Human Factors Principles in Information Dashboard Design

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Abstract

Refueling outages remain one of the largest opportunities for improving capacity factor and reducing costs available to commercial nuclear power plants. Although the nuclear industry has made steady improvement in outage optimization, each day of a refueling outage still represents an opportunity to save millions of dollars and each day an outage extends past its planned end date represents millions of dollars that may have been spent unnecessarily. Reducing planned outage duration or preventing outage extensions requires careful management of the outage schedule as well as constant oversight and monitoring of work completion during the outage execution. During a typical outage, there are typically more than 10,000 activities on the schedule that, if not managed efficiently, may cause expensive outage delays. Management of outages currently relies largely on paper-based resources and general-purpose office software. A typical method currently used to monitor work performance is a burn-down curve, where total remaining activities are plotted against the baseline schedule to track bulk work completion progress. While methods like this are useful, there is still considerable uncertainty during a typical outage whether bulk work progress is adequate and therefore a lot of management time is spent analyzing the situation on a daily basis. This paper is a case study of how new technology, in combination with established human-factors and user-centered design knowledge, can be used to support Outage Control Center (OCC) personnel decision making. In particular, we describe recent advances made in developing a framework for the design of visual outage information presentation, as well as an overview of the human factors principles that informed the development of the visualizations. To test the utility of advanced visual outage information presentation, an outage management dashboard software application was created as part of the Department of Energy's Advanced Outage Control Center project (AOCC). This dashboard is intended to present all the critical information an outage manager would need to understand the current status of a refueling outage. The dashboard presents the critical path, bulk work performance, key performance indicators, outage milestones and metrics relating current performance to historical performance. Additionally, the dashboard includes data analysis tools to allow outage managers to drill down into the underlying data to understand the drivers of the indicators.

Key Words: Visual communication; Outage Control Center; Nuclear Power Plant; Human-System Interface; Human Factors Engineering; Dashboard

1. Introduction

The conduct of refueling outages at commercial Nuclear Power Plants (NPPs) remain one of the biggest opportunities available to the nuclear industry for improving capacity factors and reducing costs. Refueling outages are some of the most challenging periods that utilities face, in both tracking and coordinating thousands of activities in a short span of time, typically between twenty to thirty days. Outage work requires a large supplemental workforce, including hundreds of contract personnel, which increases the complexity of communication and information flow. Other challenges, including work sequencing, workgroup coordination, nuclear safety concerns arising from atypical system configurations, and resource allocation issues, can create delays and schedule overruns, driving up outage costs. Although the nuclear industry has made steady improvement in outage optimization, each day of a refueling outage still represents an opportunity to save millions of dollars and each day an outage extends past its planned end date represents millions of dollars that may have been spent needlessly. Reducing planned outage duration or preventing outage extensions requires careful management of the outage schedule and constant oversight and monitoring of work completion during the outage execution. To address these challenges and conduct research into improving the management of Nuclear Power Plant (NPP) outages, the Advanced Outage Control Center (AOCC) project was launched as part of the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program.

The majority of NPPs still employ "low-tech" methods and tools to communicate critical information during outages. These tools do not take advantage of advances in modern communication technology, and what is worse, they are slow, inaccurate at times, and also rely on the physical presence of outage staff and key personnel to obtain and validate critical system and work progress status information. Some of the common practices include runners

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that hand-deliver paper-based requests for approval, and the use of radios, landline telephones, and email. Some of the outage staff members are desk-bound in the existing outage control center (OCC) and obtain their information from their desktop computers, daily printouts of the schedule, and static whiteboards that are used to display information. This information not only consumes physical space in the OCC, but also requires regular evaluation to determine its validity. These processes for controlling and disseminating information are also labor intensive and prone to error, often due to a time lag between the generation of the information and its availability in the OCC.

There have been recent initiatives at several NPPs to apply new technology in the OCC to make outage information visible and sharable among outage control center personnel. These tools utilize standard information and communication technologies to enable communication, collaboration, real-time data streaming, and information sharing to and from the field. Some of the most promising tools to have emerged in recent times are sophisticated data visualization tools like Qlik Sense® and Tableau®, and new visualization techniques in large statistical and data analysis tools like SAS® Suite, SAP®, and others. However, these tools provide only a marginal improvement for OCCs, since the information is essentially still presented in conventional formats. The technology simply changes the medium through which the information is accessed. Interpreting the raw data still requires significant mental effort due to the complexity and volume of information.

A visualization method that is growing in popularity is to aggregate and present a set of related information in a specific work context. The resulting visual representation is often called a dashboard (analogous to the instrument panel of a vehicle). When implemented in the OCC, such a dashboard would typically display various charts and graphs, numerical data in tables, and text about the status and progress of the outage. However, in spite of many new ways of displaying outage schedule and resource information, most of these displays do not take full advantage of proven human factors principles, and particularly visual communication and human visual perception. This can be detrimental to optimal decision-making and effective communication.

As more “high-tech” methods and tools are incorporated in the OCC as part of the transformation to an *advanced outage control center*, it becomes critical to provide tools that will improve the crew’s ability to perceive, process and interpret the data. This is a common theme of the “big data” challenge - extremely large data sets need to be analyzed computationally to reveal patterns, trends, and associations, especially as it relates to human interaction with such data and the responses required.

Big data is not characterized simply by the sheer quantity of data, but also by the complexities and hidden relationships between data points. The analysis of complex data requires a specialized process that conventional statistical methods and business intelligence applications cannot handle. In the evolving OCC, this process should seek to uncover hidden patterns in complex data that can then be used to make better and quicker decisions. Analysis can also leverage past performance to improve overall outage efficiency and performance.

However, conducting complex data analysis alone does not improve efficiency. An important part of a human-centered approach to OCC information design needs to do more than just introduce technology tools to assist the outage staff and optimize outage resources. This strategy is incomplete and will be ineffective without specific attention to identifying how results must be transformed into reliable, meaningful information, which is needed to assess the way outage information is communicated in the OCC, and ultimately build knowledge and improve decision-making. This requires an analytical approach to the collection, processing, and display of outage information to ensure that cognitive demands on users will be minimized.

2. Objectives of the AOCC Project

The identification of the shortcomings of existing information and communication practices in existing OCCs indicated a need to include a human factors perspective in the analysis of the nature and structure of OCC information, as well as the patterns of current communication and information flow. The ultimate aim was to develop an advanced information visualization tool that presents not only raw data, but performs some pre-processing of data before presenting it as context- and task-specific information. The aim was further to discover and highlight relationships, or, where possible, to discover patterns and interdependencies. One of the most challenging objectives was to develop methods for estimating time-to-completion of an outage using data analysis of the current schedule and historical performance of the NPP, and present this to the outage team to provide an “at-a-glance” indication of outage performance and risk.

However, it was soon determined that the complexity and sheer volume of outage information needed to not only take advantage of data analytical methods, but also data visualization techniques that would allow the human brain to process information more efficiently when presented in different forms. Although it is true that graphical presentation of information is often better than words or numbers, simply presenting raw data as graphs, as is usually the case at present, does very little to reduce the cognitive burden. Much of this burden could be reduced by applying big data analytical “pre-processing” techniques before displaying the data. This calls for a more human-centered approach, which will be explained in this article.

Currently, making sense of OCC data relies almost entirely on prior knowledge and experience. Often, the primary coping mechanism available to team members in perceiving and interpreting information is their own cognitive abilities. It is a known fact that, for much of the nuclear industry, there will soon be a large loss of knowledge and experience as senior staff retire and are replaced by younger, less experienced staff (IAEA, 2008). Combining better communication technologies with data analysis would provide an effective way to capture much of the valuable knowledge of retiring staff, while at the same time simplifying outage procedures and processes.

3. Human Factors Principles in Data and Information Visualization

Human factors principles in communication processes are fundamental to what is designed, how it is designed, how it is used, and how the designed system influences subsequent communication among users of the system. This applies to hardware or software, in any work domain, and all types of stakeholders and users.

Visual communication, whether in paper or electronic form, is an important source of information for OCC staff. For an advanced OCC, the type and quantity of information displayed would be determined by the number and makeup of staff assigned to the OCC, physical dimensions of the OCC, workstation configuration, and physical space available for displays.

Every information or operational display must be designed to support a particular task, or set of tasks. This includes functions integral to the display, such as navigation, controlling, decision-making, learning, or communication. It is essential that the display and its functions must be matched to the mental model, perceptual capabilities, and understanding of the users and enable them to process whatever information is presented. This is where human factors and visual analytics can work together to design a system that will improve the effectiveness of communication between all members of the team, under all operational conditions (Keim et al., 2010).

Communication is commonly defined as “the act or process of using words, sounds, signs, or behaviors to express or exchange information or to express your ideas, thoughts, feelings, etc., to someone else” (Merriam-Webster Dictionary). This definition is actually incomplete, because it does not take into account the factors that may determine how successful the sender is in conveying meaning, nor how successful the receiver is in interpreting the intended meaning. In information theory terms, this is the effect of entropy, that is, the amount of disorder or uncertainty that may exist between sender and receiver. This uncertainty can increase as a result of interference in the communication channel, leading to distortion of the intended message and thus loss of meaning. Meaning, and not information content, is the key factor in successful communication, and thus the failure to communicate meaning clearly (that is, misinterpretation, or incomprehension), is the failure of the communication process.

Understanding of the communication process is fundamental to what is designed, how it is designed, how it is used, where it is used, and how the designed system influences subsequent communication among users of the system. Making sense of messages conveyed by a system requires also understanding the system’s features, the context and work domain within which it is used, and the consequences of responding or not to the message. This also requires a heightened sensitivity to the characteristics of the communication medium and the ways in which communicative choices shape the perception and definition of situations (Rice & Stohl, 2008).

It is the task of the visual designer to understand how the perception, cognition, and communicative intent of visualizations will affect the observer’s mental model. This requires carefully applying the human factors principles of good design. This includes visual techniques that can be used to either emphasize important information or de-emphasize irrelevant details. Certain design choices affect the perception and cognition of the visualization, and therefore viewers' comprehension of visually encoded information, and ultimately their situation awareness, the ability to respond correctly and effectively to messages, and the ability to make well-informed decisions. (Agrawala et al., 2011).

The human factors principles underlying successful communication can be simplified as follows:

- *Messages* and *Sense-making*– A message is the fundamental unit of interaction between humans, and also between humans and systems. The latent meaning, that is, the semantic content, in a message can be described as the “…mental representations of an object or phenomenon, its properties and associations with other objects and/or phenomena. In the consciousness of an individual, meaning is reflected in the form of sensory information, images and concepts (Bedny & Karwowski, 2004). Acquiring meaning from any visual display provides not only orientation in a situation, but also regulates the executive actions of the operator. However, we know that meaning is neither constant nor consistent and is influenced by context as well as an individual’s frame of reference and experience. The semantic content of objects has a contextual character and is thus determined through the relationships between action and situation and may easily change when the context or situation changes. Because situations can persist for a long time, meaning can become "convention" and such conventions can become deeply embedded in language, culture and even operations, procedures, and policies. Even when the situation changes, such conventions can be so ingrained that they are extremely difficult to change, with the result that the original intended meaning no longer has any relevance. In a mission-critical environment like a nuclear power plant, this could have disastrous consequences. *Sense-making* is thus the ability to gain meaning from the content, context, and intent of a message. Designers should make all possible effort to ensure that information objects in the work domain support gaining and sharing knowledge among all OCC disciplines.

- *Visibility, conspicuity, foreground and background* - the shape, size, color, orientation, and location of information objects all work together to various degrees to determine the saliency (detection, discrimination and recognition) of the object. In addition, when observers view an instance of an information display, they automatically decompose the image into foreground objects and background. Foreground objects appear nearer and are more likely to be fixated and attended to. Size, shape, color, brightness, contrast, orientation and viewing distance make some objects more likely to appear as foreground while others are more likely to be seen as background. Dashboard designers should understand that these factors are the prime determinants, not only of text legibility, but of overall saliency and discriminability of information objects. Ultimately, these factors will influence the success with which a person will be able to make sense of the visual message.

Like human factors, visual analytics is also a multi-disciplinary field that involves multiple processes and a wide variety of application areas. It can be defined as a combination of automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex datasets. Visual analytics is different than 'standard' approaches to analysis. It is based on the assumption that interactive visual representations can amplify human natural capabilities for detecting patterns, establishing links, and making inferences (Tufte, 1997; 2001).

In practice, visual analytics aims to create tools and techniques to enable people to synthesize information and derive insight from large amounts of dynamic, ambiguous, and often conflicting data. Coupled with this is the desired ability to detect the expected and discover the unexpected. This requires timely, defensible, and understandable assessments of data, and the means to communicate these assessment effectively for action.

For NPP refueling and maintenance outages, it is vital to monitor the progress of activities and identify measures that must be taken to optimize resource utilization and prevent schedule overruns. During our work on the AOCC project, we have realized that information visualization can benefit from the combination of human factors principles, visual analytics, data analysis, and computational transformation techniques to support analytic reasoning, and thus the sense-making process. These techniques can help optimize the on-going progress of the outage and help staff implement mitigative measures to respond to emergent issues.

4. The Need for an Integrated Information Display

From observations during outages so far, we have seen that to achieve even a single objective often requires access to a collection of information that is not necessarily related, often coming from diverse sources related to various outage, maintenance, and operational functions. This information is often difficult to classify due to large variability, and each recipient must spend some cognitive effort on determining the relevance to his or her job. This information can be one or more key outage performance indicators (KPIs), it could be quantitative data, or it could be qualitative information that must be interpreted in the context of the task at hand. The context referred to here is multi-tiered, composed of the physical environment (the OCC), the various operational phases of the outage, specific events during the outage, resource availability, the assigned crew member, and many more. The specific user is any OCC team member that needs up-to-date information on outage status. The specific task is making critical decisions regarding the outage schedule and application of resources. The method used to display data plays a key role in its usability, that is, the extent to which a specific user can perform a specific task in a given context with effectiveness, efficiency, and satisfaction.

Experience in many non-nuclear industries (manufacturing, healthcare, banking, petrochemical, etc.) provides convincing evidence that so-called information dashboards are one of the most effective ways to improve situation awareness and therefore the ability to make well-informed decisions. When properly designed, a dashboard can reduce the complexity of massive amounts of disparate pieces of information from various sources and integrate all information on a single display panel. The outage information on a dashboard is presented as a combination of text and graphics, but with an emphasis on graphical representation. Effective dashboards are highly graphical, not to create "pretty pictures," but because graphical presentation, handled expertly, can often communicate with greater efficiency and richer meaning than text alone. As indicated before, the design process must determine optimal ways to present the information so that it can be perceived quickly and intuitively and enable OCC team members to easily extract the correct and most important meanings from it. This is the real power of an information dashboard - its ability to make the *meaning* of a message more accessible.

The purpose of an outage information dashboard therefore is the visual display of the most important information needed to achieve one or more objectives of the outage, specifically critical decisions that would affect cost, time and resources. The amount of information required should be big enough to allow well-informed decisions, and small enough to avoid overwhelming the cognitive capacity of the performer. Ideally, all information required for critical, real-time decision-making should be observable at a glance and in a single, fixed location. This implies the need for an integrated collection of information that fits entirely on a single display panel so it can be monitored at a glance by all OCC team members. Some or all of the information could also be made available for dissemination to remote locations and handheld devices.

In addition to the visual characteristics of an integrated information display, one of the most important requirements for an outage dashboard is that the information must be actionable. This means “nice to know” information does not belong on a dashboard; it wastes space, time, effort and resources.

A well-designed dashboard, that is, one that applies human factors principles, data analytics, and visual analytics, should produce its most noteworthy advantages:

- Reduce information complexity
- Reduce the number of alert conditions and instead improve the differentiation of alerts
- Aggregate and integrate disparate information
- Include analysis of past performance
- Ensure visual salience (the ability to focus on the right things for the right reason at the right time)
- Ensure a match between information and its visual representation (the right kind of graphic for the right kind of data)
- Direct expression of quantitative measures of performance
- Ensure coherence and understanding of overall context of activities

The introduction of an advanced outage dashboard in the OCC must be done in such a way that the various functions that OCC team members must perform will be retained, but the methods to accomplish these functions may change dramatically by using technology and reallocating some functions currently assigned to individuals. This might lead to a reduction in the number of staff that need to be physically located in the OCC because staff working in the field can now spend their time productively in the field and use communication technology to transmit information to the OCC.

Reiterating the benefits of visual analytics described before, we can see that by placing all of the information needed to support decision-making during outages on a single display, it becomes possible to reduce the burden on cognitive resources. Without well-designed visual communication resources, team members need to supplement short-term memory by printing paper copies and spend significant effort on moving information into long-term memory. A well-designed dashboard will reduce the need to obtain information from other sources, while reducing the need to move the information into long term memory and instead enable rapidly moving it in and out of short term memory as they make sense of it.

5. Deconstructing the Visual Message

Visual communication deals with the visual nature of any representation of quantitative and qualitative information with its diversity and complexity of signs (Hugo & Gertman, 2013). The sign is something that can be perceived by the senses, for example, an icon in the user interface that, through its visual attributes, represents a real-world object like a pump. This means that the sign refers to a specific concept, which can be an abstract mental construct (for example, “transfer of liquid”), or something concrete in the world, such as a physical pump, to which a particular object on a display refers. The same applies to any imaginable visual object on a display, whether graphical, numerical, or textual. The interaction between such objects and their meaning is a perceptive-cognitive process of converting the visual representations (“signs”) into meaning within a given context (with the context itself being another sign). This sense-making process is the innate human ability to connect *how we think* with *what we see*, and vice versa - hence the expression “I see” as a substitute for “I understand.” (Rice & Stohl, 2006, p. 154, 169). When we make sense of something, we refer to what we have learned as “insight.” This is an everyday challenge for all humans who unconsciously and continually are confronted by the meta-cognitive question: “how do I know that what I see means what I think it does?" This is the origin of many usability problems in software, that is, the disparity between how a designer represented the functionality of a system in the user interface, and the extent to which the user is able to use that interface with effectiveness, efficiency, satisfaction, and safety.

Various approaches that have a significant influence on human performance have been developed over the years. These include methods to analyze and inform graphic design, modeling of user interface elements, the design process, and whole environments (Hugo, 2005).

When applying principles of visual communication to a large sociotechnical system like an OCC, it becomes possible to define the requirements for information displays in terms of the relationships between signs and meaning in the specific context of NPP outage information management. This includes the study of the generation, processing, and presentation of primarily quantitative, but also qualitative information that relates to the management of the outage.

The OCC, like the plant's main control room, is a combination of physical and virtual (electronic) constructs. It is in fact governed and defined by a set of syntactic and semantic rules. In visual communication terms, the OCC is characterized by an abundance of concrete as well as abstract signifiers (that is, a symbol, sound, or image that represents an underlying concept or meaning) instantiated in information artifacts like individual computer workstations and display panels for outage information. Communication in the OCC, and interaction with various communication media, is mediated by signs (e.g., icons, symbols, text, and speech), which in turn are representations of various information entities. This this concept allows us to characterize the OCC information space by various forms of representation, ranging from abstract to concrete, and structured in four different sign forms: *lexical* (the "vocabulary" or collection of signs), *semantic* (the meaning of signs), *syntactic* (the syntax or rules for constructing the relations between signs) and *pragmatic* (the relation between signs and their human interpreters).

A visual analytic approach to understanding the nature of the information would consider optimal ways of translating abstract, numerical information into graphical representations (i.e., making the abstract concrete). A visual communication approach would consider the reasons why some visual representations in the OCC are better than others to convey clear meaning. It is possible to map these translations between sign systems (for example, from plant to mimic diagram, system to icon, event to alarm sound). These maps can be qualitatively analyzed, not only for consistency, coherence, and complexity, but also for the semantic value that results from sense-making (Hugo, 2005).

In environments like the OCC (as also in the plant's main control room) one would like to ensure that the display conveys information as unambiguously as possible, so that the meaning is as objective as possible and does not result in misinterpretation and human error. It is important to remember that meaning is influenced by uncertainty or conditions that interfere with accurate communication of concepts.

In the design process, one must consider how the process of sense-making accounts for the extraction of the designer's "intended meaning" from the display. Referring to the semantic content of a sign does not imply that it has *inherent meaning;* it does not. However, signs like gauges, graphs or text clearly have *intended meaning* assigned to them by the designer. This meaning could be conveyed in various ways – the most obvious way is labelling the sign, but context and relationship (for example proximity to other symbols or images) may also help to convey the intended meaning. In spite of these various methods, there is still no guarantee that the user will "get" the intended meaning, because many factors can inhibit effective communication: negative past experience, inadequate training, prejudice, poor visual literacy, interruptions and distractions, environmental interference (e.g., noise or bright lights) and many more.

Because of its usefulness in explicating the relationship between signs and meaning, a visual communication approach to the design of OCC information supports the cognitive-semantic aspects of sign composition and is thus well suited to the analysis and design of displays in this complex task domain. However, it could easily be argued that this involvement in rather abstract decompositions of what would otherwise be regarded as "intuitive design" may trap the analyst in detail that obscures the "big picture". To overcome this difficulty, a coherent taxonomy or framework of structured representations would provide a practical way to ensure consistency and coherence in the display architecture of the visual design (Hugo, 1992; 2005). Since such a coherent framework will also help to structure the information architecture of dashboards, it should be possible to ascertain with a greater degree of accuracy and confidence why, how and when certain display configurations promote and others inhibit comprehension, situation awareness, and general human performance. In terms of theories and models of visual communication, the relationship between the presentation of visual artifacts, their perception by humans, and the interpretation of the meaning of the visual signs, can form the basis of a formal set of principles and patterns that can guide the rational design of information dashboards. Thus, an analysis of the semantic and syntactic architecture of the original information and its visual represenation would also help to assess the saliency of the display overall, and the saliency of discrete signs. In other words, why a particular instantiation of a display is better to convey meaning, and thus promote performance than another.

6. A Model for Structuring the Visual Messages

In all modes of communication, meaning arises from the differences between signifiers. These differences are described as either *paradigmatic* or *syntagmatic*. (The Merriam-Webster Dictionary defines a *paradigm* as a model or pattern for something that may be copied. A *syntagm* is defined as a linguistic unit consisting of a set of linguistic forms (words, phrases, etc.) that are in a sequential relationship to one another.)

All signs, whether visual, verbal, numerical or textual, have these paradigmatic-syntagmatic dimensions that treat signs as part of a system that determines the "value" of a sign. Because of the relationship between signifiers (words, signs and symbols) and their denotation in this sociotechnical system, every artifact in the OCC has meaning or an intended message. In this way the information space of the OCC is constructed from the synthesis of all syntactic and pragmatic elements. We can call this construct the paradigmatic-syntagmatic framework (PSF). This is explicated in more detail below and illustrated in Table 1.

The *paradigmatic dimension* identifies the sign as an element in a set of signs that have a common function. A paradigmatic element serves as a contrastive factor because signifiers ("signs") in a paradigm set will shape each other's preferred meaning by virtue of mental associations. For example, icons, symbols, words or numbers that can be associated with something in a person's mental model.

The *syntagmatic dimension* refers to the combination of signifiers from a specific paradigm to form a meaningful order, or syntax. Such syntagms are commonly found in the structure of visual communication, such as drawing, painting, television, cinema, and graphical user interfaces. In this context, a syntagm can be defined as an orderly combination of interacting signifiers that form a meaningful whole in a display, which means it is a combination of selected elements from all possible paradigms.

The syntagmatic analysis of the information space (whether the information is verbal or nonverbal) involves studying its structure and the relationships between its parts. This analysis seeks to identify elementary constituent segments within the domain - its syntagms. The syntagmatic relations reveal the conventions or 'rules of combination' underlying the production and interpretation of meaning (such as in the grammar of a language). The use of one syntagmatic structure rather than another within the domain, or within a particular message, influences meaning. Some syntagmatic forms may be based on spatial relationships (for example, the arrangement of graphical or textual objects in a user interface, which works through juxtaposition) and on conceptual relationships (such as the appearance of such objects in a particular operational, technical or functional context). The OCC contains, by definition, multiple syntagmatic structures, as shown in Table 1 below.

Syntagms in user interfaces are identified in five groups or relationships that describe the signifiers in the user interface from various perspectives and levels of detail (see Table 1):

1. Physical Interaction System (PS)
2. Subject Matter (SM)
3. Spatial Organization (SO)
4. Figurative Screen Image (FI)
5. Discrete Signs (DS)

Together syntagms and paradigms create a framework that provides a coherent, structural context within which signs make sense.

A simple and convenient notation to express these relationships can be adapted from Set Theory, where a set A with four members is simply expressed as $A = \{a,b,c,d\}$. Different user interface instantiations would be represented as different sets with different members, some of which might be the same members, for example set $C = \{a,b,d,e\}$, set $D = \{a,c,d,f\}$.

Where different instantiations (e.g., set C, set D) of a user interface are compared, the appearance of the same signifiers in both instances would be expressed as a Union (using the symbol $\cup$): $C \cup D = \{a,b,c,d,e,f\}$. Set notation could also be used to describe instances of Intersection (using the symbol $\cap$), in other words, where only some signifiers appear in both set C and set D, i.e., $C \cap D = \{a,d\}$.

The same approach can be used to describe a paradigm in a dashboard, which is the selection of alternative elements to create functional contrasts between signifiers (for example, "analog instrument, or digital instrument, or trend graph", etc.). Simple set notation could be applied to, for example, a paradigm of Spatial Organization for "System Information" that identifies the following syntagms (that can also be called "syntactic sets"):

A: 2-Dimensional field (text, numerical values, static line graph)

B: 3-Dimensional field (photo, 3D image)

C: Temporal Dimension (video footage, dynamic trend graph)

For a mutually exclusive instance, this paradigm could be expressed as SO = {A,B,C}, which reads: “the spatial organization of system information will employ 2-dimensional spatial layouts or 3-dimensional component images or dynamic trends graphs and video”.

Similarly, a syntagm for an individual display (X) would be expressed as:

Interface Instance(X) = {PS,SM,SO,FI,DS}

This is exemplified in the following syntagmatic sentence (words in italics are added to render a grammatically readable statement):

Interface Instance(X) = (SO{A} "The LCD monitor [*displays*]") + (SM{A,B} "controls [*for the*] main cooling cycle") + (SO{A} "[*as a*] flowchart") + (FI{A} "at 1280 x 1024 resolution") + (DS{A,B} "[*using*] abstract and concrete representations [*of*] plant equipment").

The following two tables explain the implementation of these concepts in the PSF approach. Table 1 shows the basic framework without content:

Table 1: The Paradigmatic/Syntagmatic Framework

	MACRO LEVEL		**MESO LEVEL**		**MICRO LEVEL**
Horizontal Syntagms →	**Physical Interaction System (PS)**	**Subject Matter (SM)**	**Spatial Organisation (SO)**	**Figurative screen image (FI)**	**Discrete Signs (DS)**
Vertical Paradigms ↓	A. Computer Hardware	A. Category / domain	A. 2-Dimensional field	A. Size, brightness, resolution	A. Shapes & forms
	B. Software	B. Complexity Level	B. 3-Dimensional field	B. Color	B. Icons
	C. Environment	C. Graphic / symbolic / textual	C. Temporal dimension	C. Level of realism/abstraction	C. Indexes
		D. Concrete / abstract		D. Composition, layout, image	D. Symbols
Signifier level	Size of Objects/Signs, Spatiality, Contrast, Shape, Form, Colour, Texture				
Signification level	Connotative & Denotative content: Arbitrary Signs - figurative represtentations, realistic images Logical, cognitive or denotative content Connotative or associative meaning Stylistic meaning Affective meaning				
Syntagms	PS{A, B, C...}	SM{A, B, C...}	SO{A, B, C...}	FI{A, B, C...}	DS{A, B, C...}
Syntagmatic Individual Interface (X) thus expressed by:	**X = {PS, SM, SO, FI, DS}**				

This framework can also be regarded as an ontology of the information space where horizontal paradigms are linked epistemically to the lower ontological levels.

With reference to the earlier discussion of Meaning, we can now see that a *paradigmatic connotation* results when the meaning of a specific interface is derived from the knowledge that it is a choice from among other representations, e.g. the same system or process. *Syntagmatic connotation* results when meaning is not derived from a single element on the interface from among others, but based upon a comparison with other signs on the same display, or with preceding and succeeding displays. The difference between actual (current) and "potential" displays determines the connotation. Since this has a direct bearing on OCCs staff’s ability to predict the future state of the system, it also has a direct influence on situation awareness.

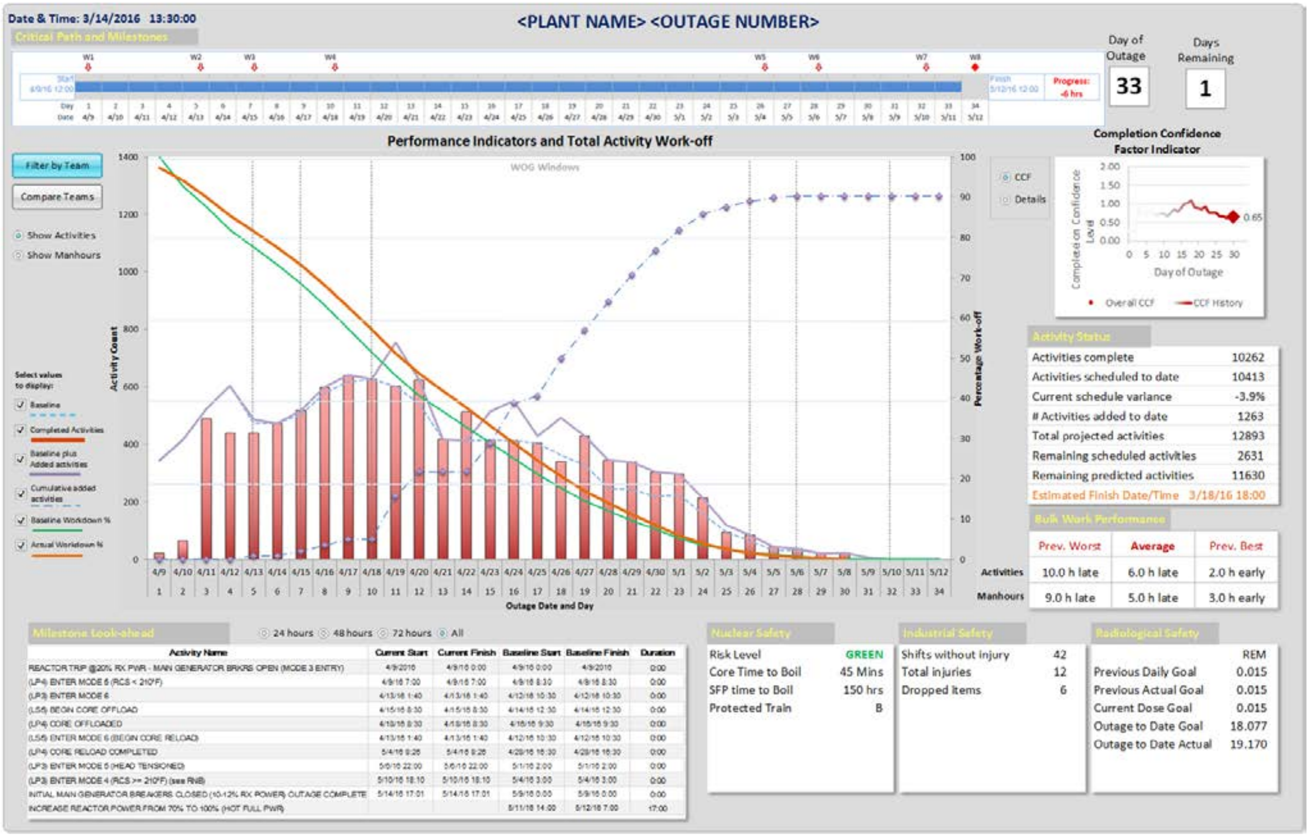
As shown in Table 2, at the signification level of the PSF, connotative meaning is influenced by a large number of factors, including what is often referred to as “conventions.” In fact, some conventions have become so pervasive that they acquire denotative meaning, for example the “conventional meaning” of objects in the Microsoft Windows® user interface, like icons and symbols that represent files, folders and functions. As Dekker and Hollnagel (2004) point out, such conventions result from assumptions about “…non-observable constructs that are conveniently endowed with the necessary causal power without any specification of the mechanism responsible for such causation”[3]. Although they were referring more to the consequences of inferences made about the reason for operator behavior and performance deficiencies, this has a direct bearing on the influence that erroneous assumptions about the meaning of representation in the dashboard design may have on OCC staff’s mental models. The PSF approach would largely avoid this problem because the focus is firstly on the objective characteristics of discrete elements, and secondly on understanding the nature of the process of sense-making in the OCC, in other words, exactly how do people get meaning from various information artifacts? It is vital that the signification level of the dashboard, and especially the origin of connotative meaning, be included in the understanding of situation awareness. The obvious reason is because connotative meaning based on false conventions may result in inaccurate mental models.

7. Application of the PSF to a Dashboard Design

Past experience in many Outage Control Centers provide compelling evidence that existing ways of providing outage performance information is suboptimal. With the advent of sophisticated software, large, high-resolution display panels, and versatile hand-held devices, it is now possible to eliminate paper and create an information dashboard on a range of devices that are easy to use and will likely lead to significant improvements in communication, as well as maintenance and work management processes.

The prototype dashboard developed for this project has provided evidence that visual communication and visual analytics together are particularly relevant in work domains that relay heavily on electronic communication media, because they are so rich in different forms of visual representation. Both fields are also closely associated with human-system interaction and situation awareness, two of the cornerstones of human performance in nuclear power plants.

Figure 1 shows an early prototype of the dashboard (a number of pop-up panels used to configure the display are not shown). This display contains a large amount of information that may seem overwhelming, but for the OCC team member, this provides an intuitive way to understand the status of the outage at a glance. Much of the display can be customized to suit the needs of the users by allowing them to show or hide specific items, or to filter the information according to certain criteria. A more advanced version that places more emphasis on the “Completion Confidence Factor” (the small graph at top right) is currently being tested by a number of NPPs in preparation for commercialization of the software.



Activity Status

Activities complete	10262
Activities scheduled to date	10413
Current schedule variance	-3.9%
# Activities added to date	1263
Total projected activities	12893
Remaining scheduled activities	2631
Remaining predicted activities	11630
Estimated Finish Date/Time	3/18/16 18:00

Bulk Work Performance

	Prev. Worst	Average	Prev. Best
Activities	10.0 h late	6.0 h late	2.0 h early
Manhours	9.0 h late	5.0 h late	3.0 h early

Milestone Look-ahead ○ 24 hours ○ 48 hours ○ 72 hours ● All

Activity Name	Current Start	Current Finish	Baseline Start	Baseline Finish	Duration
REACTOR TRIP @20% RX PWR - MAIN GENERATOR BRKRS OPEN (MODE 3 ENTRY)	4/9/2016	4/9/16 0:00	4/9/16 0:00	4/9/2016	0:00
(LP4) ENTER MODE 6 (RCS < 210°F)	4/9/16 7:00	4/9/16 7:00	4/9/16 8:30	4/9/16 8:30	0:00
(LP3) ENTER MODE 6	4/13/16 1:40	4/13/16 1:40	4/12/16 10:30	4/12/16 10:30	0:00
(LS6) BEGIN CORE OFFLOAD	4/15/16 8:30	4/15/16 8:30	4/14/16 12:30	4/14/16 12:30	0:00
(LP4) CORE OFFLOADED	4/18/16 8:30	4/18/16 8:30	4/16/16 9:30	4/16/16 9:30	0:00
(LS6) ENTER MODE 6 (BEGIN CORE RELOAD)	4/13/16 1:40	4/13/16 1:40	4/12/16 10:30	4/12/16 10:30	0:00
(LP4) CORE RELOAD COMPLETED	5/4/16 9:26	5/4/16 9:26	4/29/16 16:30	4/29/16 16:30	0:00
(LP3) ENTER MODE 5 (HEAD TENSIONED)	5/6/16 22:00	5/6/16 22:00	5/1/16 2:00	5/1/16 2:00	0:00
(LP3) ENTER MODE 4 (RCS >= 210°F) (see RNB)	5/10/16 18:10	5/10/16 18:10	5/4/16 3:00	5/4/16 3:00	0:00
INITIAL MAIN GENERATOR BREAKERS CLOSED (10-12% RX POWER) OUTAGE COMPLETE	5/14/16 17:01	5/14/16 17:01	5/9/16 0:00	5/9/16 0:00	0:00
INCREASE REACTOR POWER FROM 70% TO 100% (HOT FULL PWR)			5/11/16 14:00	5/12/16 7:00	17:00

Nuclear Safety

Risk Level	GREEN
Core Time to Boil	45 Mins
SFP time to Boil	150 hrs
Protected Train	B

Industrial Safety

Shifts without injury	42
Total injuries	12
Dropped Items	6

Radiological Safety

	REM
Previous Daily Goal	0.015
Previous Actual Goal	0.015
Current Dose Goal	0.015
Outage to Date Goal	18.077
Outage to Date Actual	19.170

Figure 1: Prototype of the Outage Dashboard

The PSF framework described before can now be applied to the conceptual design of the dashboard prototype to determine to what extent it conforms to a coherent semantic architecture suitable to outage information. The analysis of the semantic and syntactic architecture of the design will help designers and decision-makers to assess to what extent the design conforms to the basic precepts of good visual communication. This framework can also be regarded as a way to "disassemble" the interface to identify and describe its components, which will help to validate the communicative adequacy of the proposed dashboard.

Table 2: PSF Analysis of a Conceptual OCC Dashboard

	MACRO LEVEL		MESO LEVEL		MICRO LEVEL
Horizontal Syntagms →	**Physical Interaction System (PS)**	**Subject Matter (SM)**	**Spatial organization (SO)**	**Figurative screen image (FI)**	**Discrete Signs (DS)**
Vertical Paradigms ↓	A. <u>Computer Hardware</u>: LCD wide panel displays, keyboards, mouse, printers, buttons	A. <u>Category</u>: Nuclear Generating Station Outage Management	A. <u>2-Dimensional field</u>: Functional and organizational representation of outage status and key performance indicators	A. <u>Size, brightness, resolution</u>: AOCC displays are 60 inch LCD panels at 2560 x1600 pixels. Displays are spatially dedicated, continuously visible (SDCV)	A. <u>Shapes & forms</u>: • Graphs • Graphical critical path • Information pop-ups • Display control buttons (dashboard setup and navigation)

	MACRO LEVEL		MESO LEVEL		MICRO LEVEL
	B. Software: Operating system, User Interface Management System, database	B. Data organization: Moderately complex and abstract data relationships Level of subject matter complexity: High – requires considerable experience and training	B. 3-Dimensional field: None - physical appearance and spatial relationships of information on 2-D field only	B. Color: used to convey specific information (e.g. to differentiate between outage events and characteristics) and to categorize graphic elements. Within the limitation of maximum 7 colors per display, standardized color is also used to indicate interface backgrounds, functional areas and objects.	B. Icons: None in current version
	C. Environment: OCC room structure, consoles, desks, communication equipment, storage, seating, lighting, etc.	C. Combination of graphic, symbolic, textual	C. 4-Dimensional Field (Temporal dimension): Change of graph lines over time, KPI value change	C. Level of realism/abstraction: Top levels of the dashboard employ abstract metaphors (e.g. graphical representation of data value change over time) and lower levels employ more concrete metaphors (textual) to represent outage, schedule status, and resource information.	C. Symbols: Graphical rectangles (histogram bars), solid and broken lines of different thicknesses, triangles (work windows)
		D. Concrete: none Abstract: outage status, key performance indicators, schedule, and resource information		D. Composition, layout, image complexity: Composition and layout follow the outage crew member's natural task flow. Graph and information layouts are kept as simple as possible to avoid ambiguity and visual noise.	D. Indexes: outage performance trend graph, numerical values, relative position of outage graphical data.
Signifier level	Spatiality: Schedule and KPI objects and signs are not arranged on the display to correspond to the spatial layout of the plant or the location of any resource, but to reflect the status and temporal progression of the outage process. Contrast: Active schedule objects (e.g. completed activities) are highlighted to achieve the highest possible contrast with the display background. Inactive objects (e.g. Day-0 Baseline graph) are displayed with lower contrast so that staff can focus on active objects. Shape: Objects are either represented as stylized, recognizable forms (solid or broken lines and histograms) or as abstract symbols (work window symbols, etc.) Color: Graphical outage progress and status data are color coded. Colors used on the dashboard are generally limited to 7, corresponding to the number of variables that can be displayed at any time. Backgrounds are consistently dark grey. Texture: This is generally avoided in the dashboard to avoid visual noise. Metaphor: The predominant metaphor employed in the dashboard is the graphical representation of temporal progression of a number of variables. Since no physical or concrete representations are used, no ecological relationships (i.e. spatial relationships between physical entities) are included in the metaphor. All other metaphors are abstract textual representations of outage status.				
Signification level	**Connotative & Denotative content:** Arbitrary Signs: - abstract symbols for work windows and outage status and processes - trend graphs to indicate real-time value of outage variables - text, diagrams, graphs to represent plant safety and outage performance and status - digital indicators (numeric values & labels) of outage status Figurative representations (object schemata): - no realistic or semi-realistic images are employed in the dashboard - analogue representations are limited to the temporal values of outage variables				

	MACRO LEVEL	MESO LEVEL	MICRO LEVEL
	Logical, cognitive or denotative content: Graphical and textual representations on the dashboard are recognized as abstract outage process, status and performance indicators Connotative or associative meaning: Example: a specific shape of the outage graph (e.g. an extraordinary peak in the dark blue line is associated with a significant amount of activities added to the work scope, or an actual work down graph that is significantly higher than the baseline work down graph is associated with outage performance that is poorer than expected. Stylistic meaning (layout, context, etc.): Example, the spatial relationship between simultaneous representations of different outage variables indicates a possible comparison between planned and actual values at the same point on the time line.		

Syntagms:	**1. Physical Interaction System** is expressed by the paradigms of computer and display hardware, software and physical environment within which the outage crew member performs his tasks.
	2. Subject Matter is expressed by the paradigm of nuclear power station outage management with a high complexity, employing a combination of textual, graphical and symbolic information representation, ranging from concrete to abstract.
	3. Spatial organization is expressed by the paradigm of the 2-dimensional layout of the dashboard (emphasis on SDCV), and the indication of dynamic changes of variables over time during the execution of the outage.
	4. The **figurative screen image** is constructed from the paradigms of size, brightness, resolution, color, level of realism or abstraction, and composition and layout of outage graphical and textual objects.
	5. Discrete signs in the interface are constructed from the paradigms of shape and form, icons, symbols and indexes used to distinguish outage variables and information.
Individual syntagm:	Meaning is thus represented at three levels: • The "frame message" by the vertical paradigms that form the 5 syntagms. • Denotative meaning at the figurative level is represented by the signifiers of spatiality, contrast, shape, color, texture and metaphor. • Connotative meaning at the interpretive level is represented by the signification functions of context and association.

8. Discussion

The analysis above suggests that the visual structure of a dashboard like this can serve as a primary source of outage information for OCC team members. Its visual architecture also seems adequate as a navigational mechanism for users. Dashboard content and appearance has been organized in a way that reflects the nature of the information and that supports efficient and meaningful monitoring of outage status.

Observations of user experience in early trials with the prototype indicated that the combination of visual communication and visual analytics creates a powerful, direct interface between human, data, system and environment, thus amplifying human cognitive capabilities. Six key benefits of the approach have been formulated:

1. Visual communication principles can improve our understanding of how the appearance of specific objects in the real world influences the communication process, and specifically the way such objects are interpreted and how they contribute to the development of mental models of environments, functions and operations;
2. Translating complex, abstract data into directly accessible visual information increases human cognitive resources by providing an external visual resource to expand human working memory. This helps to simplify and reduce the need to search for information by representing a large amount of integrated and synthesized data in a small space;
3. An understanding of the relationship between a sign and its meaning in the overall outage context, will in turn help researchers and designers to understand the reasons why different representational modalities are better than others to convey operational information in specific contexts, thereby improving the chances of achieving the required performance;
4. It enhances the observer’s ability to recognize patterns, for example by organizing information spatially, by time relationships, by function, etc. This also supports easy perceptual inference of relationships that are otherwise more difficult to deduce;
5. It supports situation awareness by simplifying the monitoring of a large number of potential events;
6. Finally, visual analytics helps to create a coherent, consistent, interactive, manipulable medium that, unlike static, raw data diagrams, enables the exploration of the OCC information space.

Ultimately, visual representations of information help us work around a fundamental limitation that is built into our brains - a limited capacity to store information for immediate recall. Although we have tremendous long-term memory capacity, working memory is extremely limited. Graphical representations of quantitative information allow people to store the entire pattern formed by the shape of a graph (histogram, trend graph, pie chart, etc.) as a single chunk of memory. This means that we can store much more information within the limitations of working memory than we could if the values were written as numbers. Simply by encoding information visually, our ability to think and reason about it can be significantly expanded by making more of it available at any one moment.

9. Conclusion

Effective management of NPP refueling outages relies on processing and interpreting enormous volumes of data. This data comes from numerous sources, with schedule data being the largest and arguably the most important data source to analyze. The thousands of activities and associated information makes outages very challenging to manage. Specialized tools are required to allow the work to be managed with fewer resources. This project has determined that improved OCC physical design and technologies and techniques for making outage information visible and sharable are not enough to reduce the workload and reduce risk. What is also needed is new ways to visualize and display information that take human abilities and limitations into account.

The proposed method to analyse and visualize complex data in the design of an interactive dashboard shows significant promise. The dashboard described here takes advantage of lessons learned from data visualization techniques, visual communication, and human factors principles that allow the human brain to process information more efficiently when presented in different forms. Additionally, this kind of dashboard can incorporate historical performance data to help outage managers compare current outage productivity with historical outages. This new dashboard concept not only presents information, but also attempts to predict the completion of the current outage using data analysis of the current schedule and historical performance of the NPP.

However, further investigation and usability testing is necessary to determine optimal placement and configuration of information segments. Further research is also needed to determine how a formal description of the user interface, like the conceptual paradigmatic/syntagmatic framework, can complement usability testing by providing a syntax to describe how an interface might either prevent, or induce human error. Special attention must be paid to visual and cognitive saliency. In other words, does the relative prominence of an information item encourage rapid perception, reduced need for information search, and improved decision making? Such an analysis could also help to describe and remedy critiques by users as interfaces are evaluated.

This article describes some of the principles behind information presentation and dashboard design and how their application has resulted in an innovative software application. This software has been made available to a number of nuclear power plants for testing purposes. After sufficient testing trials, the software will be released commercially to assist nuclear utilities in presenting and understanding true outage status as a method to improve overall outage management.

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