Decisions and Disasters: Modeling Decisions that Contribute to Mishaps

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Abstract
Ever since the decision to launch the Challenger – and the deadly explosion that followed – it has been widely known that “decision failure” can lead to disaster. But despite this awareness and the availability of a wide variety of decision models, we found no single model that adequately describes all the ways that decisions can fail and how flawed decisions contribute to mishaps.

In this paper, we present our model of decision failure. Then we show how we used this model to gain insight into those decisions that have contributed to NASA mishaps (including the Challenger). This work presents both the model and the insights from its application. The theoretical contribution is a new way to encode and analyze the decision data found in mishap reports, providing insight into the causes of decision failure. The practical contribution is the potential for using this to improve decision-making at NASA and other high-reliability organizations.

1. Introduction
This paper examines a particular class of decisions that are implicated in mishaps (or accidents). In each case, a decision has "failed" in some way, and the decision failure has contributed to a loss beyond what was expected or tolerable. That is, the loss was unexpected given the decision uncertainties. The decision to launch the space shuttle Challenger is perhaps the best-known example of such unexpected loss [1].

When such mishaps occur, ensuing investigations attempt to uncover the proximate cause (the immediate cause of the technical failure), as well as contributing factors and conditions. Decisions that contributed to the failure are also often noted, yet such considerations are conspicuously absent in current normative decision models used to make those decisions. This work develops a decision failure model to address this gap. Our new model enables a deeper analysis of decisions that contribute to mishaps and is validated through empirical data from NASA mishap reports.

1.1. Research Questions
Mishap reports often describe decisions as part of the chain of events leading to an accident [2]. Reports typically include a causal analysis, and decisions are often cited as contributing cause or factor in an accident [3]. Rarely is there a single, definitive cause on an accident. Generally there are multiple interacting causes and factors that lead to a mishap. Our focus, though, is not on the accident, but on the decisions that contribute to them. Our research questions are:

Q1: How do the decisions that are implicated in mishaps fail?
Q2: Are there common patterns to their failure?

In other words, this study seeks to identify common "failure modes" in the decisions that contribute to mishaps.

1.2 Research Approach
To answer these questions, we developed a model of decision failure and applied it to a sample set of publically available NASA mishap reports. The remainder of this paper describes this model and its application.

In Section 2 – Building a Decision Failure Model, we review the literature to examine existing decision models. We determined that there is no single model we can use "off the shelf" for our purpose. However, we found useful theory and model components and used these to build a custom model for our needs.

In Section 3 – Applying the Model to Mishaps, we discuss our methodology, describing how we applied our Decision Failure Model to a sample of mishap
reports from the National Aeronautics and Space Administration (NASA). We also explain why we chose the NASA reports as our sample data.

In Section 4 – Results, we present our research results, summarizing the insights and patterns we’ve gleaned from the mishap reports, using the Decision Failure Model.

In Section 5 – Conclusion, we describe the research contributions from this study. Both theoretical and practical implications are discussed. We also discuss the limitations of this study and plan for future work, building on the results presented here.

2. Building a Decision Failure Model

Building an initial decision failure model was a two step process: first reviewing the literature for existing applicable models, then synthesizing information to create a model useable in this study.

2.1. Literature Review

When decisions are discussed in a mishap report, they are, in a sense, already modeled. That is, they are part of whatever causal model was used to explain the mishap itself. The mishap's causal model depends on the investigation technique used, which might be expressed, for example, in a cause-and-effect ("fishbone") diagram, event tree, fault tree, failure mode and effects analysis (FMEA), and so on [4].

We might then consider modeling decision failures by using the same causal model that was applied to the mishap itself, "carried down one level" into the details of the decision. Labib takes this approach, applying fault tree analysis to both the accident and the decision-making component of the failure [2].

There are two weaknesses to this approach. First, it doesn’t give us a common framework for comparing decision failures across multiple reports, which we need in order to find the patterns we are seeking. Second, this approach doesn’t support an analysis specific to the nature of decision-making. It doesn’t make use of the decades of research in decision theory.

To correct these weaknesses, we need to use a decision-focused model – and fortunately, the literature gives us many to choose from.

Decision models are generally classified as normative (how decisions should be made), prescriptive (how decisions should and can be made, recognizing certain constraints and limitations), or descriptive (how decisions are actually made) [5].

We have chosen to build our model using the normative model known as Decision Analysis (DA), as the foundation [6]. As a normative model, DA gives us a standard for judging a good decision vs. a failed one – and provides an important theoretical insight: there is no guarantee that a good decision will result in a good outcome! Because we don’t have perfect control and understanding of the world, there is always a degree of uncertainty about the outcome of our decisions [6]. Our model is therefore probabilistic by nature, and we need to look multiple decisions and their outcomes to understand whether a decision-making process is successful or not.

DA provides six elements of “decision quality,” from which we can derive how those elements can fail. Table 1 summarizes the decision quality elements and the failure modes we derived from them [7]:

<table>
<thead>
<tr>
<th>Decision Quality Element</th>
<th>How the Element Fails</th>
</tr>
</thead>
<tbody>
<tr>
<td>Framing the decision</td>
<td>Solving the “wrong problem”</td>
</tr>
<tr>
<td>Set of decision options</td>
<td>Using a flawed set of options</td>
</tr>
<tr>
<td>Information on options</td>
<td>Misinformation on options</td>
</tr>
<tr>
<td>Clear basis for trade-offs</td>
<td>Unclear basis for trade-offs</td>
</tr>
<tr>
<td>Logical reasoning</td>
<td>Flawed reasoning</td>
</tr>
<tr>
<td>Commitment to action</td>
<td>Failure to act on decision</td>
</tr>
</tbody>
</table>

The DA model gives us guidance on how decisions fail, that is, how they deviate from the normative decision model. However, this model doesn’t tell us why they fail. For that we have to turn to descriptive models, which inform us of the ways that individuals and groups “go wrong” in real-world decision-making.

One of the first breakthroughs in this area was the work of Kahneman and Tversky, who discovered that human decision-making is fraught with cognitive biases, or “mental illusions” that are built into the way we make decisions and lead to incorrect results. One example of a cognitive bias is “anchoring,” insufficiently adjusting after forming an initial opinion. Another is “recall,” believing a phenomenon is more common than it is because examples are easily remembered [8].

Since Kahneman and Tversky’s work, other researchers have expanded the list of cognitive biases. There have also been attempts to create a comprehensive taxonomy of cognitive bias. Arnott discusses various taxonomies in the literature and offers one of his own [9].

The Arnott taxonomy provides a list of individual cognitive biases, but does not cover group biases, which arise from the dynamics of team collaboration [9]. We were unable to find a comprehensive taxonomy of group biases, but have attempted to collect these from various sources, including Janis, who explored the notion of “groupthink” [10] and Jones & Roelofsma, who examined group biases more generally [11].
In addition to individual and team biases, we also wanted to consider the social, cultural, and economic assumptions of the organization behind the decision-making. These assumptions often provide pressures on the decision-makers (for example the budget and schedule pressures that lead projects to “cut corners” in quality assurance) as well as the “hidden biases” that come from a particular organizational culture. These are discussed, for example, by Vaughan [1], who describes the phenomena of “normalization of deviance” and in Starbuck collection on the organizational aspects of the Columbia disaster [12].

2.2. Synthesis

In our literature review, we found no single model of decision failure that we could use “off the shelf” to describe decision failure in mishaps. However, we found the components that we needed to assemble such a model.

Our Decision Failure Model uses the DA notion of decision quality to derive a classification scheme for describing decision failure modes. These tell us how decisions fail to meet the normative standard of a “good decision.” To capture information on why decisions fail, the model looks at three levels of failure causality from the literature: individual cognitive biases, social biases that arise in the decision-making groups, and organizational factors that tell us what underlying assumptions and pressures operate in the decision-making organization.

Finally, we needed to include decision variables that accounted for individual differences in the decision context. These variables include: the type of decision being made and its criticality.

When we put these components together, we obtained the multi-dimensional model of decision failure summarized in Figure 1, below:

The “Failed Decision Element” shows the place in the process where the decision failed, based on the DA decision quality model, shown in Table 1, above. The “Decision Context” provides contextual metadata for the decision in question, including: a decision name (identifier), project name, name type (e.g., gateway decision, design trade, acceptance decision, etc.)

The “Cognitive Biases,” “Social Biases,” and “Organization Factors” provide reasons why the decision failed, taken from the literature, as described above. Based on its importance in the literature and the mishap reports, themselves [12], we emphasize the biases and organizational factors as “Sources of Overconfidence.” When decision-makers are too confident about one of the of the inputs to decision-making (for example, too confident that a system that has flown before has already been adequately tested), it can lead to “Decision Element Failure,” as shown by following the solid arrows in Figure 1, above.

2.3. Bias and Decision Risk

The Decision Failure Model indicates that overconfidence in judgment contributes to decision failure. More generally though, any bias, be it over- or under-confidence leads to a poor decision in terms of not meeting the normative decision standard.

Consider the decision to launch the space shuttle Challenger knowing there are some concerns about the performance of the O-rings in low temperatures. Ideally with higher uncertainty, the decision to launch would swing towards holding due to the potential catastrophic loss from an O-ring failure. That is, the conditions are such that there is a large risk from making a wrong decision to launch because of the uncertainty in what the decision is based on. If there is overconfidence, then this risk appears smaller as the uncertainty in O-ring failure is taken as less than is justified. As a result, a decision to launch will appear to be, normatively, optimal. However in reality there is additional risk in making a poor decision because of the uncertainty and not accounting for bias in how this uncertainty is accounted for in arriving at a decision. Similarly if there is under-confidence the decision to hold the launch may be unjustified. This also leads to a poor decision and increased decision risk and potential loss due to slipped schedule, opportunity loss, etc.

Under-confidence leads to unjustifiably conservative decisions. Because we are studying only occurrences of mishaps resulting from overconfidence, our proposed model is not able to detect such situations even though we suspect they commonly occur. However bias should be detectible as increased variability in outcomes (both mishaps and success).
compared to the expected variability from decision failures. In this work we concentrate on the effects of overconfidence on decision failures that led to mishaps.

3. Applying the Model to Mishaps

Once we constructed a Decision Failure Model (DFM), our next step was to apply it, in order to understand a sample of the decisions associated with mishaps.

3.1. Research Methodology

This portion of the study can be considered grounded, archival research. [13]. We examined a set of artifacts, coded them, and analyzed their content for patterns. The process was as follows:
1. We selected a sample set of mishap reports as the data source (artifacts)
2. We read and recorded what the reports say about decision-making without regard to a pre-existing model
3. Using the Decision Failure Model (DFM), above, we coded and classified information from the mishap reports
4. We analyzed both the “raw record” and the coded information for decision-making patterns across the sample
5. We also validated that the model accurately covered the information in the mishap reports without significant gaps
6. When errors or gaps are found, we adjust the model to improve coverage and accuracy

3.2. Sample Selection

We chose NASA to represent organizations making complex, highly critical – sometimes even life-and-death – decisions. Decision-making is important and pervasive in the NASA project life cycle. For NASA management, there are key decision points that control whether projects advance to the next phase of development [14]. For systems engineering, there is decision analysis used in technical trade-off decisions [15]. For systems safety, risk-informed decision-making is critical [16]. Port & Wilf identified the reduction of decision risk as the primary value of systems assurance [17].

NASA also has a wealth of data on mishaps. NASA requires investigation and analysis of every mishap; and this extends to “close calls,” events that had the potential of becoming a mishap [3]. Mishap reports or their summaries are released and available to the public at large. The most serious accidents have been extensively analyzed. On Challenger, for example, there was a presidential commission [18], report to congress [19], as well as extensive analysis in the literature [1], etc.

From the set of NASA mishaps, we used quota sampling to select 10 mishaps that represented a range of time (1986-2013), mission types (including human and robotic space missions, earth orbiters, and aeronautic test vehicles), and degree of severity (ranging from loss of human life to the loss of spacecraft and mission, down to a “high visibility close call”). In two cases, there was a recovery from an initial loss of mission.

Table 2, below, shows our sample set of mishap reports. Under the “Loss” column, “Life” indicates loss of life (shuttle crew); “Mission” indicates that the mishap ended the mission; “Recover” indicates that there was recovery or repair from a mishap that would have potentially ended the mission; and “Close” indicates a “close call:”

<table>
<thead>
<tr>
<th>Year</th>
<th>Mishap</th>
<th>Mission</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Challenger</td>
<td>Shuttle</td>
<td>Life</td>
</tr>
<tr>
<td>1990</td>
<td>Hubble</td>
<td>Telescope</td>
<td>Life</td>
</tr>
<tr>
<td>1999</td>
<td>Mars Climate Orbiter</td>
<td>Orbiter</td>
<td>Mission</td>
</tr>
<tr>
<td>1999</td>
<td>Mars Polar Lander</td>
<td>Lander</td>
<td>Mission</td>
</tr>
<tr>
<td>2003</td>
<td>Columbia</td>
<td>Shuttle</td>
<td>Life</td>
</tr>
<tr>
<td>2003</td>
<td>Helios</td>
<td>Drone</td>
<td>Mission</td>
</tr>
<tr>
<td>2004</td>
<td>Genesis</td>
<td>Sample Return</td>
<td>Recover</td>
</tr>
<tr>
<td>2005</td>
<td>DART</td>
<td>Earth Orbiter</td>
<td>Mission</td>
</tr>
<tr>
<td>2010</td>
<td>Compton Telescope</td>
<td>Balloon</td>
<td>Mission</td>
</tr>
<tr>
<td>2013</td>
<td>Suit Water</td>
<td>Space walk</td>
<td>Close</td>
</tr>
</tbody>
</table>

We used the methodology described in Section 3.1 to apply the DFM and analyze the ten mishap/accident reports of the sample mishaps [18], [20], [21], [22], [23], [24], [25], [26], [27], [28]. These are the primary source data for our study. Secondary sources were also read and have been cited where used.

4. Results

In applying our model to the sample mishaps, we found that in every case, decisions or the decision-making process played an important role.

4.1. The Role of Decisions in Mishaps

In eight out of ten, decisions were a contributing cause of the mishap (if the decisions had been
different, the mishap would not have occurred). In the other two, decisions were a contributing factor (not directly in the causal chain, but influencing the result).

Table 2, below, describes a contributing decision for each of the ten mishaps, along with the role played by the decision, where “CC” means “Contributing Cause” and “CF” means “Contributing Factor:"

<table>
<thead>
<tr>
<th>Mishap</th>
<th>Decision</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Challenger</td>
<td>Launch</td>
<td>CC</td>
</tr>
<tr>
<td>Hubble</td>
<td>Mirror Quality Review</td>
<td>CC</td>
</tr>
<tr>
<td>Mars Climate Orbiter</td>
<td>Trajectory Correction</td>
<td>CC</td>
</tr>
<tr>
<td>Mars Polar Lander</td>
<td>Test Acceptance</td>
<td>CF</td>
</tr>
<tr>
<td>Columbia</td>
<td>Flight Readiness</td>
<td>CF</td>
</tr>
<tr>
<td>Helios</td>
<td>Red Team Review</td>
<td>CC</td>
</tr>
<tr>
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<td>CC</td>
</tr>
<tr>
<td>DART</td>
<td>Design Acceptance</td>
<td>CC</td>
</tr>
<tr>
<td>Compton Telescope</td>
<td>Balloon Launch</td>
<td>CC</td>
</tr>
<tr>
<td>Suit Water</td>
<td>EVA Go-ahead</td>
<td>CC</td>
</tr>
</tbody>
</table>

As the table shows, mishap-contributing decisions can happen at a variety of points in the life cycle. Some are the go/no-go decisions just prior to launch or EVA (extra-vehicular activity / space walks). The decision cited in the Columbia report is interesting because it was the flight readiness decision for a previous shuttle launch. It was during this earlier flight readiness review that NASA downplayed the risk from losing insulating foam from the fuel tank. Underestimating that risk would later prove fatal to the Columbia [23].

4.2. Organizational Factors

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4.3. Cognitive and Group Biases

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4.4. Overconfidence and Decision Failure

Finally, reading the mishap reports through the lens of the DFM model revealed many sources of overconfidence, which contributed to decision failure. As Feynman noted in an appendix to the Challenger report, the managers were very overconfident about the reliability of the shuttle [29]. The Genesis report mentions overconfidence about the quality of inherited system components, believing that since they had already been flown successfully, they needed less testing [24]. The Helios report talks about overconfidence in analysis (models and simulations). The models then failed to predict the break-up of the solar-powered drone aircraft under high turbulence [25].

Overconfidence about quality, uncertainty, and risk was common, and the model showed it often led to decision failures. The two most common decision elements (listed in Table 1 above), that failed were: 1) misinformation on (decision) options and 2) unclear basis for trade-offs. Overconfidence played an important role in both these kinds of decision failure.

5. Conclusions

In this study, we have developed a Decision Failure Model (DFM) and applied it to a quota sample of ten NASA mishap reports. In nearly every report, there were decisions implicated as a contributing cause or factor in the mishap. Our DFM enabled a better analysis of how these decisions failed and we found patterns that held across a range of dates, project types, and severity of loss.

5.1. Contributions

This study makes both theoretical and practical contributions. On the theoretical side, the new DFM provides a better way to encode and analyze the decision data found in mishap reports. The insights gleaned also open potential avenues for further research.

The practical contribution this work is its potential to improve decision-making at NASA and other organizations that have to make critical decisions about complex systems.

5.2. Limitations and Future Work

The scope of this study was limited to NASA, though we believe the results will generalize well to areas such as nuclear power generation, medical devices, automotive computing, and the like.

Even within the realm of NASA, we have only applied the DFM to a small sample of mishaps. NASA keeps a mishap database with thousands of entries for all its mishaps and close calls [3]; and we look forward to applying the DFM to this larger dataset. We also plan to augment our decision diagnoses with surveys and interviews of project personnel.

Beyond diagnosis, we are searching for solutions, for “treatments” that address the persistent patterns of flawed decision-making. Are there tools or processes that can help us discover and reduce bias? How can systems assurance make us more justifiably confident in critical decisions?

These questions remain open for future studies. The current work should therefore be considered as only the first entry in a larger research program.

6. Acknowledgement

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7. References


