognized uncertainty. Paul and Elder stress the importance of such exploration in their discussion of the elements of reason and the articulation of assumptions, evidences, inferences and consequences [16]. Exploring the range of plausible futures (rather than just the predicted future) is especially important in the face of wicked problems, such as making sense of the operational environment. In particular, Roberts highlights the value of competing analyses as a promising method for managing wicked problems [2].

Connecting data-driven approaches with knowledge-driven approaches, however, can further empower the sensemaking process – not only through collective support but also through synergy between the approaches. In particular, data-driven approaches (associated with information retrieval/fusion) can be connected to knowledge-driven approaches (associated with modeling and simulation) through the encoding loop. Here, military doctrine regarding the desired characterization of the operational environment (e.g., PMESII-PT) frames the encoding process. Exploratory visual interfaces are essential to this activity as they help modelers identify which evidences to encode and which representations to employ. As illustrated in our discussion of Gap 2, these capabilities in particular can help modelers develop new models, adapt existing models and configure models for exploration and analysis.

7.0 SUMMARY

Making sense of the operational environment is arguably a wicked problem. We believe that interactive exploratory visual analysis can offer important affordances to the sensemaking process in this context. To that end, this paper presents a framework for interactive, exploratory visual analysis. This framework is grounded in the sensemaking process and characterized by three essential dimensions: information retrieval/fusion, interactive visualizations and modeling and simulation. The utility of the framework is found in the direction it offers to tool and method research and development in relation to the ability to characterize operational environments quickly and accurately – relative to mission requirements. Furthermore, we believe that the volume, velocity and variety of data that describe the operational environment as well as the complexity of the systems they represent necessitate both knowledge-driven and data-driven approaches to analysis. To support our contentions, we present to research gaps and associated applications. The first gap and associated application illustrates the benefit of exploratory visual analysis to a data-driven approach to the identification of emerging topics and trends within large corpora of unstructured data. Such support can offer important affordances to characterizing operational environments. The second gap and associated application illustrates the benefit of exploratory visual analysis to integrated modeling and simulation. Integrated modeling and simulation can provide multi-dimensional (e.g., PMESII-PT) representations of the operational environment in support of the sensemaking process. The second gap and application also illustrate data-driven and knowledge-driven methods working in concert to understand better the properties of these integrated representations.

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