Towards Design Principles for Visual Analytics in Operations Contexts

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ABSTRACT

Operations engineering teams interact with complex data systems to make technical decisions that ensure the operational efficacy of their missions. To support these decision-making tasks, which may require elastic prioritization of goals dependent on changing conditions, custom analytics tools are often developed. We were asked to develop such a tool by a team at the NASA Jet Propulsion Laboratory, where rover telecom operators make decisions based on models predicting how much data rovers can transfer from the surface of Mars. Through research, design, implementation, and informal evaluation of our new tool, we developed principles to inform the design of visual analytics systems in operations contexts. We offer these principles as a step towards understanding the complex task of designing these systems. The principles we present are applicable to designers and developers tasked with building analytics systems in domains that face complex operations challenges such as scheduling, routing, and logistics.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

operations; theory; design principles; design research methods; qualitative methods; visual design; visualization; contextual inquiry; information seeking & search

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INTRODUCTION

Many tasks are routine, but their reliable performance is not always indicative of regularity in procedure. The term "operations" often classifies tasks that require a calibrated response to complex variables governing a domain. For the purposes of this paper, we define operations as processes that 1) require time-sensitive attention, 2) generate an action-oriented output, and 3) assess risk and impact across multiple scenarios. There are many domains that deal with operations issues, including air traffic control, supply chain logistics, and search-and-rescue missions. As it is critical that operators are able to make quick, deliberate, and thoughtful decisions, special tools are often needed to support their tasks.

Spacecraft systems engineers at the NASA Jet Propulsion Laboratory manage the *Opportunity* rover on Mars. To support their work, we designed *Meridian*, a tool for analyzing predictions about the amount of data *Opportunity* can transmit to overpassing satellites under changing conditions. *Meridian* drives rover path planning decisions efficiently, particularly critical given a hard drive failure that wipes *Opportunity*'s data cache upon entering power-saving "nap" mode. *Meridian* is also adaptable to shifting priorities, from maximizing data transfer to facilitating uplink at a certain location on the horizon. While only a handful of experts use *Meridian*, the needs met by this tool are ubiquitous in analogous contexts.

The visualization community has contributed a number of systems that assist with operations tasks, but their design often targets domain specificities that seldom extend across contexts. To ensure that the lessons learned from work done across these many domains are not overlooked, we developed a suite of principles to guide the creation of visual analytics tools supporting various operations tasks.

Through the design of *Meridian* — via direct observations, simulations with paper- and code-based prototypes, and inquiry into failed representations — we crafted strategies for optimizing operations tasks. We submit the following principles to facilitate an understanding of the particular challenges of designing for these contexts, and offer suggestions for prioritizing focus and framing expected trade-offs. We believe these principles contribute to a growing scholarship on designing for operations and the continued investigation of this space.

RELATED WORK

Research in visual analytics has seen a number of systems designed to help analysts across domains, from risk management, to enterprise decision management, to multi-objective optimization. These domains require a human operator to oversee complex processes, ensure they run nominally, and make real-time decisions at important junctures.

For example, *ViDX* is a system for real-time monitoring and diagnostics of assembly line performance in smart factories [17], a domain that requires quick decision making about automated factory processes. Malik et al. [8] offer a visual analytics system to help coast guards allocate their maritime resources and evaluate the risks associated with potential actions; Tomaszewski and MacEachren present a geovisual analytics system in support of crisis management [13], discussing the importance of providing context in visual analytics tools [12]. Both domains require operational oversight of tasks of critical importance that deal with human lives. Another tool, the *Decision Exploration Lab* [2], targets operations problems generally, providing users with ways to represent abstract business goals and create decision models to optimize them. The system is focused on automating decision-making tasks and testing user-defined rules that can be used to perform relevant decisions.

While these systems address the specific challenges of their particular verticals, we see them as representative of a more general category of tasks that we refer to as "operations." The operations tasks we examine share three characteristics: they require time-sensitive attention, generate an action-oriented output, and assess risk and impact across multiple scenarios. Under this definition of operations, we can find commonalities across problems, and as a discipline, look to understand how one solution manifested in one domain might in some way help solve similar problems in an analogous domain.

Towards that end, rather than characterize our contribution around the impact of the single artifact that we designed, we instead reflect on the design decisions we made. We present not the *what* but the *how*, and look to use the knowledge generated through making. This "Research through Design" [18] approach to visual analytics leads us to communicate the space of choices that we faced, and explore how these choices manifested in terms of visual encoding and interaction.

Previous research has investigated visualization principles that apply more generally across many design contexts. Tufte, for example, offered a broad set of guidelines [14], to drive efficiency and integrity in visual encoding choices. Card and Mackinlay proposed a framework that includes concepts like the efficacy of choices visualization designers might make [3]. Recently, other designerly techniques have looked to infuse the information visualization discipline with broader Design knowledge, such as prototyping [15].

This process of moving from individual systems to design principles that reach across individual systems also follows precedent from a number of other research domains. For example, Davidoff et al. developed a set of seven design principles to help designers navigate the burgeoning field of smart home control [5], and Horvitz presented an influential set of principles for developing mixed-initiative user interfaces [7]. Rule and Forlizzi distilled design principles for interfaces in multi-user, multi-robot systems [10].

Our work adds to this conversation about designerly knowledge in visualization by contributing principles and best practices for visual analytics systems that focus on the less explored domain of operations. Wang et al. developed a two-stage framework for designing visual analytics systems in organizational environments [16]. The organizational domain has overlap with operations, given that there are competing interests to be prioritized, and tasks may be time-sensitive and mission-critical. The framework presented, however, is very high-level and may be more useful for characterizing the design process than for informing it. With the principles we present, we aim to help guide the design visual analytics systems for operations in practice.

MERIDIAN

Meridian was designed for the Mars Exploration Rover team at the NASA Jet Propulsion Laboratory. Operators working with *Opportunity* needed a way to analyze predictions about the amount of data the rover would be able to send back to Earth via an overpassing satellite. They then needed to relay this information to other team members, including scientists who may update their data collection plans, and path planners who may choose to take a path that optimizes for data transfer.

> *Currently our method of evaluating our heading choices is to open all of the plots on different computers or windows and to examine each one, moving them around the screen to compare next to each other. Sometimes we will even print out some of the plots and hold layered paper up to the light to compare them together.*
>
> — NASA operations engineer

The design of Meridian began with field user research with 4 spacecraft operations engineers (the entire active MER mission operations team). The 2-hour engagement included semi-structured interview and artifact walkthrough using a Think Aloud protocol with the 3-person research team. The team coded observation notes which they translated into design hypotheses.

These hypotheses were refined over 10 weeks via 6 rounds of prototype evaluations with 1-4 users per test, totaling 13 evaluations with 9 distinct users. Tests included 2-4 problem-solving tasks, sampling from examples we drew from formative field observations. Participants were asked to solve tasks while thinking aloud, and the researchers conducted semi-structured post-interviews to review problem solving strategies and discuss critical incidents.

Evaluations evolved from paper to software prototypes that represented real data using mission-accurate models. During the entire research and iterative design process, on the order of 150 distinct critical incidents were observed. Design iterations that successfully resolved critical incidents were

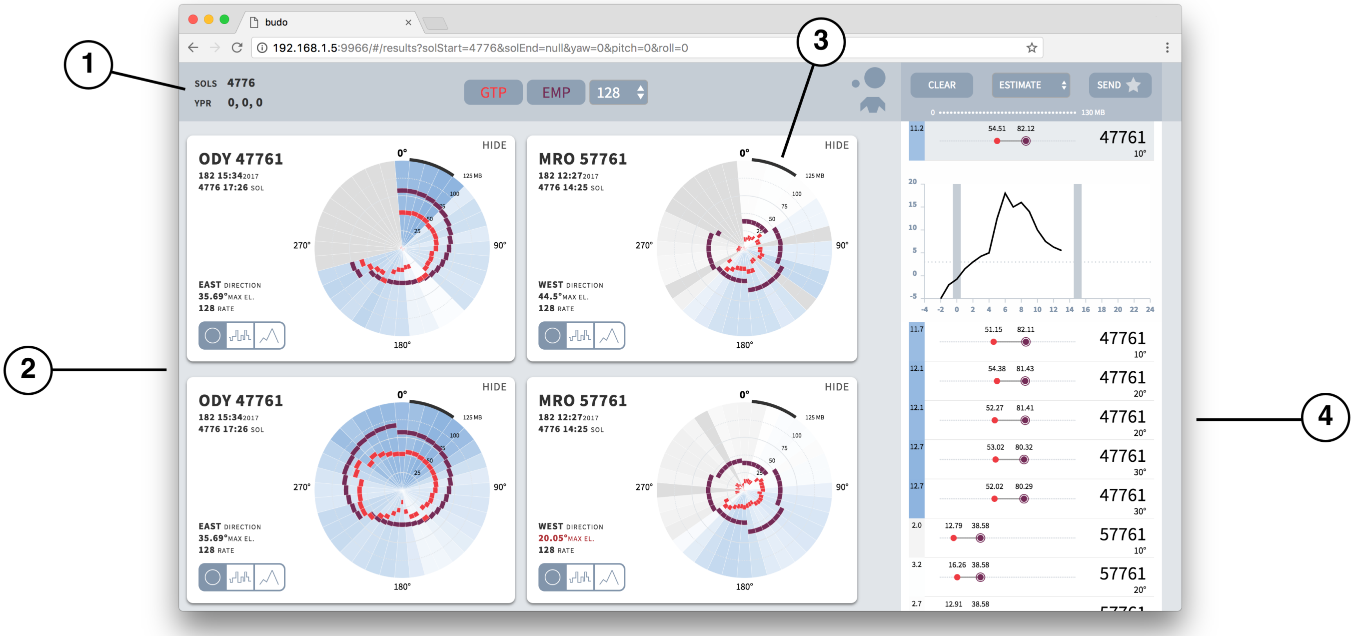

Figure 1. The *Meridian* system was designed for operations engineers at the NASA Jet Propulsion Laboratory. Engineers using the system are tasked with selecting a heading at which to park the rover and an overpass to use for transmitting data. Users of the system (1) enter information about the rover's location; (2) observe the available overpasses given the provided information; (3) brush on the polar plots to select a range of headings for additional inspection; (4) use the detail panel to select a heading and overpass pair.

noted, and these collected key insights were then consolidated and abstracted into the presented design principles.

Shown in Figure 1, the tool we built assists operations engineers with analyzing telemetry predictions, enabling them to surface information important for making decisions about path planning, data collection, and data transfer. The engineers must quickly find information to inform their daily planning of the rover's path, considering multiple possibilities and the risks associated with them.

Each day, our users are tasked with (1) recommending a satellite to connect to *Opportunity* and (2) picking an angle at which to park the rover in order to optimize data transfer to that satellite. Each combination of satellite and angle would result in a different amount of potential data transfer ("Data volume is what counts!" U1). By way of a computational artifact, previously engineers organized data by satellite overflight. This made it easy to compare data rates across parking angles within a single overflight (Figure 3B). However, during evaluation of the original system, multiple users shared that the real cognitive task for spacecraft engineers was to compare parking angles across several overflights. "[I want to] click on 180° and have info about 180 show up for all three [overpasses]," U1 explained. In other words, users were not so much selecting an overpass to connect to as they were selecting an optimal heading at which to drive.

Subsequent prototypes offered direct comparison among particular satellite-heading pairs, resulting in a new design that offers detailed comparison of these pairs on demand through linked-brushing interaction (Figure 3C). The updated design adheres to P3 and results in a system that allows users to make time sensitive decisions much more efficiently. Upon evaluation, for example, U1 noted that "With this change it takes way less effort to make the right call [on heading]."

Meridian's interface displays two estimates of the amount of data that can be transferred to each overpassing satellite in accordance with different orientations of the rover. These estimates are displayed on polar plots (shown in Figure 2). The user is able to select portions of the polar plots in order to see a more detailed view of the information pertaining to those headings. They can then manipulate this detailed view to further sort and filter results, enabling them to surface and report data points relevant to the mission. A video providing a more in-depth discussion of *Meridian*'s user interface is included in the supplementary materials.

Our design process was first informed by in-depth contextual analysis [1] with all the operators, including semi-structured user interviews where we observed them conducting their work. After conducting user and task analyses [6], we then iteratively engaged users in systems usability evaluations with both rapid paper- [9] and code-based prototyping. During these tests, we used a grounded theory analysis to interpret our successes and failures, and saw themes emerge from within individual tests. We describe these cross-test unifying themes as our design principles.

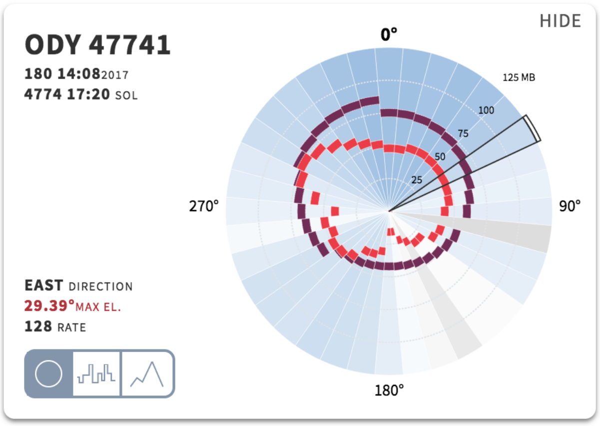

Figure 2. This card is one of the primary widgets in the *Meridian* system. It efficiently communicates information and provides an affordance for users to further investigate specific subsets of the data.

PRINCIPLES

We offer the following seven principles to guide designers who create visual analytic systems for operations contexts:

- **P1** Data must come with context
- **P2** Visualize relationships as well as individual data points
- **P3** Let users travel through the data along the most important decisional dimension
- **P4** UI flexibility needs to be deeper than linking and brushing
- **P5** Surface issues early, with diagnostic tools if necessary
- **P6** Don't remove data, even if it may not be used
- **P7** Use data at a resolution appropriate for the task at hand

In this section, we outline our design principles, unpack their significance, and offer illustrative examples of how they can successfully be employed.

Data must come with context

Data analytics systems often enable complex ways to filter, sort, and otherwise sift through data across dimensions. Card et al. note that systems should provide users with both overview and detailed information simultaneously [4]. In an operations setting, cues must also be provided to relate data back to the decision being made. When operators search for an answer to a specific question about the data, they often need to understand a variety of the data's features. Tomaszewski [12] and MacEachren stressed the importance of providing context when discussing their visual analytics system for crisis relief. When drilling down into details, users need to be cognizant of where the data came from, enabling a better understanding of how the data relates to other data points around it.

In early designs of *Meridian*, we offered users a powerful way to drill down into data by implementing an interaction that spanned many small multiple visualizations. These visualizations consist of polar plot overviews drilling down into various dot plot graphs and line charts. The result of this interaction was a selection of data points about particular headings, collected among several overpasses. This interaction assisted comparison across relevant subsets of the data, but was limiting if users couldn't link the selections to their origins. During tests of an early mock up of the system (shown in Figure 3C), users were able to select data points from certain headings to be shown in a detailed view, but expressed confusion and lost track of where the detailed data came from. Although the overview and details were shown simultaneously as Card et al. suggested, the principle was violated because the system didn't provide any visual callback to the decision of choosing a proper heading. In the final iteration, we provided context by establishing a sequential order: users first make heading selections dependent on the estimates, GTP and EMP, and then examine the link margin value. This context allows users to interrogate not only the values of data, but to also understand its origin and build a more holistic model of the current circumstances.

Visualize relationships as well as individual data points

Data cannot be looked at in isolation. In addition to providing the user with information about where data came from and its relevance, an effective tool for operations must highlight relationships embedded in data. These relationships may be important trends (*"This value is higher than normal!"*) or highlight critical system configurations that impact decisions (*"We have additional capacity in subsystem B, but thermal levels are concerning, so avoid making any changes for now"*).

When designing *Meridian*, we learned through interviews with operators that "Data volume is what counts." To this end, we layered predictions from multiple overpasses to show the predictors' total reach, enabling clear identification of the heading at which operators would receive the highest data transfer rate. This was problematic, however, because each of the predictions contained 64 data points (two for each heading from 0-360° in 10° increments). This led to incomprehensible visualizations when comparing across predictions for more than two satellites. Furthermore, through testing our designs, we found that operators often used direct comparisons between both predictors to confirm the accuracy of the prediction. By isolating plots in small multiples instead of layering them, we limited each plot to showcasing the relationship between predictors for a given overpass. This visual encoding places an emphasis on their consensus rather than a particularly good reading from one or the other.

Let users travel through the data along the most important decisional dimension

Operations tasks typically involve balancing various priorities and investigating numerous options in order to arrive at a decision. For example, *Meridian* users needed to choose a heading to steer the rover and a satellite for it to connect to. This choice is driven by priorities for scientific collection and the predicted amount of data available to transfer at each heading for each satellite. Shifting priorities could affect the workflow and present many possible entry points to the task.

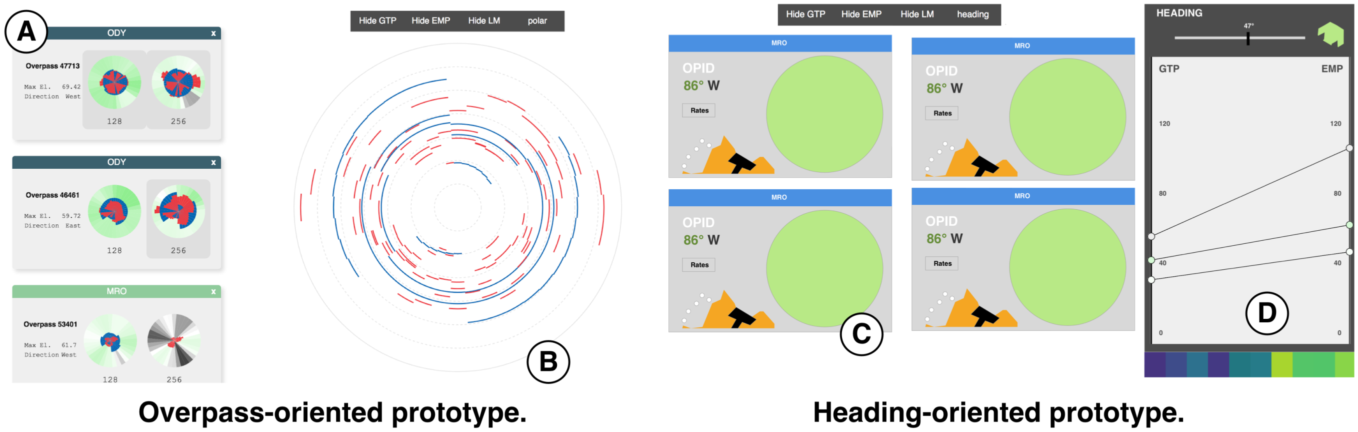

Figure 3. Two early renderings of the *Meridian* system. In the overpass-oriented prototype, users use cards (A) to select particular satellite overpasses for direct comparison in the large central plot (B). This overlaying of multiple overpasses in a single plot was hard for users to parse and violated Principle 3. In the heading-oriented prototype, the panel (D) on the right displayed the values for a particular heading for each overpass, but operators found it difficult to connect the panel on the right to the cards on the left (C) — this design violated Principle 1.

An early design (seen in Figure 3A) violated this principle by prompting users to navigate by satellite rather than by heading, and users struggled to find answers to their questions. We wanted to give users a path through the data that would surface answers quickly and confidently, so we examined which of the dimensions in the data were the most important for decision-making. In addition to picking a satellite, users needed to select a specific heading at which to orient the rover: one which would offer a reasonable quantity of data and prevent steering the rover off-course. We therefore redesigned the interface to center around the heading as the operative dimension. Operators were able to quickly access data they needed and make important comparisons across a smaller data set.

The *LiteVis* system shows a more explicit implementation of this principle. The interface allows users to provide information about their weighted priorities in determining a lighting model. They can run simulations and traverse results along a vector sorted by this multi-objective optimization, allowing them to explore the space of a particular optimization.

UI flexibility needs to be deeper than linking and brushing

As operational priorities shift, it's important that visual analytics tools are flexible enough to keep up. Designers of these tools cannot rely on a static workflow where operators will use the same patterns to access data daily. It is common for visual analytics toolkits to offer interactive features like linking and brushing to enable users to analyze different portions of data for different tasks. However, in operations contexts where decisions need to be made quickly, these generic interactions often aren't enough to support the task.

Designers should strive to build a system that supports users as their priorities shift, potentially allowing entire portions of the UI to change based on user input. The *Decision Exploration Lab* takes this idea to the extreme, allowing users to view a visualization of a decision space generated by the program based on input from the user about business logic and rules.

A simpler execution of this principle can be seen in *Meridian*'s polar plots. Most days the operator will consider different possible headings. However, some days they may only be interested in a specific range of headings, say those near 160°. We found in our tests that users would often cock their heads when looking at plots to realign the center. To reflect this natural impulse, the tool controls allow users to re-orient all the visualizations in the interface to center around 160° , reducing the cognition required to make the comparisons necessary for this specific task. On a different day, the operator may know they must make a connection to a particular satellite, and choose a heading only based on predictions about that satellite. In this case, the interface allows them to resize the card corresponding to the satellite overpass of interest, thereafter conducting analysis on a nearly full-screen view of the information about that particular overpass.

Surface issues early, with diagnostic tools if necessary

Operations systems should raise warnings as early as possible in the design process, both to save users valuable time and to provoke further investigation as needed. While the types of issues the system could flag may include anomalies in the data, issue awareness should not be limited to anomalies. Often a certain configuration of data may render some decisional options off-limits for a particular task — the system should flag these scenarios, too.

Users of *Meridian* initially requested that the tool include a way to explore the shape of terrain around the rover. After discussing potential designs, we realized that the operators weren't concerned with the terrain itself, but rather with whether an overpassing satellite's trajectory would intersect with any objects surrounding the rover. This is a calculation that computers can perform efficiently, so instead of providing a 3D window to view terrain from the perspective of the rover, we simply provided a warning in the case that occlusion was likely. In these circumstances, the operator could further investigate and decide whether that satellite pass was appropriate for use. The operator could therefore address this potential issue at the commencement of their analysis instead of spending valuable time investigating a certain satellite overpass only to realize its limitations.

Don't remove data, even if it may not be used

It is of utmost importance that operations engineers are able to trust their analytics tools and understand any operations that the system is performing. As designers, we may be tempted to simplify the interface by removing pieces of data that we know aren't relevant for certain tasks; however, design choices like this may have repercussions.

For example, some of our designs removed data from headings that weren't appropriate for a particular task. This led to confusion because it removed important context that operators wanted to see: "There will sometimes be outliers, so I go to look at the link margin plot and that will tell me if I have an outlier, and then I'll check the terrain data and that will tell me if I have an outlier." Operators relied on seeing the overview of the entire space of possibilities to make some implicit estimates about the reliability of their predictions, a skill that was honed over years of working with this particular data set. Removing items affected the way that operators could reason about the larger ecosystem of data.

However, we do want to empower users to remove or hide data as they see fit. This follows from research into agent-based systems: actions in the interface should be initiated by the user [7]. To preserve a user's confidence in an analytics system, the user must feel as if they are in control of its operation. To this end, we give the user the option to hide and recover overpass cards at their discretion.

Use data at a resolution appropriate for the task at hand

While we've expressed the importance of not hiding or removing data without the user's consent, it is acceptable (and in most cases essential) for a system to display data at various resolutions, providing the user with only as much information as is relevant for the task at hand. This principle often manifests in visual analytics systems through hierarchical views with "overview-first" and "drill-down" stages of inquiry [11]; however, it can take many forms.

For example, in the *ViDX* system, the interface intelligently aggregates data points. Temporal data following an expected trajectory is displayed in a highly compressed form. Even so, data points that are considered outliers are displayed at a higher resolution, and thus stand out visually.

In our *Meridian* system, the heading for each overpassing satellite has an associated time series of link-margin strength that predicts the strength of the connection throughout the duration of the satellite's overpass. We operationalize this time series with multiple encodings relative to its relevance for each step in the task. In the overview step, we encode its maximum value with just a color (see Figure 2). All values above a preset threshold manifest along a spectrum of blue, but if the value never reaches this threshold it is displayed in grayscale, signaling to users that they can immediately filter out that heading or demote it in their consideration. When users select a satellite and some individual heading to investigate, we then display the entire time-series, allowing users to ensure they understand the characteristics of the overpass and double-check that the conditions are acceptable. In this way, the data is displayed at the granularity appropriate for the particular step in the task.

CONCLUSION

Tasked with improving the workflow for Mars Exploration Rover telecommunications operators, we transformed a complex, distributed process into a singular interface that supports efficient and flexible decision-making. Reflecting on our design process, we discovered that many of our findings could be distilled into principles broadly applicable across similar domains. In this paper, we have presented seven design principles to inform the design of visual analytics systems in operations contexts. We hope that this contribution inspires continued examination of this space, enhancing the experience of individuals and teams engaged in this constant yet supple work practice.

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