SCHOOL OF INDUSTRIAL ENGINEERING

# Simulation and Human Factors in Modeling of Spaceflight Mission Control Teams

PURDUE INDUSTRIAL ENGINEERING

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rethink IE

# Background

| Four Team Processes | GROUPER History |
| --- | --- |
| Asking<br>A novice comes to experts with a question. | 2005 paper<br>by Caldwell |
| Sharing<br>Experts share opinions, experience, and backgrounds. | 2006 paper<br>by Ghosh & Caldwell |
| Solving<br>An expert finds a problem, and the team need to solve it. | this paper |
| Learning<br>Experts study together to expand their knowledge. | future work |

# NASA Flight Control Team

**Flight controllers are highly trained experts all on one team.**

Their job is to monitor the crew and the Shuttle subsystems via their consoles.

**The flight director is the decision lead of the team.**

The team is grouped according to engineering and scientific disciplines.

They communicate on voice loops.

**They solve problems together; no one simply dictates instructions.**

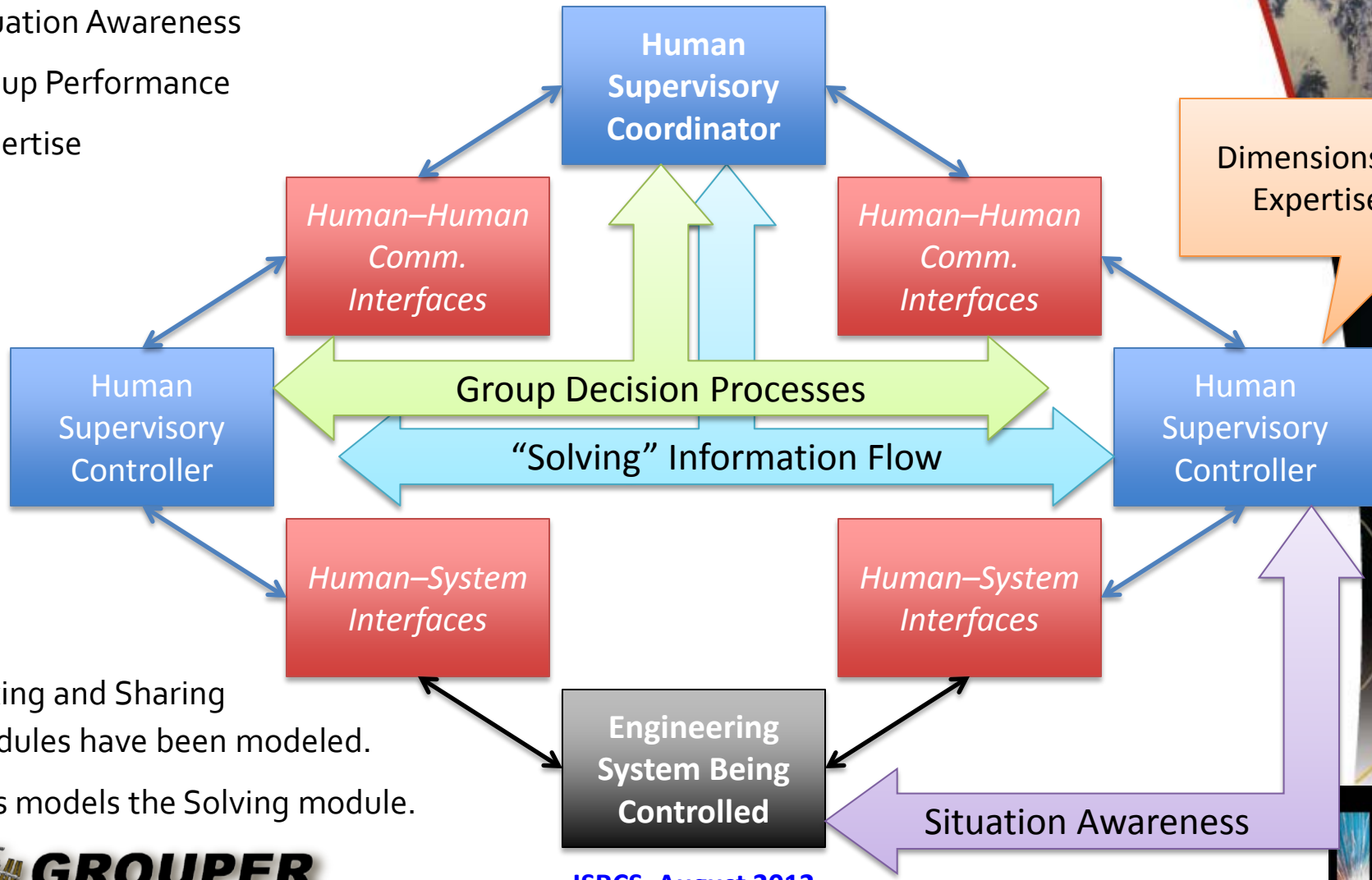
# Foundational Work

Distributed Supervisory Coordination

Situation Awareness

Group Performance

Expertise




Asking and Sharing modules have been modeled.

This models the Solving module.

# Problem Statement: Analysis of Alternatives

How do we guide the design of an MCC?

Trial and error takes years, is very risky, and is limited to only slight variations.

An offline research MCC would be prohibitively expensive and still take a long time.

→ A model & simulation is cheap, fast, and safe.

| | | Figures of Merit | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Safety | Robustness | Effectiveness | Adaptability | Extensibility | Sustainability | |
| Alternatives | Wght | 21 | 5 | 8 | 1 | 2 | 3 | Total |
| Status Quo MCC | | ? | | | | | | ? |
| Skeleton MCC (=10) | | | | | | | | ? |
| Smaller MCC (-10) | | | | | | | | ? |
| Larger MCC (+10) | | | | | | | | ? |
| Unmonitored Sleep | | | | | | | | ? |
| Mobile Team?? | | | | | | | | ? |

# Challenges for a Good Model Integrating Human Factors and Simulation Disciplines

## An Effective Model Must Include:

- **Realistic Examples of Anomalies**
  - Taken from actual spaceflight mission
- **Believable and Realistic Dynamics of Agents**
  - Based on authors' experience, research literature on "intellective" and decision making tasks, permitting "non-rationality" (but "truth wins" convincing)
- **Recognition of Task Demands and Constraints**
  - Dynamic function allocation and mission safety criteria
- **Stability and Convergence of Estimates of Parameter and Scenario Performance**
  - Monte Carlo analyses, 300 trial convergence

# Telemetry and Anomalies

## Telemetry is data from subsystems.

Regular telemetry is nominal.

Flight-control consoles display telemetry.

## Anomalies are irregularities.

Anomalies is off-nominal telemetry.

Anomalies **may** be evidence of underlying problems (may be blip in sensor or comm.)

Anomalies are problems that the team must solve.

**Decisions must be made by the team, all together, to keep the crew safe.**

**The flight controllers cannot ignore any anomalies.**
**The one they ignore may be the one that kills the crew.**

# Fault Detection, Isolation, and Recovery (FDIR)

**The JPL Purdue Architecture Analysis (PAA) project introduced a FDIR model.**

Anomalies

1. start appearing in telemetry at some mission elapsed time (MET)
2. disappear after some set **lifetime**
3. impart some penalty based on whether they are **degrading**

**There is a process of anomaly detection,**
**another process of anomaly isolation,**
**and another process for anomaly resolution.**

→ The anomaly model and anomaly resolution process are based on this.

# Working The Problems, When They Arise

## Anomalies

Evidence of problems

Could be anything from nonissues to catastrophes.

## FDIR

NASA calls problems faults.

Fault Detection requires situation awareness.

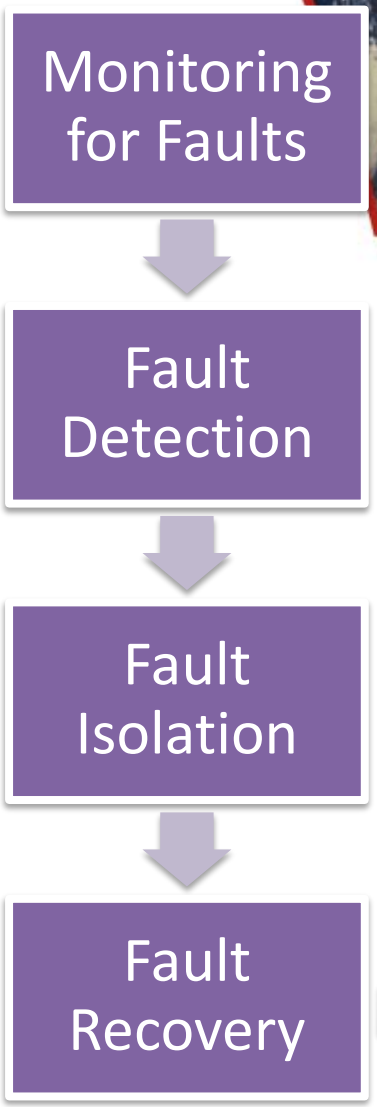
Fault Isolation requires hypotheses.

Fault Recovery requires a solution.

## Fault Tolerance

Some on-orbit systems may not tolerate any downtime.

The MCC works to maximize reliability and availability.



# Anomaly Model

## Anomaly Severity

All anomalies expire after some lifetime.

- Minor anomalies do not penalize the score.
- Impairing anomalies do.
- Critical anomalies make the score zero.

| Anomaly Severity | *Minor* | *Impairing* | *Critical* |
|---|---|---|---|
| *Non-degrading* | No effect | | |
| *Degrading* | | | Worst effect |

Some anomalies affect objectives.

- Non-degrading anomalies do not block objectives.
- Degrading anomalies block all objectives. They must expire or be resolved to unblock.

## Resolving Anomalies

Agents are not privy to anomaly details.

Agents resolve anomalies through Hypotheses.

# Agent Model

## Agent-based Modeling

Agents represent flight controllers.

Agents are dynamic model elements.

## Character Stats

Character stats simplify complexity through all-inclusive attributes.

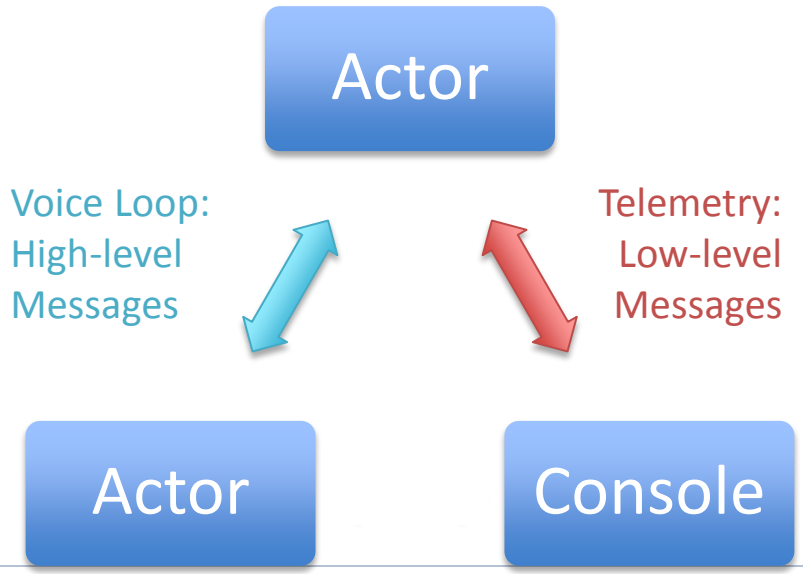
Agents have four of the six dimensions of expertise.

- Subject-matter expertise
- Situational-context expertise
- Communication expertise
- Expert-identification expertise

Agents have two more character stats.

- Saturation
  - total demand of simultaneous tasks
- Independence
  - autonomy to do their own tasks without discussing them with others

# Multidisciplinary Modeling Framework




## Agents each have 4 character stats.

Three are constant. Saturation is dynamic.

These influence the actor's effectiveness.

Information requirements for acquiring and maintaining situation awareness also influences the actor's effectiveness.

## Agents communicate on voice loops.

Information sharing occurs via loops.

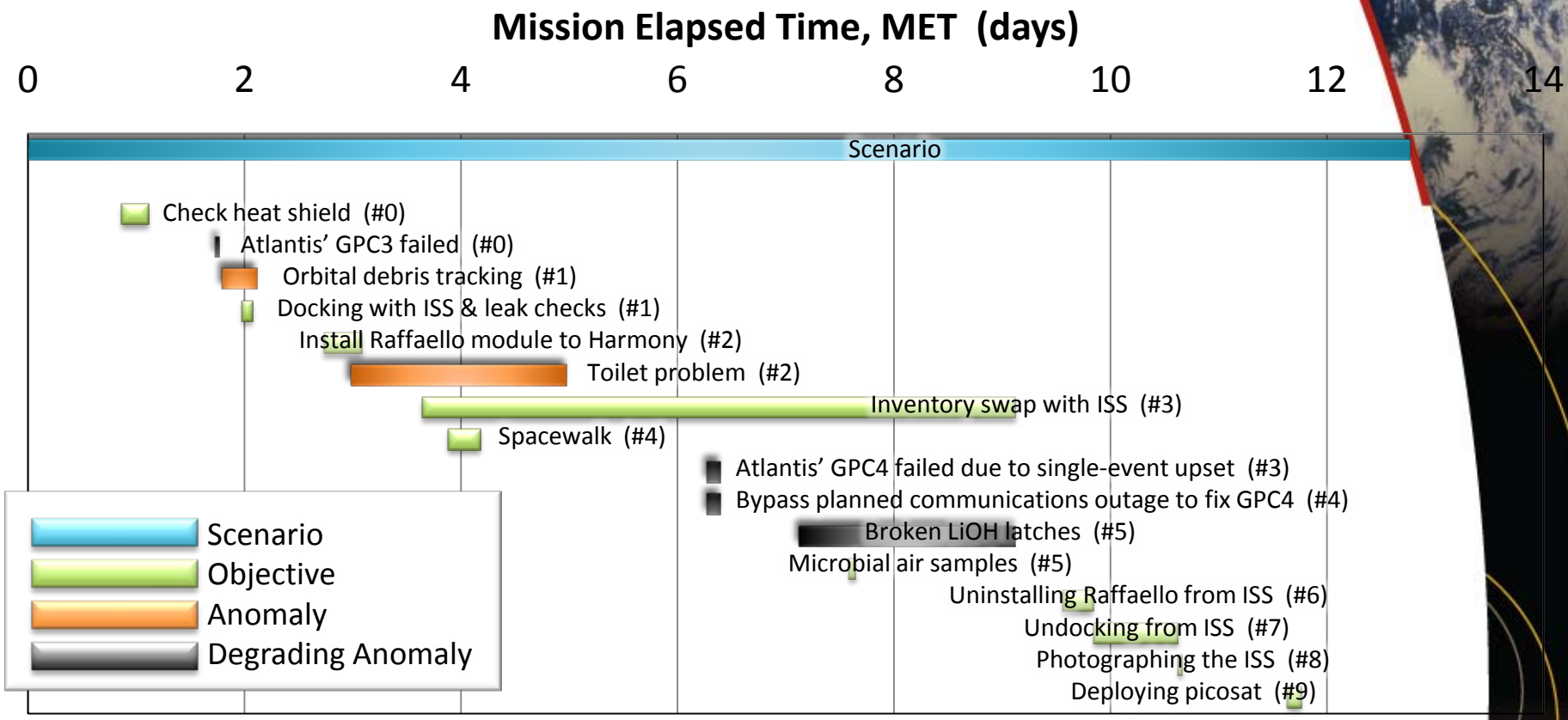
Anomalies occur within loop domains, not across them.

## Anomalies & Hypotheses

The team must arrive at a **consensus** to select the best hypothesis.

**Degrading** anomalies block progress on mission objectives.

# The Baseline: STS-135 Timeline: Scenario 0




These objectives and anomalies were taken from the mission status reports, with times estimated from context.



Discussion

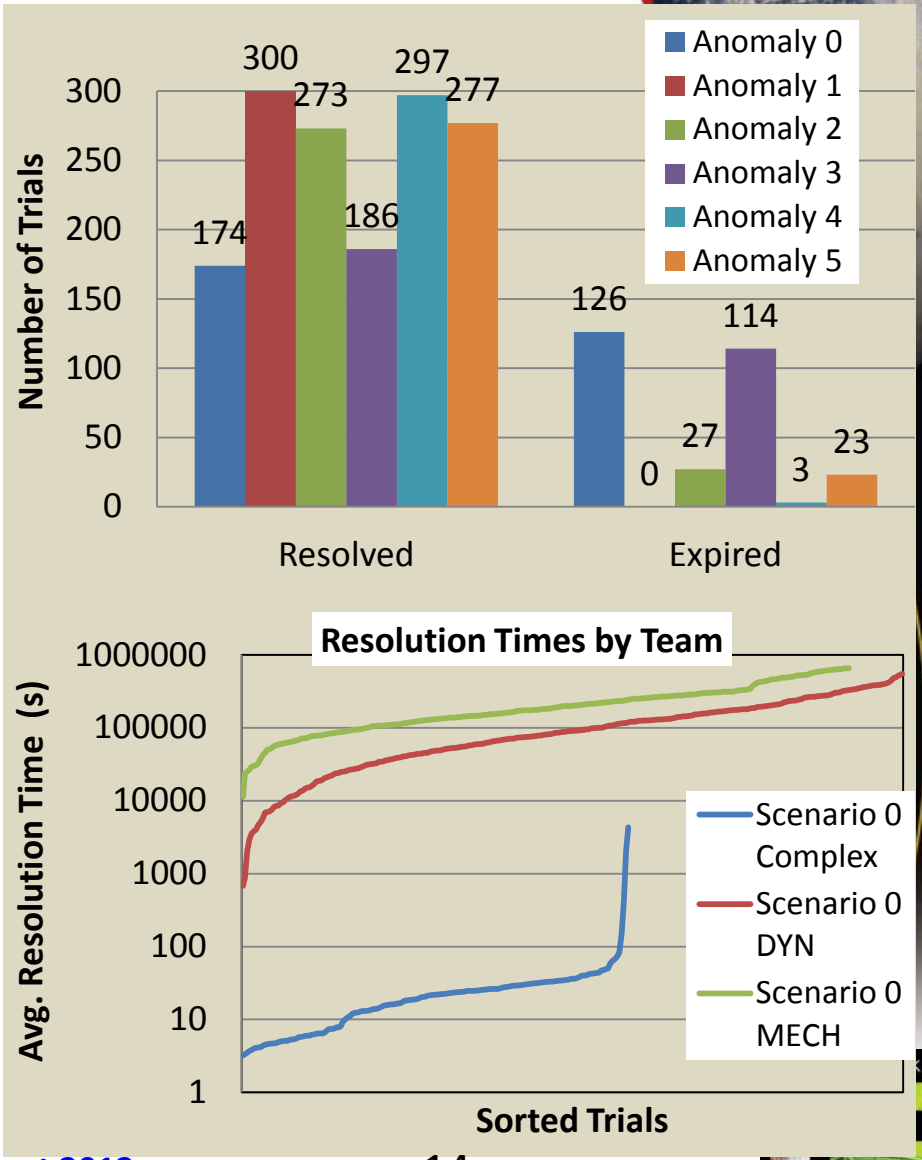
# Scenario 0: Convergence and Anomaly Resolution

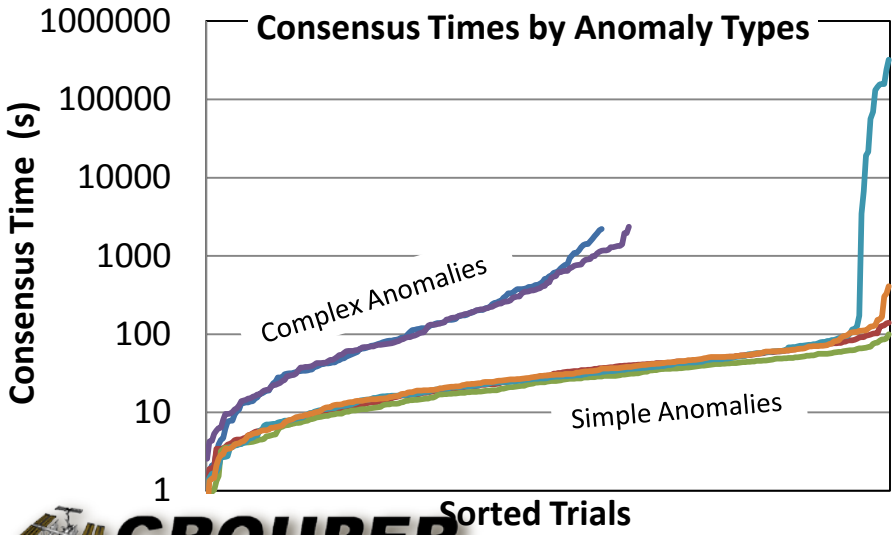
**There were big differences between complex and simple anomalies:**

Outcome

Time to first consensus

Time to resolution (after first consensus)



# Scenarios

| Scenario | probability of correct hypothesis | team sizes | level of integration | probability of hypothesis competition |
|---|---|---|---|---|
| **Scenario 0** ***the baseline*** | 0.2 | 3, 13, 11 | Level 2 | 0.1 |
| **Scenario 1** | increased to 0.8 | | | |
| **Scenario 2** | | decreased to 3, 3, 3 | | |
| **Scenario 3** | | increased to 13, 23, 21 | | |
| **Scenario 4** | | | increased to Level 4 | |
| **Scenario 5** | | | increased to Level 4 | increased to 0.5 |
| **Scenario 6** | | decreased to 3, 9, 7 | increased to Level 4 | |
| **Scenario 7** | | decreased to 3, 9, 7 | increased to Level 4 | increased to 0.5 |
| **Scenario 8** | | decreased to 3, 9, 7 | | |

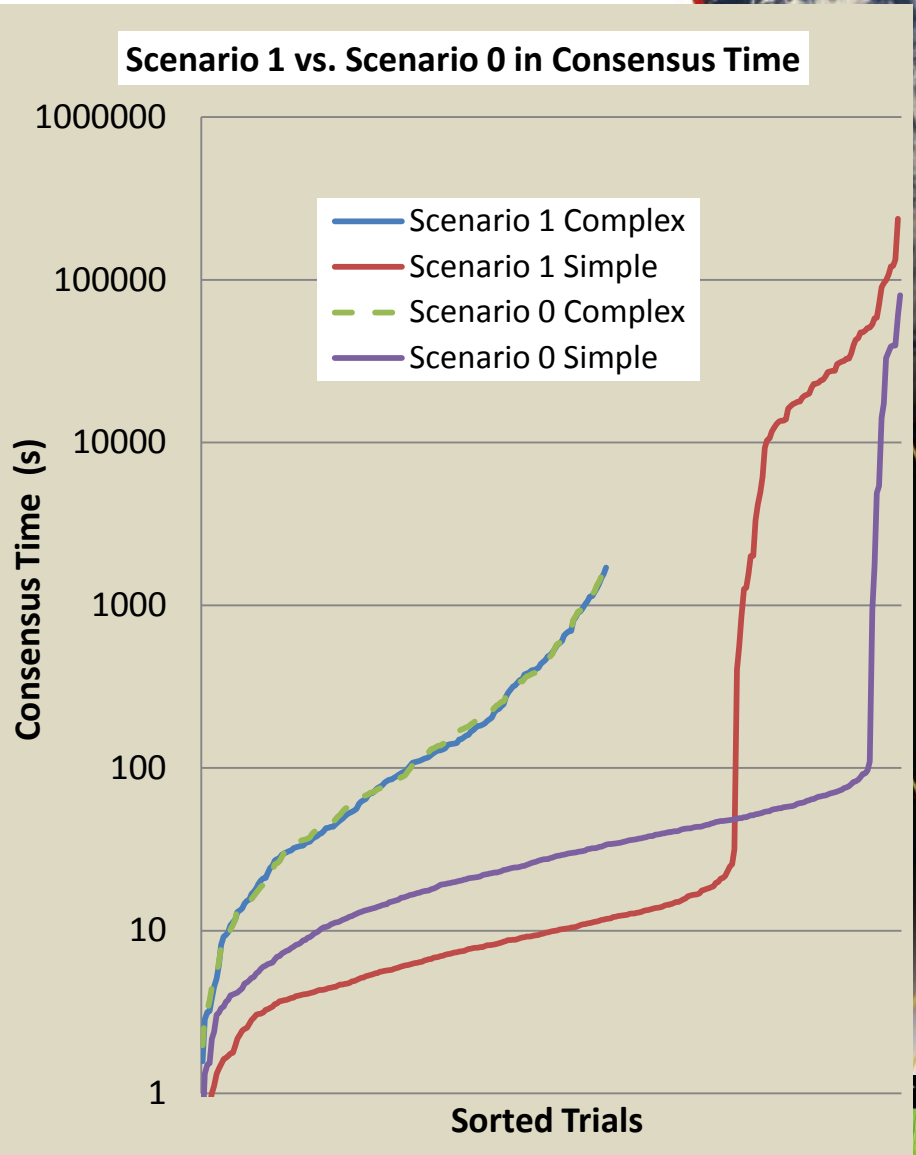
# Variability: Model Parameter

**Changing a model parameter to see how the results vary.**

**Decreasing** the probability of correct hypotheses for simple anomalies results in a

**decrease** in the time to first **consensus** for **simple** anomalies and

no change to complex anomalies.



# Variability: Scenario Parameter

**Changing a scenario parameter to see how the results vary.**

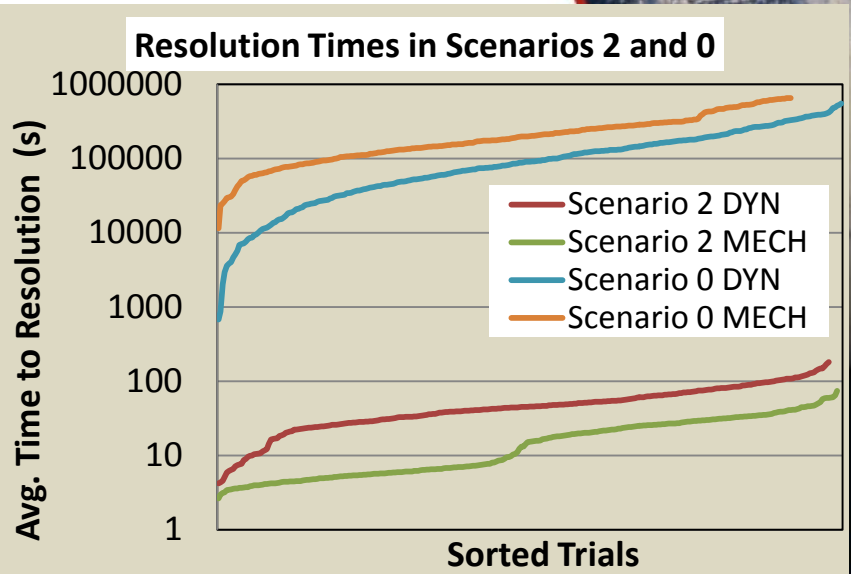
**Decreasing** the teams' sizes down to three members each

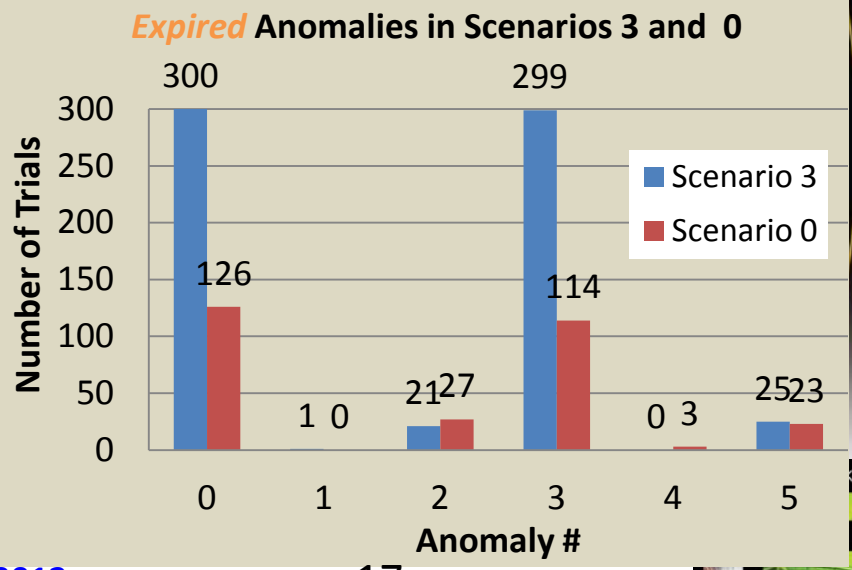
does not affect consensus time

**increases** the speed at which the teams get through the anomaly-**resolution** process for **simple** anomalies

**Increasing** the teams' sizes by ten members each

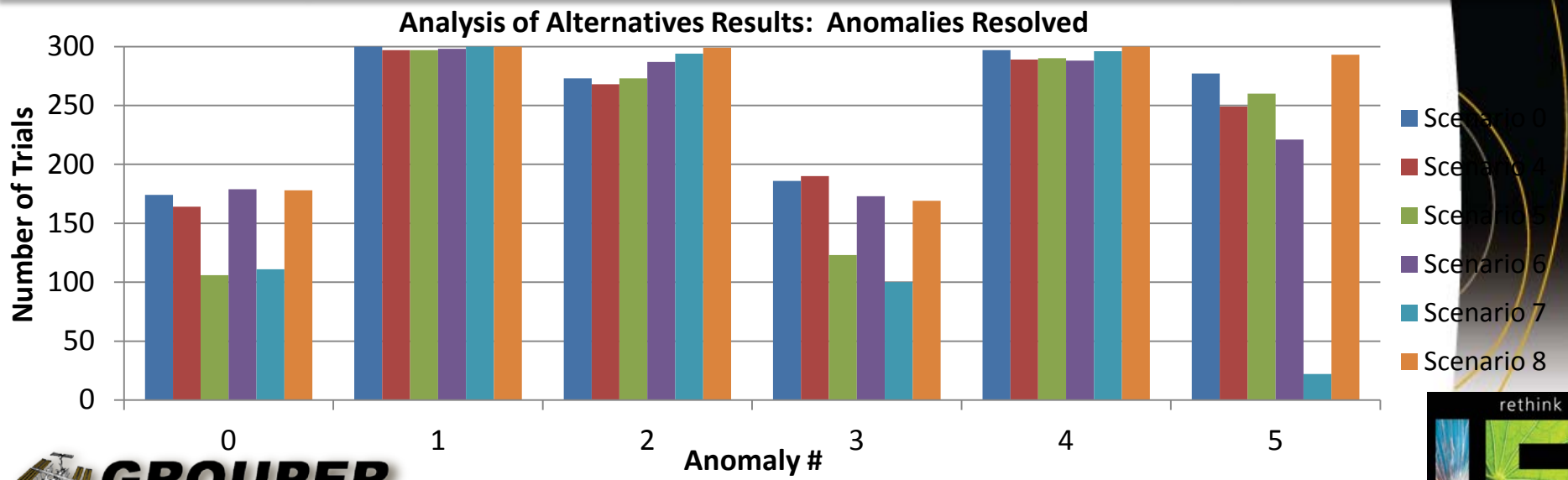
**prevents** the teams from reaching consensus for **complex** anomalies



# Analysis of Alternatives Results

| | Increased Level of Integration on Consoles | Reduced Team Size | Increased Probability of Hypothesis Competition | Effectiveness at Resolving Anomalies |
|---|---|---|---|---|
| Scenario 0 | Level 2 | 3, 13, 11 | 0.1 | Good |
| Scenario 4 | -> 4 | | | Almost As Good |
| Scenario 5 | -> 4 | | -> 0.5 | Pretty Bad |
| Scenario 6 | -> 4 | -> 3, 9, 7 | | Good |
| Scenario 7 | -> 4 | -> 3, 9, 7 | -> 0.5 | Pretty Bad |
| Scenario 8 | | -> 3, 9, 7 | | The Best |



# Sample Unexpected Insight: Cliffs in Consensus Time

## Cliffs appear in the distribution of consensus time.

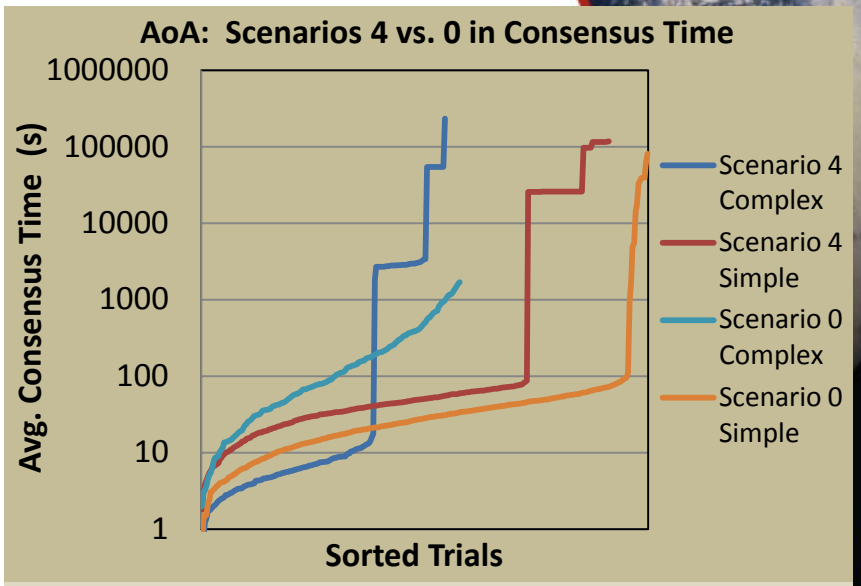
The cliffs appear in both simple and complex anomalies.

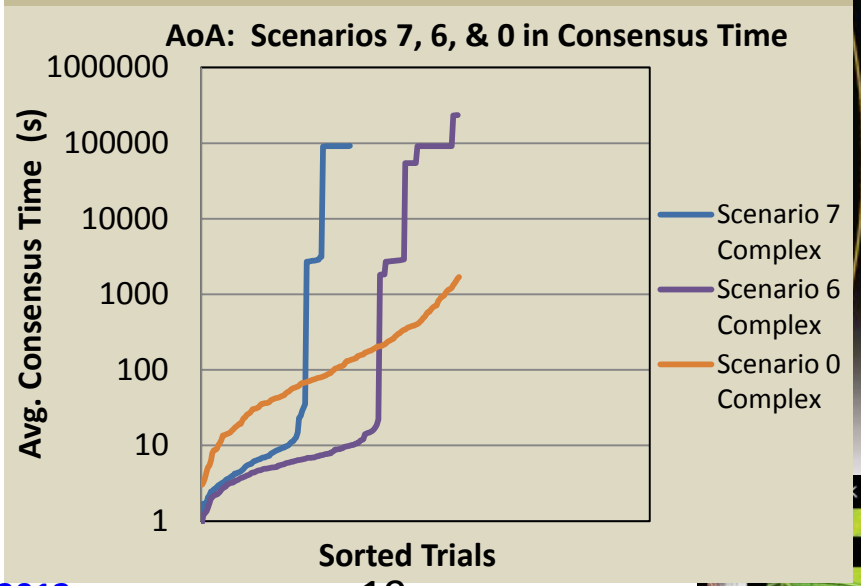
These are consensuses that the team reaches hours or days after their first attempts fail, long after the anomaly disappears from their telemetry. ***--Not rational agent behavior!***

## These are retrospective consensuses.

The team revisits old problems to try again to solve them.

- Small mutations in hypotheses occur at a steady state; eventually they lead to breakthroughs.



# Some Conclusions

Cheaper than Building New Control Rooms, but Not Trivial

Effective Analysis of Alternatives Planning and Design Requires Plausible Agents, Plausible Scenarios, Plausible Mission and Task Dynamics

Such Multidisciplinary Integration Supports Novel Links of "Simulation-informed Human Factors" and "Human Factors-informed Simulation"

Agent Models Demonstrate Learning and "Retrospective" Behaviors Suggesting Memory and Integration—Are Such Findings Reliable? Useful?

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