Managing Complexity Through Quantifying Communication in High Reliability Organizations

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Abstract. Organizational communication is a tool to help manage the increasing complexity found in the development of large-scale aerospace programs. System faults found early in the development process are easier to overcome, it is also where faults are more difficult to find because the system design is less mature and there's comparatively more chaos in the process. An organization that follows high reliability principles increases effective communication in a way that can be quantified. The intersection between reliability principles of an organization and the people who work within it then enables communication to increase the likelihood of uncovering undesired and unexpected system properties. Set theory offers a way to represent elements of a human system that differ relationally in qualities or functions. The extent to which communication can be modelled by set theory extends the information available to the organization to predict undesirable outcomes and enhance the reproducibility of reliability. Principles of a high reliability organization emphasize good team making, which leads to good decision making, which leads to better performance. The set theory framework for organizational communication provides a transition from ideas to data so others can particularize their organization's operations such that high reliability principles can be successfully implemented. This will reduce the frequency and impact of unexpected events.

Complexity in Aerospace

Complexity is a key issue in aerospace system development and new ways of managing complexity are currently being explored. Many large programs uncover errors at the end of the integration process rather than during the design phase where the corrections would be less expensive. In fact, the existing enactment of systems engineering needs to somehow be 'fixed' [1]. It doesn't need to be fixed with new processes, but with a new view of the core function of systems engineering. This is difficult because the search is for a fault or organizational structure that will result in a fault that does not or may not exist at the time of the search.

Former NASA Administrator Michael Griffin advocates for what he calls an elegant design, which includes principles of perspective in engineering processes [1]. When failures occur, they seem to

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be at the interfaces between components, and often between components that were thought not to have any connection. Finding these faults earlier in the design process requires holistic thinking. Griffin emphasizes how modern systems engineering is intrinsically a team effort, with members of different disciplines working together to utilize their own specialized talents in a collaborative way. The organizational structures that produce designs will inevitably produce faults, so there is an intrinsic responsibility to design the organizations around the designers. In his own words, "any comprehensive theory of systems engineering must include the study of human interactions which lead to the final result of that effort" [1].

An examination of faults during the design and integration processes in Figure 1 show that while 70 percent of the faults are introduced early in the design phase, faults are not found until closer to the end of the test phase where they are much more expensive to fix [2]. If the faults and organizational structures that result in faults could be found earlier in the development process, the program schedule and budget would be less impacted.

The principles of high reliability applied in aerospace development programs provides a mechanism to uncover faults through communication. An examination of failure in systems designed for use in space found that they overwhelmingly include some element of miscommunication and failed communication modes [3]. Further, although experienced systems engineers are capable of mitigating this problem, it requires the strategic and coordinated sharing of data and other critical information, which may not be known to be critical at the right times [3]. These experiences are not limited to aerospace.

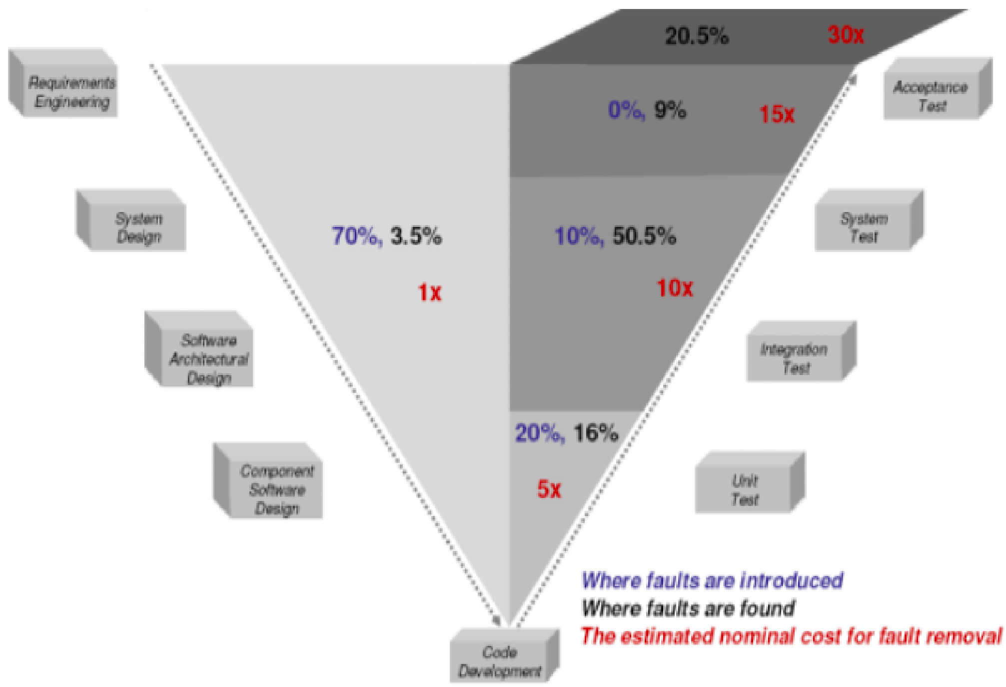

Figure 1. Where Faults are Introduced and Found in Aerospace Systems [Becz]

In the field of crew resource management, it has been found that problems emerge overwhelmingly by failure of cognitive and social skills rather than technical sophistication of the design [4]. A meta-analysis of aesthetic practitioners showed how the communication improved the effectiveness after the application of crew resource management techniques [5]. The issues of urgency and planning present within crew resource management are very similar to the goals of implementing high reliability principles. Using and quantifying the techniques of high reliability organizations can help increase and improve communication effectiveness [6].

Communication and High Reliability Organizations

One way to understand the impact of human interactions in aerospace complexity is as a sensemaking process as defined by Ancona, “a situation that is comprehended explicitly in words and that serves as a springboard into action” [7]. Griffin suggests that systems engineering value the context over structure, interactions over elements, and the whole over the sum of the parts [1]. Ancona then poses the appropriate sensemaking questions within that suggestion, such as what makes an organization explore the wider system, question and test its assumptions, refine or abandon ideas, or adopt multiple perspectives?

Being a highly reliable organization involves coming up with plausible understandings, testing them via action and then either refining these understandings or abandoning them in favor of new ones that better explain a shifting reality. At an organizational level, leaders simultaneously understand why their teams are not functioning, why their customers are leaving, and why their operations are falling short on safety and reliability. Effective leadership includes self-awareness, the ability to deal with cognitive complexity, and the flexibility to go between the “what is” of making sense of the situation and the “what can be" of visioning its future [7].

This sensemaking attention can be brought to aerospace system development through principles that Weick describes as a high reliability organization (HRO). Certain qualities define high reliability, including an organizational culture that supports a way to enact alertness, broaden customattention, reduce distractions, and forestall misleading simplifications. Weick presents the five principles that create high reliability organizations, as listed in Table 1 [8].

Table 1: High Reliability Organization Principles

1	**Preoccupation with Failure**	track small failures to prevent big ones
2	**Reluctance to Simplify**	check your assumptions, be skeptical
3	**Sensitivity to Operations**	adjust to prevent errors from growing
4	**Commitment to Resilience**	bounce back from inevitable errors
5	**Deference to Expertise**	get input from varied sources

HROs pay more attention to small failures. Generally, the HRO looks, rather than waits, for unexpected things to happen. They create an infrastructure that supports paying attention and being mindful, which emphasizes being aware, calmly focused and conscientious. Then HROs clarify the qualities and traits that constitute how and why attention is paid. In short, they don’t know what the failure will be but they know that it will occur. Actively searching for and acknowledging failures certainly affects the frequency and severity of unexpected events [8]. Moreover, encouraging organizations to follow guidelines that anticipate what is coming helps with seeing the little failure before it is a big failure [8].

HROs also pay attention to interactions out of the ordinary, which allows them to proactively learn from mistakes. Interacting on an interpersonal basis as well as a subsystem-to-subsystem basis can be done in a way that both creates and finds failures. Within subsystems there may be a reliance on sensors and telemetry for detecting possible failures. Within people there may be a reliance on principles of communication structures to determine what is atypical. Comparing the intended outcome and requisite knowledge about what can go wrong, the HRO extends the fail safe of the design to the organization responsible for its creation.

Observance of failures and developing a healthy attitude towards failure fosters an environment where everyone can feel comfortable speaking up about what doesn't work. Focusing on resilience means moving on when it becomes clear that a new direction is needed. Built in resilience allows the organization to continue operations after an error has occurred, even in stressful situations. An HRO also knows the value of having people around who have knowledge and experience that can make a difference for solving a specific issue.

When it comes to errors, in cases where progression is slow enough, small errors get bigger, but the errors are repeatedly ignored. The thinking is that maybe they will just go away or never get worse; perhaps the Boeing 787 and its unexpected battery fires labeled as stages of growth or 'teething' is an example [9]. People want to confirm that their existing routine is correct, without any new data and without checking regularly. Inherent biases, which are underlying factors or assumptions that skew viewpoints of a subject under discussion, are common in aerospace. These inherent biases can create blind spots that just get larger because we do a biased search for evidence that confirms the accuracy of our original expectations [10]. Having a preoccupation with failure means that our basic assumptions about modus operandi might be challenged often enough to prevent the small from becoming the large. Naturally, the tendency to overlook accumulating evidence and overestimating the validity of our expectations is likely to increase when we are under pressure [8].

The example Weick uses is an aircraft carrier which would not be able to function without adherence to the five HRO principles. The situation is high pressure, always uncertain, high stakes and has a lot of moving parts. Emergency response teams are in a similar situation and follow these principles to keep major errors to a minimum. The situation in aerospace development is not as extreme in operations but can be in consequence. Each airplane flight requires components of a high reliability organization. If the high reliability organization is thought of as the entire aviation industry, each flight has to have a component of high reliability for success. Communication is at the heart of anything that is human, so it is usually the strongest point for change.

A hallmark of a high reliability organization is the refusal to draw a hard line between quantitative-qualitative knowledge. Neither stands higher than the other in the HRO value hierarchy. Questioning assumptions means that the HRO will view close calls as a learning opportunity that reveals potential danger [8]. All the HRO principles together add up to an increase in the quantity and quality of communication within the organization.

Mathematically Representing A Communication Framework In High Reliability Organizations

The principles of high reliability organizations can be implemented by looking at a theoretical framework based on increased communication. Predicate calculus or set theory mathematics is used to form logical relationships between abstract ideas, or in other words to provide a translation from ideas to data. This opens up the realm for quantifying HRO principles and communication structures via modelling. Complexity management utilizes communication as an asset through the implementation of high reliability principles. Simple, intuitive, and relational expressions can be derived to show the relationships between communication and the management of complexity. The lexicon of spoken language can be concisely and succinctly represented in its bare logical relations, exposing the organization’s framework. So a theoretical communication framework enables us to quantify phenomena that are otherwise implicit by regulating the effects of complexity in system development. Then, incorporating high reliability principles becomes more accessible.

For example, consider properties and resources of an organization. The properties and resources carry the potential to change the interaction to increase communication. The set {department} will be ephemeral, and a subset {teams} can be one department composed of a set of many teams. Alternatively, a piece of hardware like a computer may be an element of a department that a team interacts with, but it is not a part of the team like it is a part of the department. The units of the department may be stated as something ephemeral like “x number of *teams”*, “y number of *computers*”, or something more encompassing like “z number of *makers of productivity*”.

Consider a scenario where it is theoretically possible to say a team's interaction with a computer resulted in an increase in interdepartmental communication within the organization, which led to a reduction in unexpected events during design, integration, and testing. Perhaps the computer ran a simulation program. The more the team ran it, the more they needed to correspond with other teams and departments in order to develop parameters and return demonstrations. They discovered faults sooner and at a greater pace, thereby the cost of the overall development process was reduced. Basically, the communication increased just by talking through and about the simulation.

In attempting to reduce unexpected events in the next project, it might seem the solution is to introduce more simulation programs. The answer is actually to do whatever gets people to increase communication. The abstract concept of HRO principle 3, “sensitivity to operations", could be interpreted as a need for “more simulating” in order to reduce complacency. The computers and simulations may actually result in an increase in communication between people. Even though this may have been facilitated by the computers, the goal was to get people communicating effectively.

This example illustrates a communication framework. Following this example, a proposed communication framework that could help model communication can be described as:

1) People build teams, teams form departments, and departments constitute organizations with properties and resources
2) At every level of the organization, there is communication that occurs
3) Events in the organization occur in response to communication either are expected or unexpected depending on how well you are operating as an HRO
4) At the level of the organization, if you increase communication, you decrease the impact of unexpected events

The communication framework is extrapolated using predicate mathematics. It suggests a real time model of communication to manage complexity. First, it is stated that people build teams, teams form departments, and departments constitute organizations. This is akin to going from the cell to the ecosystem in hierarchical ecology. Figure 2 shows how each is contained with the next, all being affected by the external environmental context in which the organization operates.

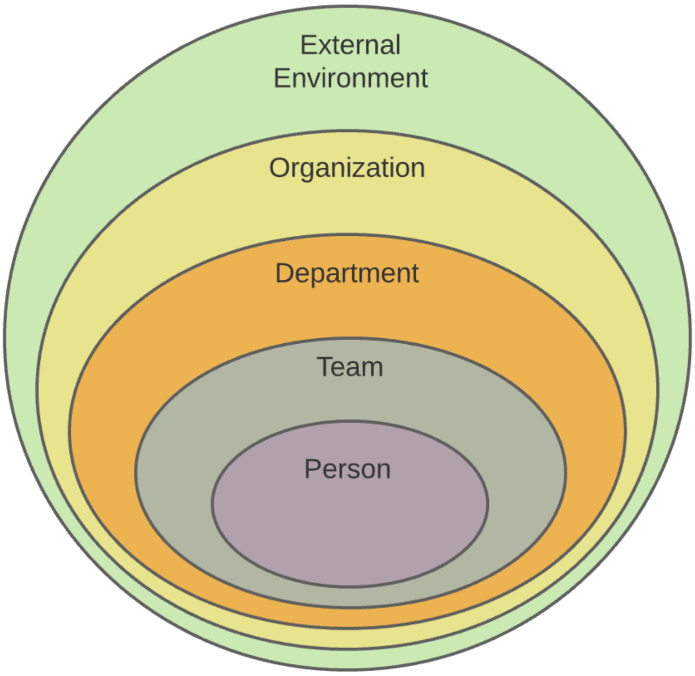

Figure 2. Organizational Hierarchy

Mathematically this organizational hierarchy is written as:

$$person \subset team \subset department \subset \{organization \Leftrightarrow company\}$$

Second, it is important to state that communication is what occurs across teams, departments, and organizations. Teams talk to other teams in other departments and other organizations. Different departments interface across an organization, where the interfaces are multilayer, and utilize multilayer resources. At every level of the organization, there is communication that occurs:

$$communication \subset \{teamCommunication \cup departmentCommunication \cup organizationCommunication\}$$

Third, it can be said that events in the organization occur in response to communication in a predictable or unpredictable direction. That is, the range of events spans from expected to unexpected, and the events themselves occur with communication. An organization operating like an HRO will experience more expected events than unexpected ones.

$$\forall events \subset \{expectedEvents \cup unexpectedEvents\},\ communication \leftrightarrow events$$
$$HRO \Rightarrow eventsExpected$$

Fourth, if communication goes up then the impact of unexpected events goes down.

$$\uparrow communication \rightarrow \downarrow unexpectedEvents$$

The statements are summarized in Figure 3, according to the communication framework. As holistic communication is distributed across an organization, and with the organization following principles of high reliability, the overall outcome is a decrease in the impact of unexpected events within the organization.

$$person \subset team \subset department \subset \{organization \Leftrightarrow company\}$$
$$communication \subset \{teamCommunication \cup departmentCommunication \cup organizationCommunication\}$$
$$\forall events \subset \{expectedEvents \cup unexpectedEvents\},\ communication \leftrightarrow events$$
$$HRO \Rightarrow eventsPredictable$$
$$\uparrow communication \rightarrow \downarrow unexpectedEvents$$

Figure 3: Set Theory Framework for Communication

Weick's 2007 *Managing the Unexpected: Resilient Performance in the Age of Uncertainty*, explains how expectations can be modelled to explain the reason complex organizations can operate successfully [8]. Actions come from assumptions which come from expectations. Expectations provide an infrastructure for everyday life, which is a suggestion of a probable course of events or inquiry. Expectations make it easier to make quick decisions, so we use them regularly and most of the time, innocuously. The expectation of gravity only disappoints when we are in space. Weick calls for a process that actively updates expectations (routines) in a way that encourages the updating. Figure 4 shows how a situation can be acted upon according to expectations that are biased and lead to a particular hypothesis, but an unbiased search can be executed to test whether or not the hypothesis is true.

$$\lim_{expectation \rightarrow action} situation = hypothesis$$
$$\exists search,\ \Delta expectations \forall situations \in \{search\}$$
$$search \subset \{balancedSearch \vee unbalancedSearch\}$$
$$\lim_{\rightarrow pressure \uparrow} search = bias \subset unbalancedSearch$$
$$(hypothesis \rightarrow tests) \rightarrow plans$$

Figure 4: Hypothesis Formulation and Testing

Expectations come from personal experience and correction of negative consequences. In executing a biased search, people will tend to give weight to disconfirming evidence lower than confirming evidence. Biased searches quickly become problematic when leading to overlooking evidence and overestimating expectations. Pressure to make a decision quickly exacerbates these issues.

For example, Weick describes how the expectation that nothing bad will happen when a bolt is left on the deck of an aircraft carrier results in an action of not cleaning up the bolt. The situation is such that there is now a bolt on the deck with a hypothesis that the bolt will do no harm. When an aircraft ingests the bolt, explosively, the hypothesis is disconfirmed and the original expectation must be unilaterally modified. The bolt was harmless until it wasn't, thus becoming a hypothesis that was tested.

Since hypotheses must be tested, plans are needed to guide people on a search. But if the initial expectations are misguided, so will be the plans, and the search may result in unfavorable situations. Weick's solution is to be skeptical of expectations [8].

The increase of pressure in a situation increases the likelihood of bias occurring in decision making, but the effects are not uniformly distributed between situations. Weick's landing signal officers must receive pilots that are dealing with an array of pressures during nighttime carrier landings. The landing officers may expect that a pilot is calm and cool headed, but will be skeptical of these expectations to listen for subtle signs of lack-of-calm and tension, in order to properly forecast the situation.

Aviation in general also needs to account for expectations through preparation. Both the engineering process of making the aircraft and the operation of the aircraft must be highly reliable.

Examining expectations is a way to be prepared for the unexpected. The unexpected events are found during operations, so the design process should take into account the expectations. Here is where the high reliability principles are implemented.

For example, in a case of ineffective communication, an air traffic controller out of Newark unfortunately and understandably misinterpreted communication that could have saved 73 lives. The pilot, when repeating instructions to the ATC, vaguely hinted at what was a dire situation, “Climb and maintain three-thousand and ah, we’re running out of fuel”. In Malcolm Gladwell’s *Outliers*, the Avianca 052 crash is described as akin to a customer in a restaurant saying, “Yes I’ll have some more coffee and, ah, I’m choking on a chicken bone” [11]. Running out of fuel is something planes do the moment the engines turn over. In a highly reliable organization, being preoccupied with failure reduces the anxiety of failing and removes reticence of their acknowledgment. Planes do not relay fuel data to controllers, the increased communication between the pilot-copilot-controller team was the only preventative in this incident.

In another incident, a light aircraft broke apart mid air when its pilot flew it into low-visibility weather and lost orientation, in 2015 over Bakersfield California [12]. Worse, the pilot was accompanied by a wife and three children. The husband-wife team exhibited “get-there-itis”, a colloquial term in general aviation for plan-continuation bias, by using the airplane as a means of transportation to a Christmas party in another state. Principles of high reliability obstruct the simplification of operations, where in this case the complicated act of flying a plane was simplified to that of a common road trip. Unfortunately the assisting aircraft controller gave instrument rated instructions to a visually rated pilot, although it was beyond the ATC’s obligation to know this information. Pilots are not required to state their qualifications to controllers, the assessment by the pilot must be authentic and indisputable.

Learning takes place regardless of the outcome and the process of quantifying communication as discussed in this paper must be employed. All passengers survived a water landing uninjured after all engines were lost in the case of US Airways 1549. The cause of failure was bird strike [13]. Communication on the flight deck and between the ATC was indicative of excellent resource management, causing no further error while responding mindfully to each pressure as it occured. Crew and rescue teams exceptionally employed their crew resource management training. The airplane was designed soundly enough to sustain the water impact and float safely until rescue. A commitment to resilience is displayed as a principle to the ongoing success of the organization. After this incident, modifications to future Airbus engine designs incorporated learnings from this failure. Similarly, flight deck and crew training scenarios for water landings became air-industry standard as was not the case before 1549. Bird strikes are random and unpredictable events that are now better managed through this commitment.

These stories show how HRO principles can help communication develop to a point of performance enhancement and failure reduction. Learning from failure is a process which becomes the central topic for training in the future, especially since we know our expectations lead us to search for proof of our preexisting position. That can lead to a biased position or an unbalanced solution.

Where does modelling communication come into play? Information about organizational communication unfolds as a companywide narrative [14] as it does in the stories above. A company-wide narrative, or shared vision of applied high reliability principles shows that communication works.The example of the computer simulations in the beginning of this section described that communication improved, not necessarily by the simulation, but just by the conversation it induced.

Though communication is language based, it can be understood also through the stringent analysis of mathematics. Set theory offers suggestions for a way to more easily quantify the processes and successes of a highly reliable organization. The theoretical communication framework presented in this section spans the individual, team, and organization but comes from conclusions that their needs for development of complex systems are aligned. Quantifying communication provides an onramp to incorporate new forms of information to increase reliability, and make it reproducible across programs.

Conclusion

Increased communication decreases the impact of unexpected or unpredicted events. This happens through following principles of high reliability that go looking for something to happen that is unpredicted, changing expectations. Increasing communication is a way of challenging expectations, and being skeptical of expectations is key. When the situation is high pressure, the tendency toward quick conclusions induces biases that make decision making overall less effective. Quantifying communication can help with seeing what expectations are there and how the expectations may not be ready for an actual event.

Quantifying the ways that an organization tends to think of solutions leads to knowing how effective the organization is at embodying the five principles of a high reliability organization. The high reliability organization principles focus organizational attention towards the shared vision that drives the day-to-day operating culture. A form of crew resource management in engineering that is similar to that already applied in aviation and medicine, as well as other high reliability industries, can be a way of implementing high reliability principles. Then, modelling the relationship between communication and the design can help to show the success of the implementation.

Modelling communication is an implementation strategy in which real time information about how people are communicating is just as important as real time information about how hardware is operating. The use of a set theory model for a communication framework allows system designers to more easily use it as a prediction process. Further, a communication model opens up the possibility for statistical methods for quantification and use across greater scales.

It is clear that high reliability principles have been shown to work in the various cases analyzed by Weick. High reliability principles outline a method for managing complexity through increased communication and a decrease in the impact of unpredicted events.

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