The Art & Science of Managing Command File Errors

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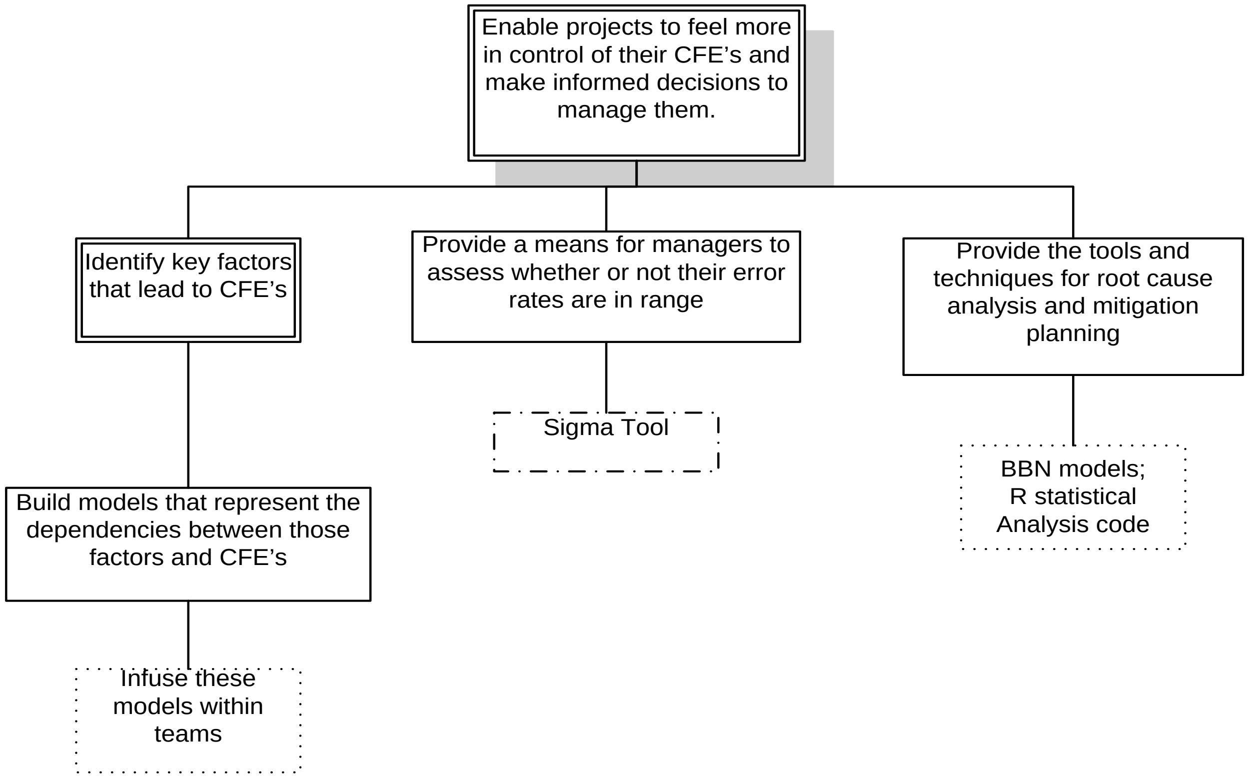
Problem Statement

- Develop and infuse techniques to reduce the rate of operations errors at JPL and NASA.
  - A command file is a piece of software sent to the spacecraft for command & control purposes. Therefore, along with flight software and avionics modules, commands contribute to the command and control functions of a spacecraft.
  - Command File Errors(CFEs) account for an alarming fraction of spacecraft anomalies and near misses.

Approach


Enable projects to feel more in control of their CFE's and make informed decisions to manage them.
Identify key factors that lead to CFE's
Provide a means for managers to assess whether or not their error rates are in range
Provide the tools and techniques for root cause analysis and mitigation planning
Sigma Tool
BBN models; R statistical Analysis code
Build models that represent the dependencies between those factors and CFE's
Infuse these models within teams

Summary of Tools & Techniques

	Sigma-Tool	Bayesian Belief Networks	Empirical Analysis
Purpose	Distribution for the likelihood of CFE's	Sensitivity Analysis, Root Cause Analysis, Dependency Modeling	Underlying analysis for building the Sigma-Tool and BBN models.
Utility	A visual understanding of how a project is doing as compared to other similar projects and helps anticipate future error rates.	understanding effect of changes in likelihood of one element on other system elements and probability of CFE;	Finding the correct probabilistic models for the Sigma-Tool.
Dependencies	If rates are not acceptable, the BBN model is used to determine the root cause for it and how best to mitigate those rates.	Finding the base rate for the Sigma-Tool probabilistic model.	Verification & Validation of Sigma Tool and BBNs.
Tool Underppining	Excel-based	Freeware from UCLA	R Studio - freeware
Basis	Standard error rates for missions based on their levels of novelty.	Bayesian Probability Theory.	Probability & Statistics applied to existing data sets.

Sigma Tool

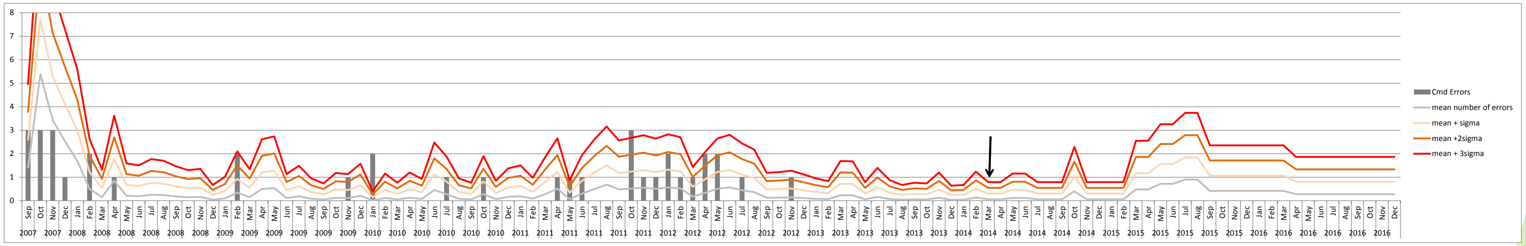
- Uses Excel to enable cheap, multi-platform deployment

- Limits input parameters
  - Project duration built into spreadsheet
  - Number of Files sent per month
  - High or low novelty to be applied to any given month
    - High novelty raises the risk of an error by 50% for any given 'trial' for that month

- Uses a binomial distribution to model each SCMF radiated as a trial which might result in a commanding error
- Calculates the mean expected number of errors in a given month
- Calculates the one, two and three sigma levels associated with the mean expected number of errors
- Captures the data in a spreadsheet and in a graphical output

Sample Project Results!

- One look at the plot gives the answers to our example questions and a lot more….
  - The post-launch CFEs were not unexpected, in fact the team did great!
  - We should expect a CFE every two months during novel operations
  - Our current drought of CFEs may not ***just*** be because we are good, but because we are commanding so little and so repetitively
  - There were times during Novel operations when we were ***appropriately*** concerned



Empirical Analysis

- Data Sources:
  - Information about the command files sent to the spacecraft, in terms of the number of blocks, commands and files in each month of the mission and the number of CFE's observed.
  - Information about the level of activity (in terms of the products produced) by the flight team during each month.
  - Information about the novelty levels associated with each month of the mission.
  - General information in the databases in terms of the various errors that have occurred during the lifecycle of the flight projects and details about their causes and mitigations.
  - Our main goal in data analysis was to validate the results of the sigma tool. This is the first of the tools to be adopted by flight teams as it is the simplest to use. The sections below describe the different types of analysis conducted for this purpose.

Correlation Analysis

- At the onset of the study, we decided to look into the correlations between the following variables in each month of the mission:
  - Command File Errors
  - Number of files
  - Number of commands
  - Number of blocks
  - Activity levels during the month (in terms of products produced by the flight teams.

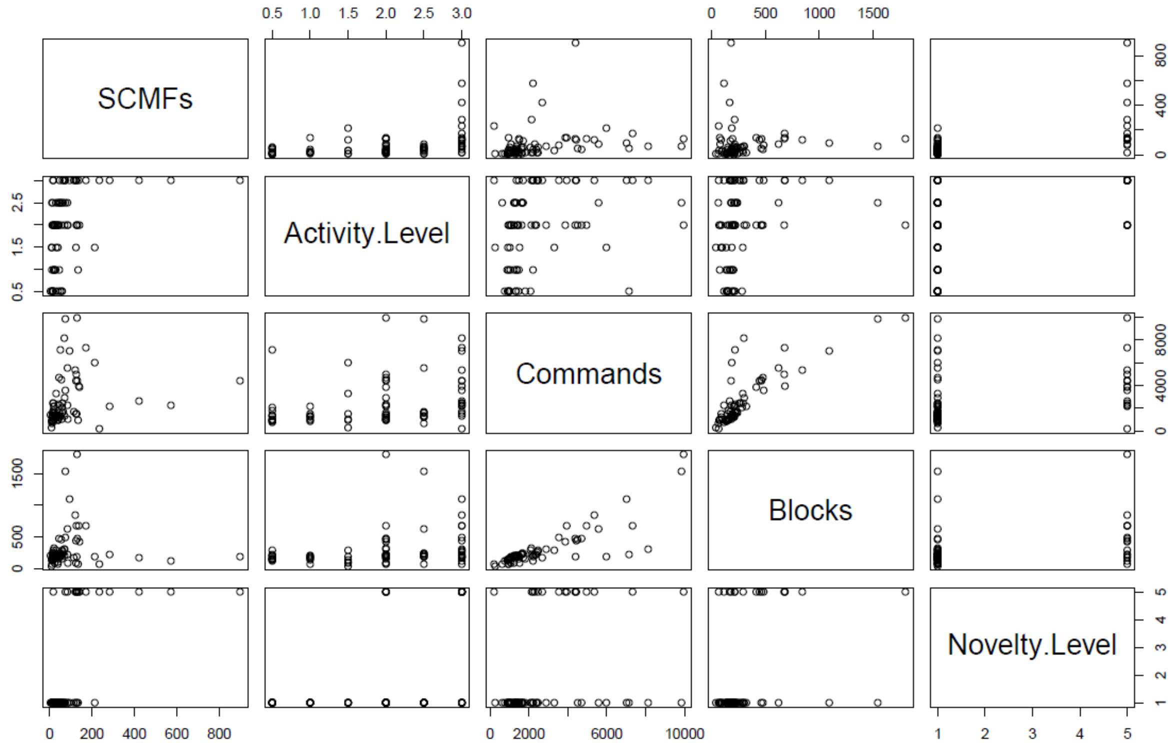
	Cmd Errors	SCMFs	Activity Level	Commands	Blocks
Cmd Errors	1				
SCMFs	0.571368518	1			
Activity Level	0.22474755	0.380494123	1		
Commands	0.3104797	0.23939474	0.298713416	1	
Blocks	0.296127799	0.052130687	0.268910971	0.822762979	1

Correlation Analysis

- Experiments Conducted:
  - Phasing
  - Time shifting for activity levels
- Result: Add Novelty Factor

	Cmd Errors	SCMFs	Activity Level	Commands	Blocks	Novelty Level
Cmd Errors	1					
SCMFs	0.57136852	1				
Activity_Level	0.22474755	0.380494	1			
Commands	0.3104797	0.239395	0.298713	1		
Blocks	0.2961278	0.052131	0.268911	0.82276298	1	
Novelty	0.53297418	0.579055	0.44023	0.36065182	0.345509	1

Correlation Analysis for Sample Project



Regression Analysis

- The goal of this analysis was to determine how much of the variability in the Command File Errors can be explained with a nonlinear function of the variables in question.
- Of course the caveats of this study are that
  - (1) the CFE's are not continuous variables and therefore they can't be predicted as a continuous function of the variables and
  - (2) we know that the behavior of the system is probabilistic rather than quadratic, so a quadratic equation does not completely capture the variability of the CFE's.
- For the flight projects analyzed, the R-squared value was approximately 50% based on all the variables.
- When we conducted a regression analysis only on the Novelty factors and the number of files, the R-squared value was reduced to about 40%.
- Given the caveats listed above, we conclude that the variables in question, especially the novelty levels and the number of files are very significant factors.

Chi-Squared Goodness of Fit Test

- We used a chi-squared goodness of fit test to test the hypothesis that the Binomial distribution with the parameters we had used was in fact the correct distribution for the distribution of the command file errors.

- For this purpose, we binned the files into those with errors and those without errors.

- We then calculated the expected number of files with errors based on our distribution, and also assessed the observed number of errors in each case.

- Then, using the equation $X^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$, where Oi is the observed frequency for bin i, and Ei is the expected frequency for that bin based on the hypothesis that our distribution is correct, we obtain the value to be compared with a chi-squared distribution with one degree of freedom to assess the goodness of fit.

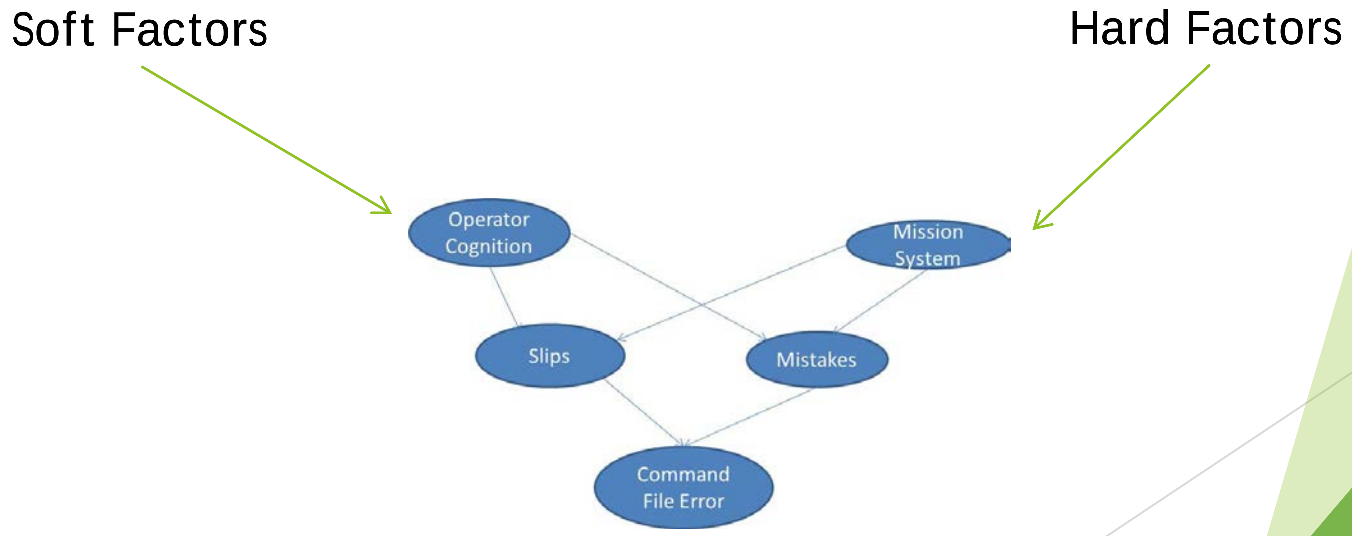
Principal Component Analysis

- Since the variables SCMF, Commands and Blocks are correlated, we conducted a Principal Component and Factor Analysis to determine an equation for “Adjusted SCMF”.
  - The idea is that all SCMF’s are not equal – the ones with more blocks and more commands are slightly more error prone.
  - Equation obtained from Principal Component analysis. This equation can be used for the parameter “n” in the Binomial Distribution.
    - the “p” parameter will depend on the novelty level of the mission.

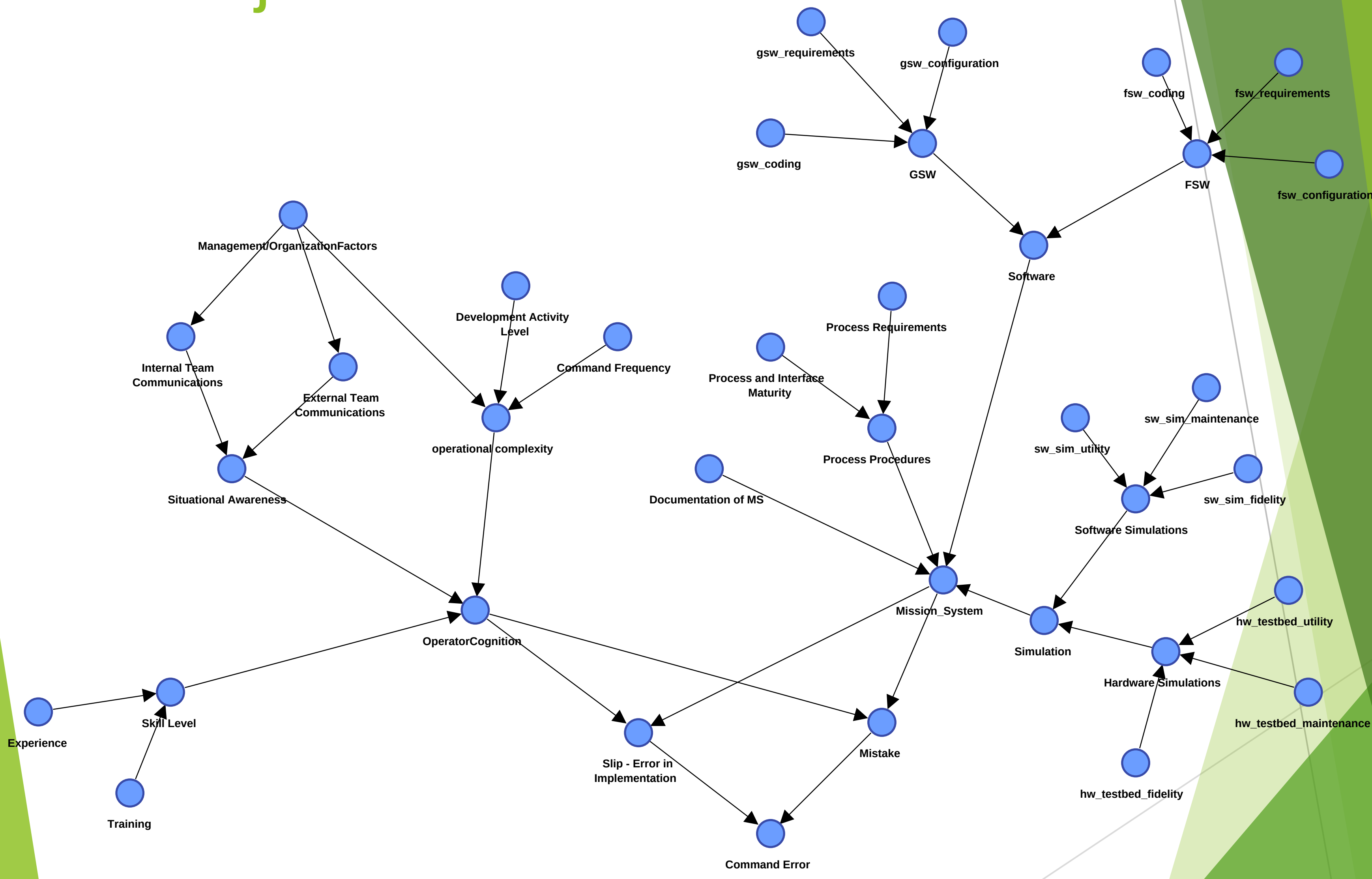
Bayesian Belief Networks

- The investigation into the root causes of command file errors has led us to abstract these causes and represent them in compact, executable Bayesian Belief Network (BBN)models.

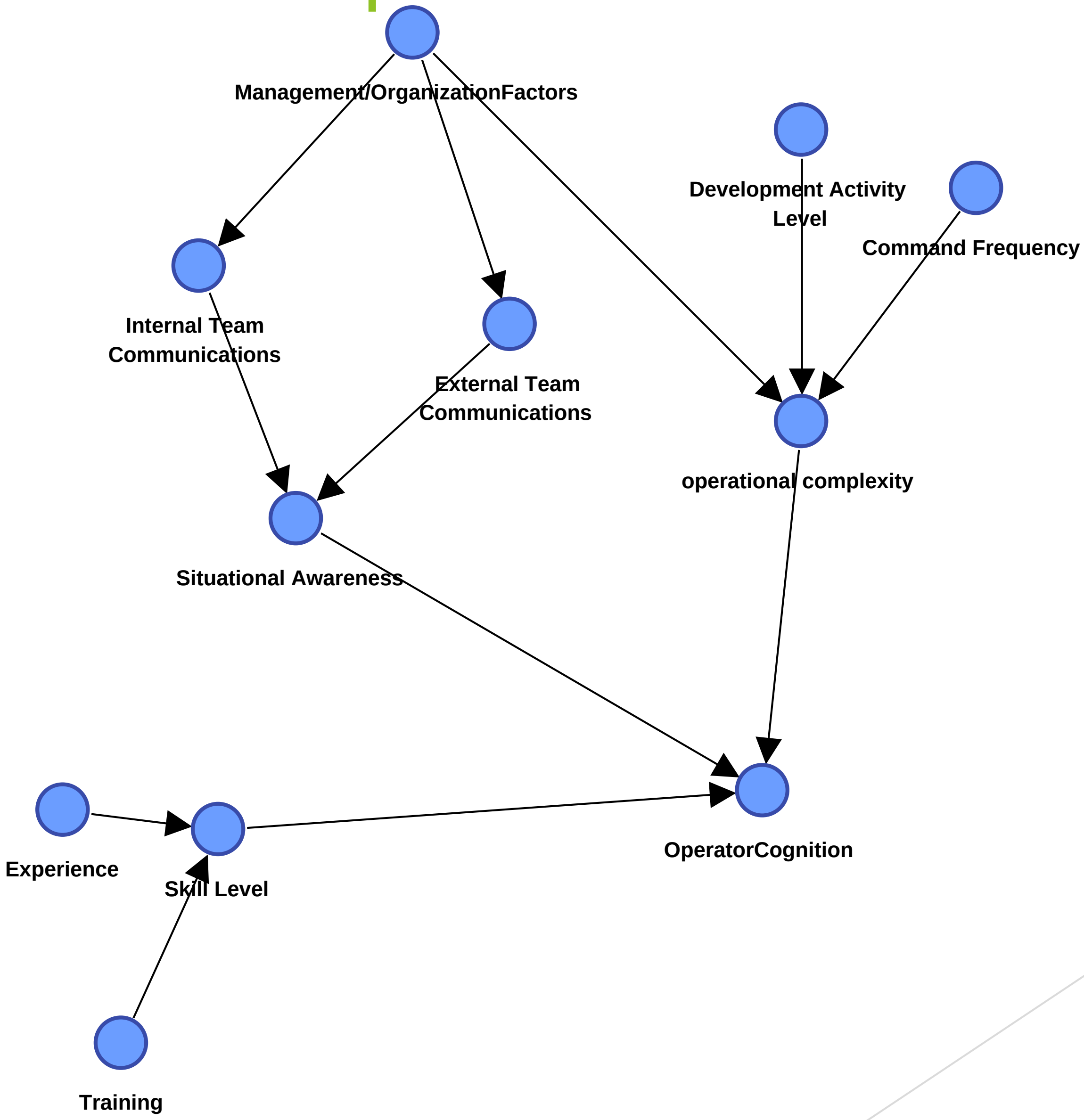
- A simple abstraction of the model is:



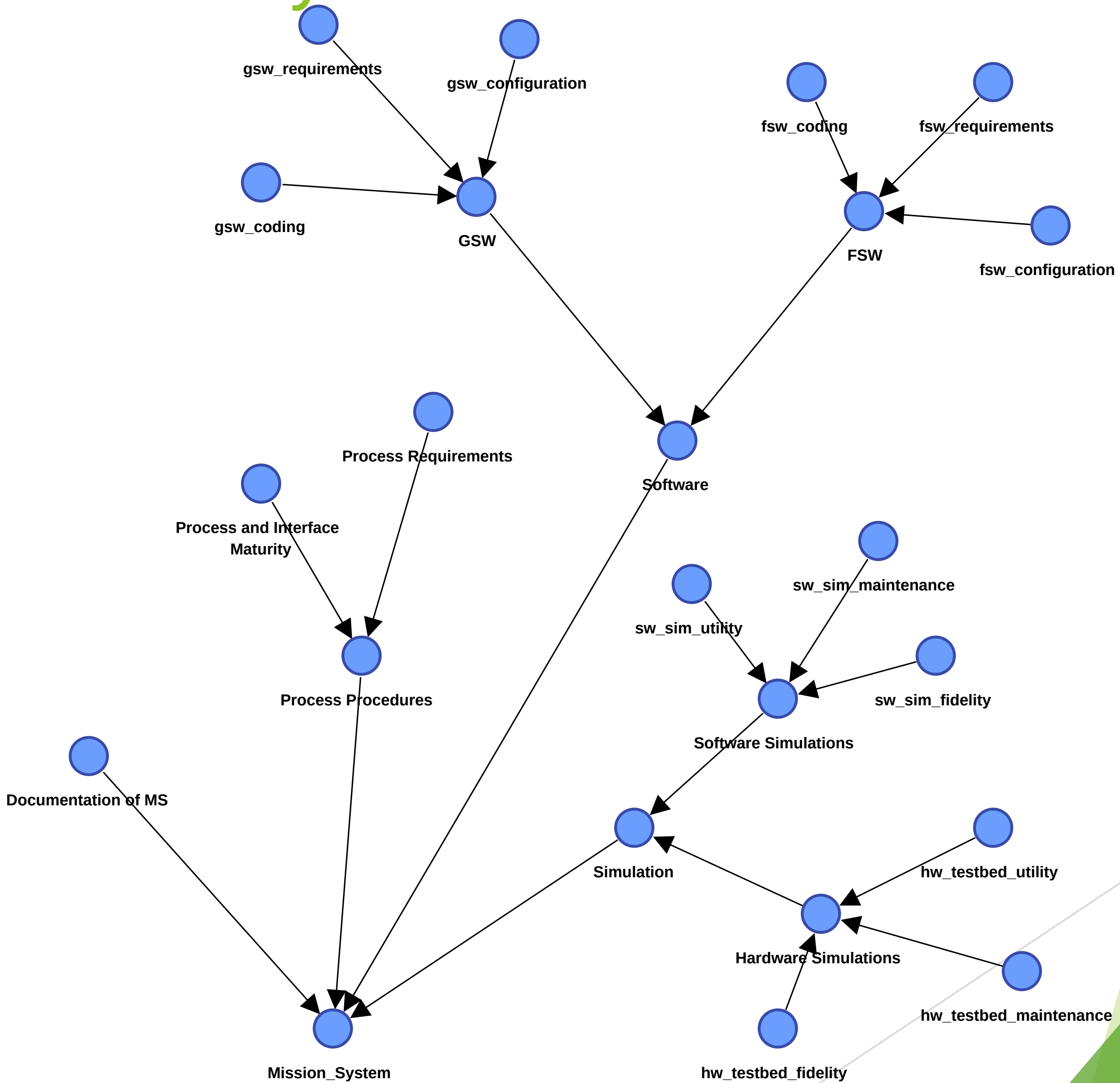
Project Model



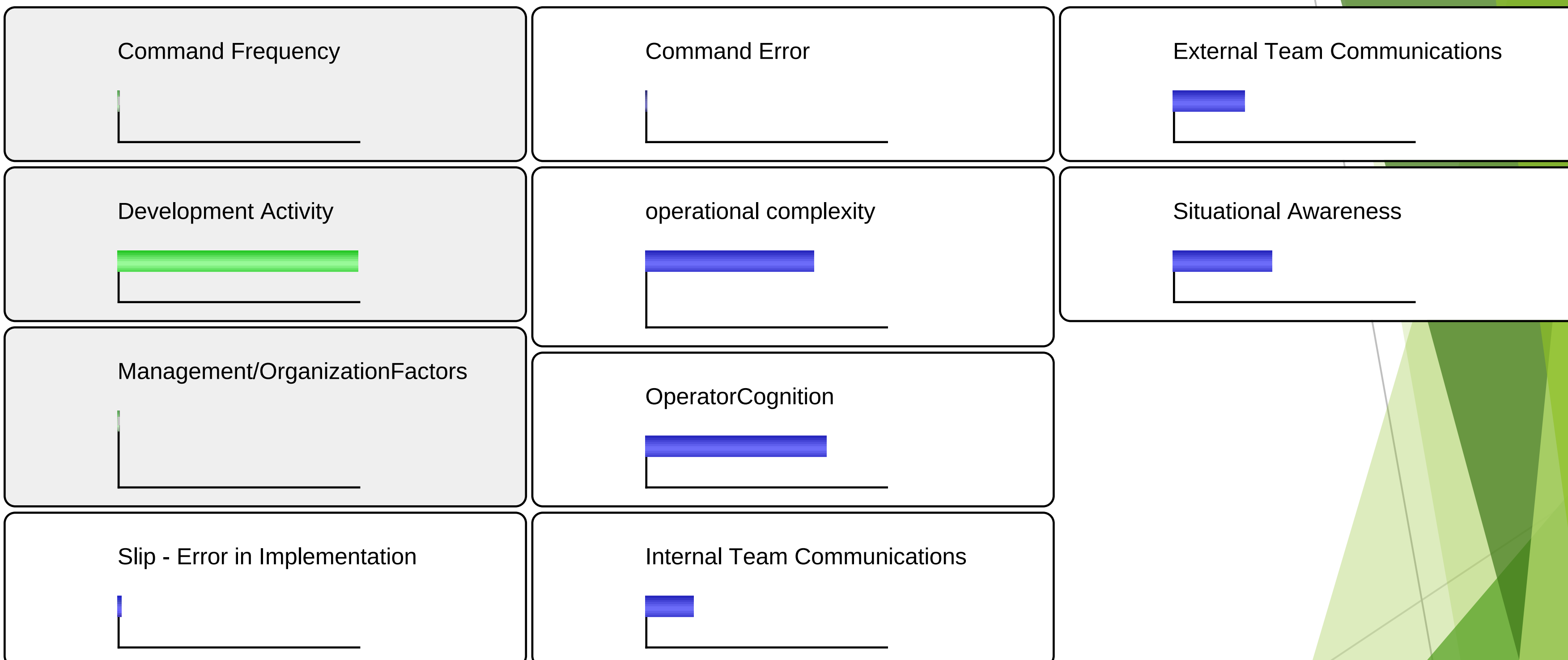
Process Compliance – Soft Factors



Mission System – Hard Factors

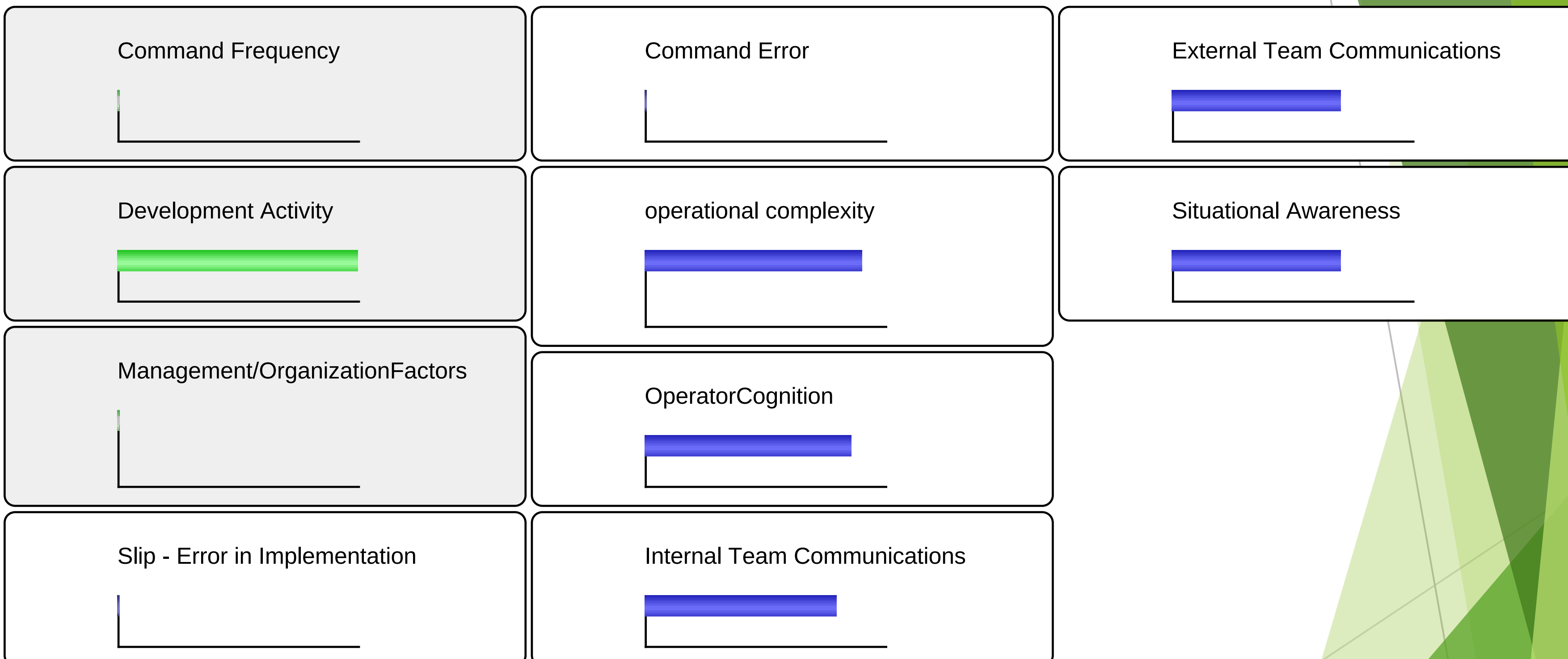


Use Case 1
Adversarial Management – Low Activity



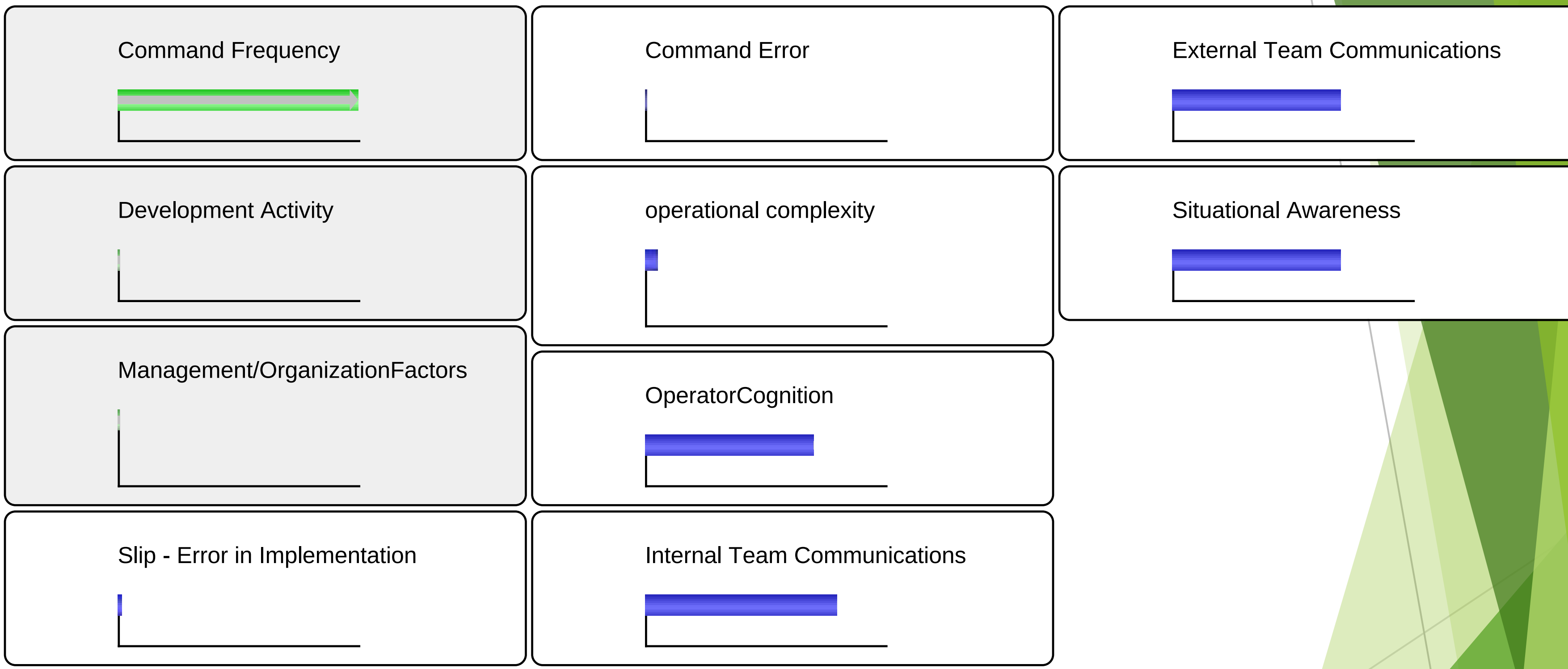
Message: Adversarial management can cause an increase in CFE’s even during low activity phases.

Use Case 1 – Teaming Management – Low Activity



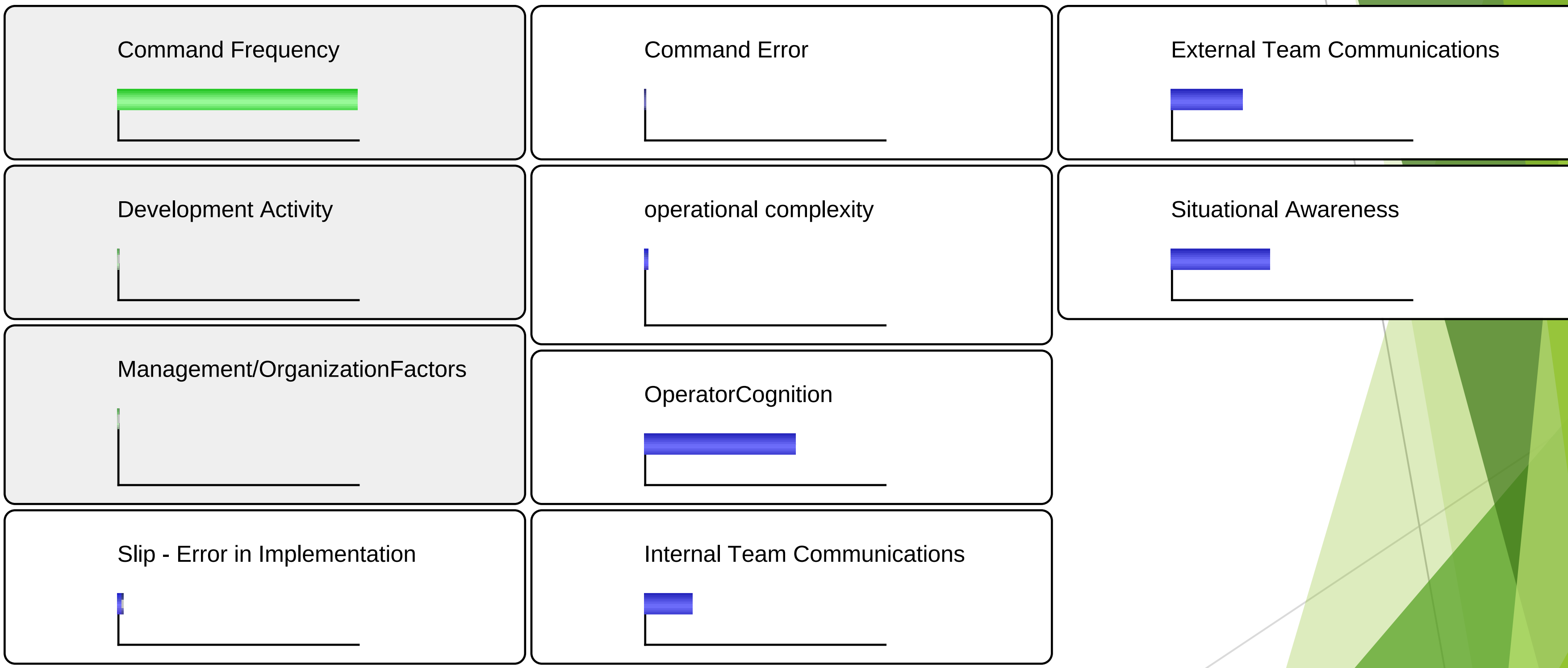
Message: Teaming management (as compared to Adversarial) reduces CFE's by ~ 0.4% during low activity phases.

Use Case 2 – Teaming Management-High Activity



A teaming management with high activity levels yields only ~0.1% higher chance of CFE as compared to adversarial management in low activity times.

Use Case 2 – Teaming versus Adversarial Management – High Activity



An adversarial management during high activity phases increases CFE rates by 0.23%

Use Case 3: Analyzing the effect of evidence on dependent nodes

- Now let’s assume that we have evidence that a node has occurred.
- We can use this information to find the updated likelihood of other nodes in the mode.
- Below are sample root cause analyses and scenarios based on this concept.

Use Case 3: Analyzing the effect of evidence on dependent nodes

Mission System Inadequate?	Operator Cognition Incorrect?	Documentation of MS Inadequate?	Process Procedures	Simulation Inadequate ?	Software
Yes	No	85.00%	7.00%	7.00%	8.11%

Simulation Inadequate?	Software Simulations Inadequate?	Hardware Simulations Inadequate?
Yes	31.00%	74%

HW Simulations Inadequate	Fidelity of Testbed Inadequate?	Maintanence Inadequate?	User Friendliness Inadequate?
Yes	52.00%	20.00%	75.00%

SW Simulations Inadequate	Fidelity of Testbed Inadequate?	Maintenance Inadequate?	User Friendliness/Utility Inadequate?
Yes	17%	17.00%	60.00%

Software Inadequate?	GSW Inadequate	FSW Inadequate
Yes	72%	30.00%

GSW Inadequate?	Coding Inadequate?	Requirements Inadequate?	Configuration Inadequate?
Yes	21%	44%	21%

FSW Inadequate?	Coding Inadequate?	Requirements Inadequate?	Configuration Inadequate?
Yes	9%	0%	0%

Use Case 3: Analyzing the effect of evidence on dependent nodes - continued

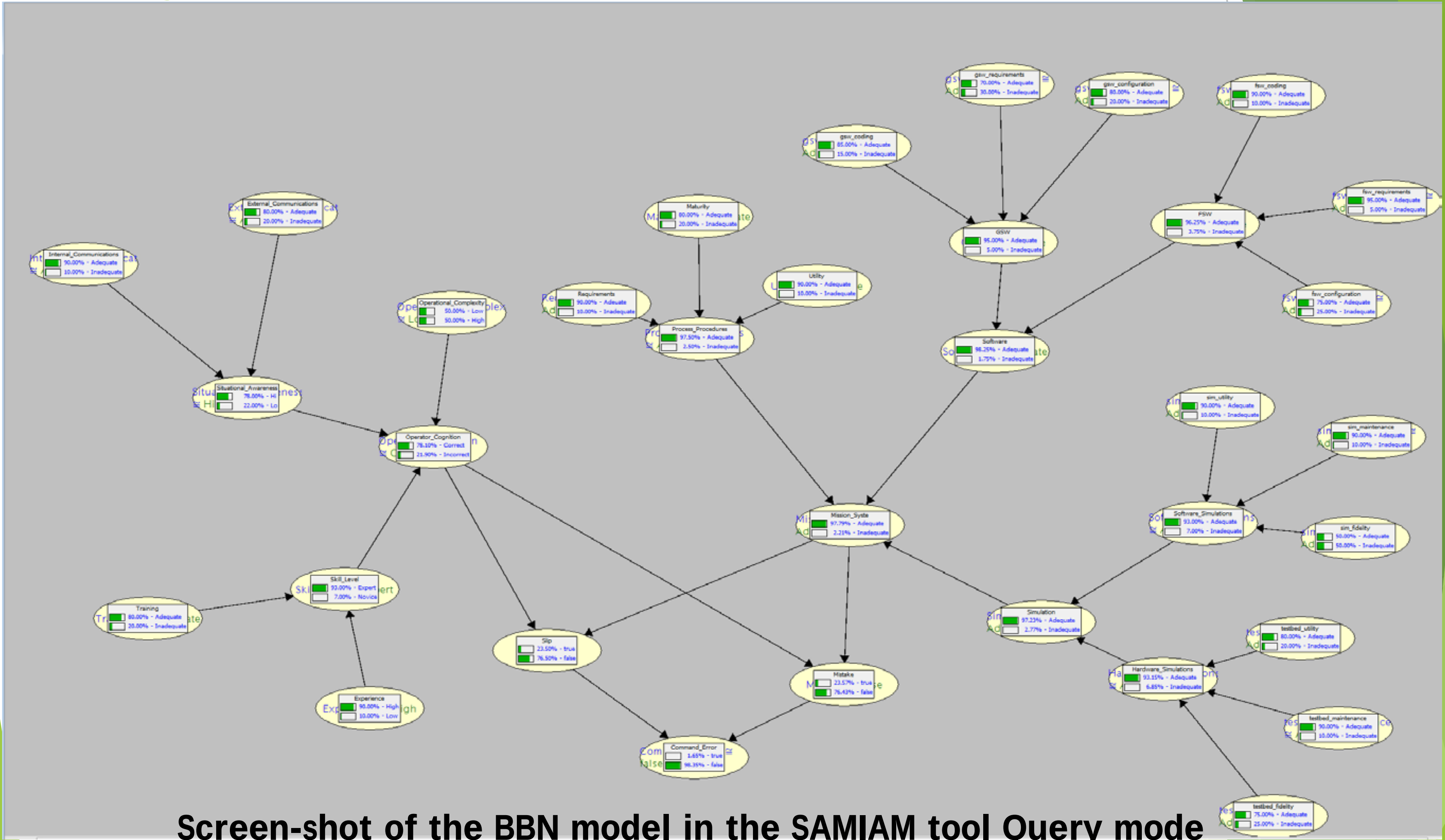
Mission System Inadequate?	Operator Cognition Inadequate?	Operational Complexity High?	Skill Level Low(Novice or Journeyman)?	Situational Awareness Low?
No	Yes	78.00%	40.00%	50.00%

Operational Complexity High	Management/Org Adversarial?	Development Activity High?	Command Frequency Hi?
Yes	6.00%	67%	66%

Situational Awareness Low?	External Team Communications Inadequate?	Internal Team Communications Inadequate?	
Yes	58.00%	48.00%	

Communications Inadequate?	Management/Organizational Factors Inadequate?
Yes	51.00%

Use Case 4: Complete Model for Project 2



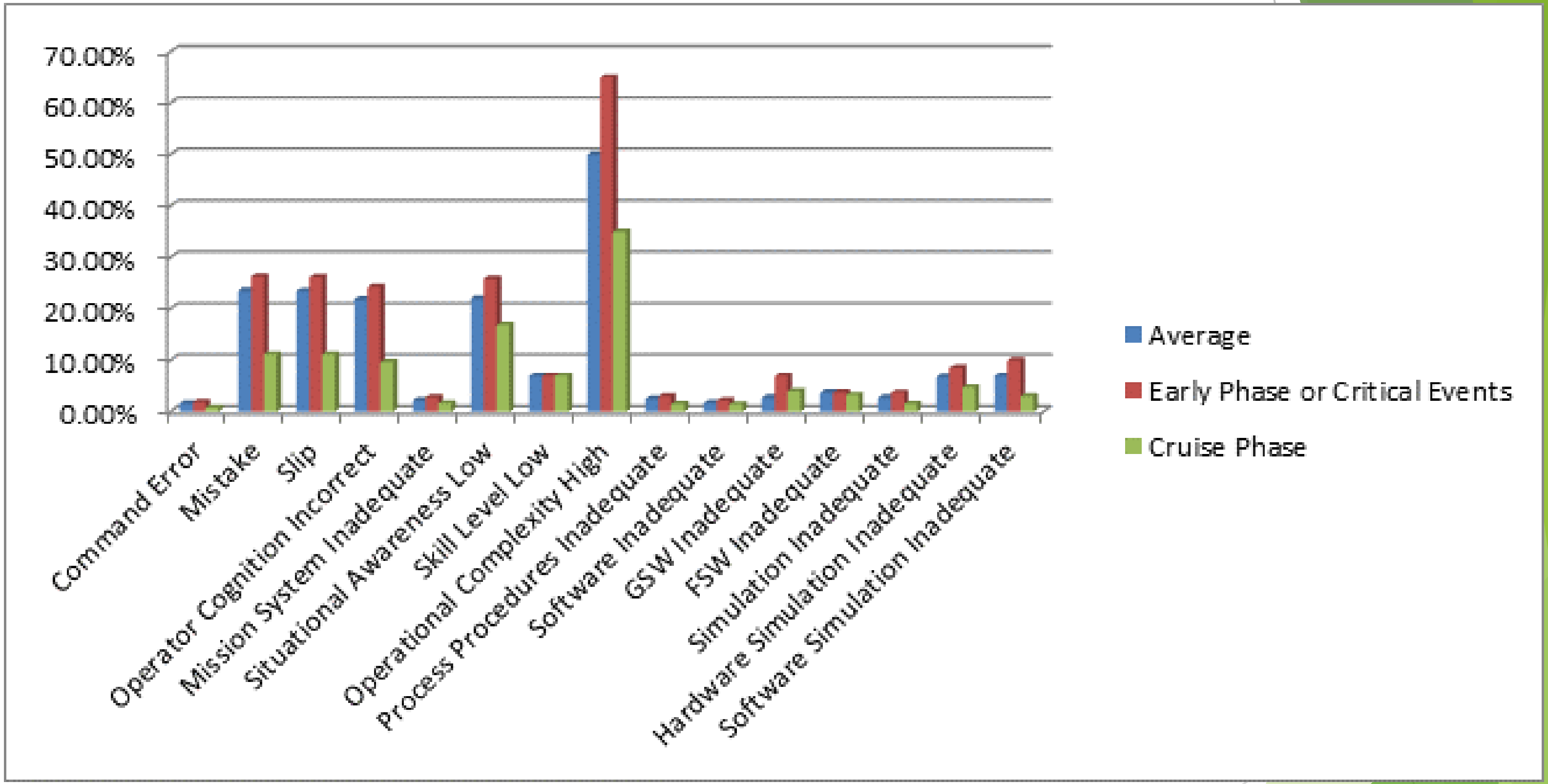
Screen-shot of the BBN model in the SAMIAM tool Query mode

Use Case 4: Complete Model

	Average	Early Phase or Critical Event	Cruise Phase
Command Error	1.65%	1.84%	0.78%
Mistake	23.57%	26.24%	11.15%
Slip	23.50%	26.16%	11.11%
Operator Cognition Incorrect	21.90%	24.24%	9.68%
Mission System Inadequate	2.21%	2.73%	1.66%
Situational Awareness Low	22%	25.81%	16.85%
Skill Level Low	7%	7.00%	7.00%
Operational Complexity High	50%	65.00%	35%
Process Procedures Inadequate	2.50%	3.00%	1.50%
Software Inadequate	1.75%	2.15%	1.45%
GSW Inadequate	3%	7.00%	4%
FSW Inadequate	3.75%	3.75%	3.25%
Simulation Inadequate	2.77%	3.71%	1.54%
Hardware Simulation Inadequate	6.85%	8.55%	4.72%
Software Simulation Inadequate	7.00%	10.00%	3%

Comparison of probability of key nodes during different mission phases.

Use Case 4: Complete Model



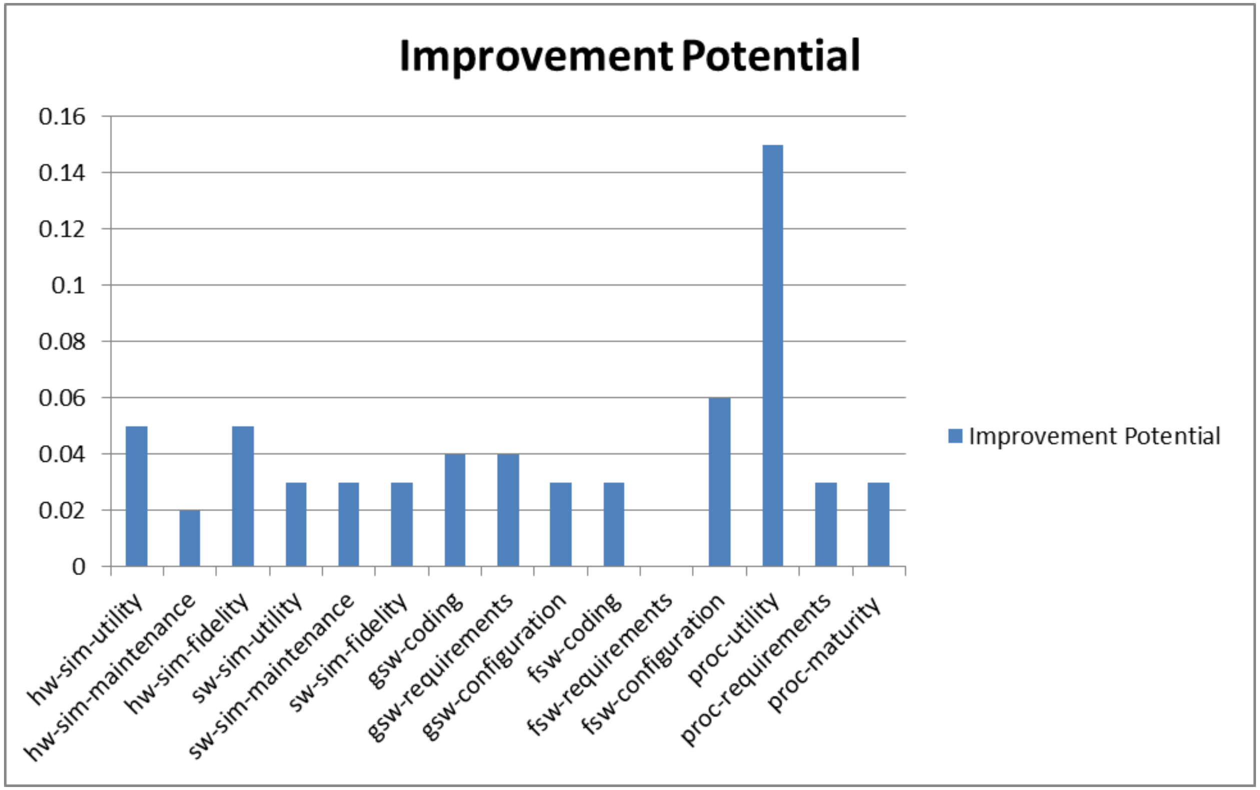
Graph corresponding with the probability of key nodes

Use Case 5: Hard Factors

			Sensitivity of Mission System Inadequacy to:
Simulation			14
	Hardware Simulations		2.8
		utility	0.48
		maintenance	0.26
		fidelity	0.25
	Software Simulations		2.8
		utility	0.28
		maintenance	0.28
		fidelity	0.28
Software			15
	Ground Software		3
		coding	0.3
		requirements	0.15
		configuration	0.3
	Flight Software		3
		coding	0.3
		requirements	0.15
		configuration	0.3
Process Procedures			15
		utility	1.5
		requirements	0.75
		maturity	0.75

Sensitivity Analysis for the Hard Factors

Use Case 5: Hard Factors



Root Level Node	Improvement Potential
hw-sim-utility	0.05
hw-sim-maintenance	0.02
hw-sim-fidelity	0.05
sw-sim-utility	0.03
sw-sim-maintenance	0.03
sw-sim-fidelity	0.03
gsw-coding	0.04
gsw-requirements	0.04
gsw-configuration	0.03
fsw-coding	0.03
fsw-requirements	0
fsw-configuration	0.06
proc-utility	0.15
proc-requirements	0.03
proc-maturity	0.03

Improvement Potential for Root Nodes

Conclusions

- There two main elements associated with Command File Errors (CFEs)
  - The base rate which is dependent on the underlying infrastructure.
  - Variations to this base rate which are driven by characteristics of flight project in question.
- Managing CFE's requires the development and combination of custom tool base and methodologies.