Aviation Accident Modeling Using Bayesian Networks for NASA Aviation Safety Program Portfolio Assessment

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Presentation to MATH410 – Analysis of Big Data – Prof. Rex Kincaid
College of William and Mary
April 2nd, 2014

Outline

- NASA ARMD AvSP and Aviation Safety Systems Analysis Overview
- Loss of Control Accident Framework (LOCAF) Model
  - Literature Review
  - System Modeling Selection
  - LOCAF Overview & SME Sessions
  - Results
- Conclusions

Current NASA Aeronautics Portfolio

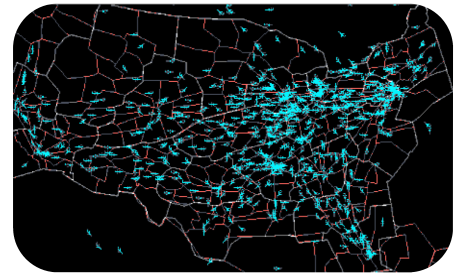


Fundamental Aeronautics Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

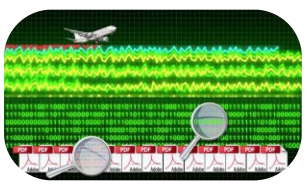
Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment

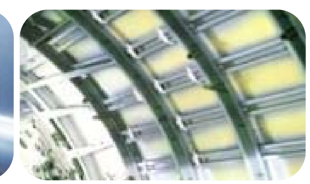
Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.




Aviation Safety Program (AvSP)

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.



Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.

AvSP Technical Challenges

- Technical Challenges (TCs) are aligned to Program goals and Project objectives
  - Provide research focus to solving aviation safety problems
  - Provide consistent framework to focus, direct, plan, execute, manage, and communicate Center-distributed research
  - Form basis for “contract” between Program and Project and Center

Project	Technical Challenges
System-wide Safety Technologies (SSAT)	➢ Assurance of Flight Critical Systems (AFCS) ➢ Discovery of Precursors to Safety Issues (DPSI) ➢ Assuring Safe Human-Systems Integration (ASHSI) ➢ Prognostic Algorithm Design for Safety Assurance (PDSA)
Vehicle Systems Safety Technologies (VSST)	➢ Improve Crew Decision-Making and Response in Complex Situations (CDM) ➢ Maintain Vehicle Safety between Major Inspections (MVS) ➢ Assure Safe and Effective Aircraft Control under Hazardous Conditions (ASC)
Atmospheric Environment Safety Technologies (AEST)	➢ Engine Icing: Characterization and Simulation Capability (EI) ➢ Airframe Icing Simulation and Engineering Tool Capability (AI) ➢ Atmospheric Hazard Sensing and Mitigation Technology Capability (AHSM)

NASA AvSP Portfolio* Assessment

- Provide an independent analysis of the AvSP portfolio
- Assess the AvSP portfolio using a variety of metrics, including a *risk-based causal model*
- Provide a gap analysis to indicate aviation safety risk areas not being addressed, and
- Provide information to the Program Manager for decision making and communication

* There are 46 safety technologies (or products) as of July 2013.

Aviation Safety Systems Analysis

Current Team Members

NASA LaRC

Aviation Safety System Modeling

Dr. Ann Shih LaRC (VAB)

Lawrence Green LaRC (VAB)

Aviation Safety Systems Analysis

Dr. Nipa Phojanamongkolkij (detailed to ASAB)

Aviation Safety Statistical Data Analysis

Joni Evans (AMA, Inc.)

NASA Glenn

Aviation Safety Systems Analysis

Mary Reveley (RTM)

Colleen Withrow (DSS)

Karen Leone (Vantage Partners, LLC)

David Fuller (DSV)

NASA AMES

Aviation Safety Systems Analysis

Dr. Indranil Roychoudhury (SGT, Inc.)

Volpe National Transportation Center

Safety Benefits/Cost Modeling and Risk Analysis

Dr. Lawrence Barr

National Institute of Aerospace

Aviation System Modeling and Systems Analysis

Dr. Ersin Ancel

Aviation Safety Modeling Refinement and Knowledge Elicitation

Dr. James Luxhoj (LCR, LLC)

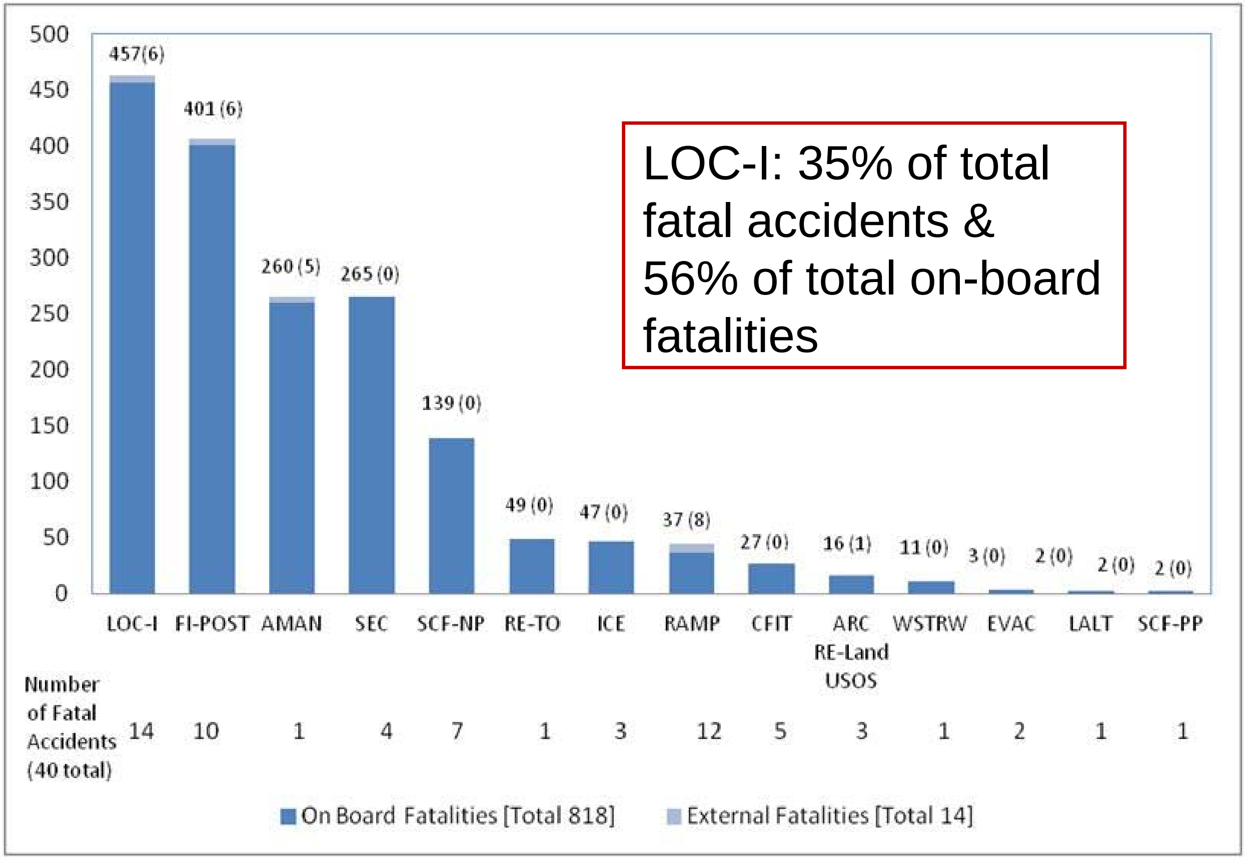
Loss of Control Accident Framework
Team Members

- Ersin Ancel, Ph.D. (NIA at NASA Langley - ASAB)
- Ann T. Shih, Ph.D. (NASA Langley – VAB)
- Sharon Monica Jones, Ph.D. (NASA Langley – ASAB)
- Mary S. Reveley (NASA Glenn)
- James T. Luxhøj, Ph.D. (NIA/LCR)
- Joni K. Evans (AMA, Inc. at NASA Langley - ASAB)

Loss of Control Accident Framework
Why Are LOC Accidents Important?

LOC Accidents

- Low probability but high consequence of aviation accidents
- Fatal accidents statistics: U.S. Part 121 and scheduled Part 135 (Commercial) operations, 1997-2006



Loss of Control Accident Framework

Modeling Objectives & Philosophy

- Use state of the art systems of systems modeling and other operations research techniques to examine the integration of AvSP portfolio elements to address future safety “tall poles”

- Provide **quantitative** analysis and results of the impact of safety products on the aviation risk reduction

- A generic, high-level, system-integrated model
  - Not a representation of a specific accident/incident case
  - Not a detailed simulation analysis
  - A systems level risk-based causal model
  - Capture of the multi-dependencies (interactions) of causal and contributing factors from various problem domains

Loss of Control Accident Framework

Overall LOC Modeling Steps

- Conduct a LOC accident database review to determine the causality and develop a generalized LOC framework
- Model the framework using appropriate system modeling
- Conduct subject matter expert (SME) sessions to evaluate the model and elicit data
- Insert AvSP safety technology products from AEST, SSAT, and VSST projects into the model for portfolio assessment
- Assess the impact of new technologies on the reduction of future risk of LOC, i.e., the likelihood of LOC accidents

Loss of Control Accident Framework

Accident Database Review

Review Constraints

- In-flight LOC definition for this modeling: LOC followed by system component failures or malfunction, pilot induced oscillations, maneuvers and stall; also including uncontrolled altitude deviation, aerodynamic stall, in-flight collision with terrain, or uncontrolled descent

- 1987-2009 within FAR Part 121 & Part 135 scheduled and non-scheduled

Database Sources/References

- Aviation Safety Information Analysis and Sharing (ASIAS) – based on NTSB database, maintained by the AvSP Systems Analysis team

- National Transportation Safety Board (NTSB) factual and detailed reports

- Commercial Aviation Safety Team/International Civil Aviation Organization (CAST/ICAO) Common Taxonomy Team (CICTT) taxonomy

Total # of LOC accidents on the initial list: 315

Loss of Control Accident Framework
Accident Database Review (cont’d)

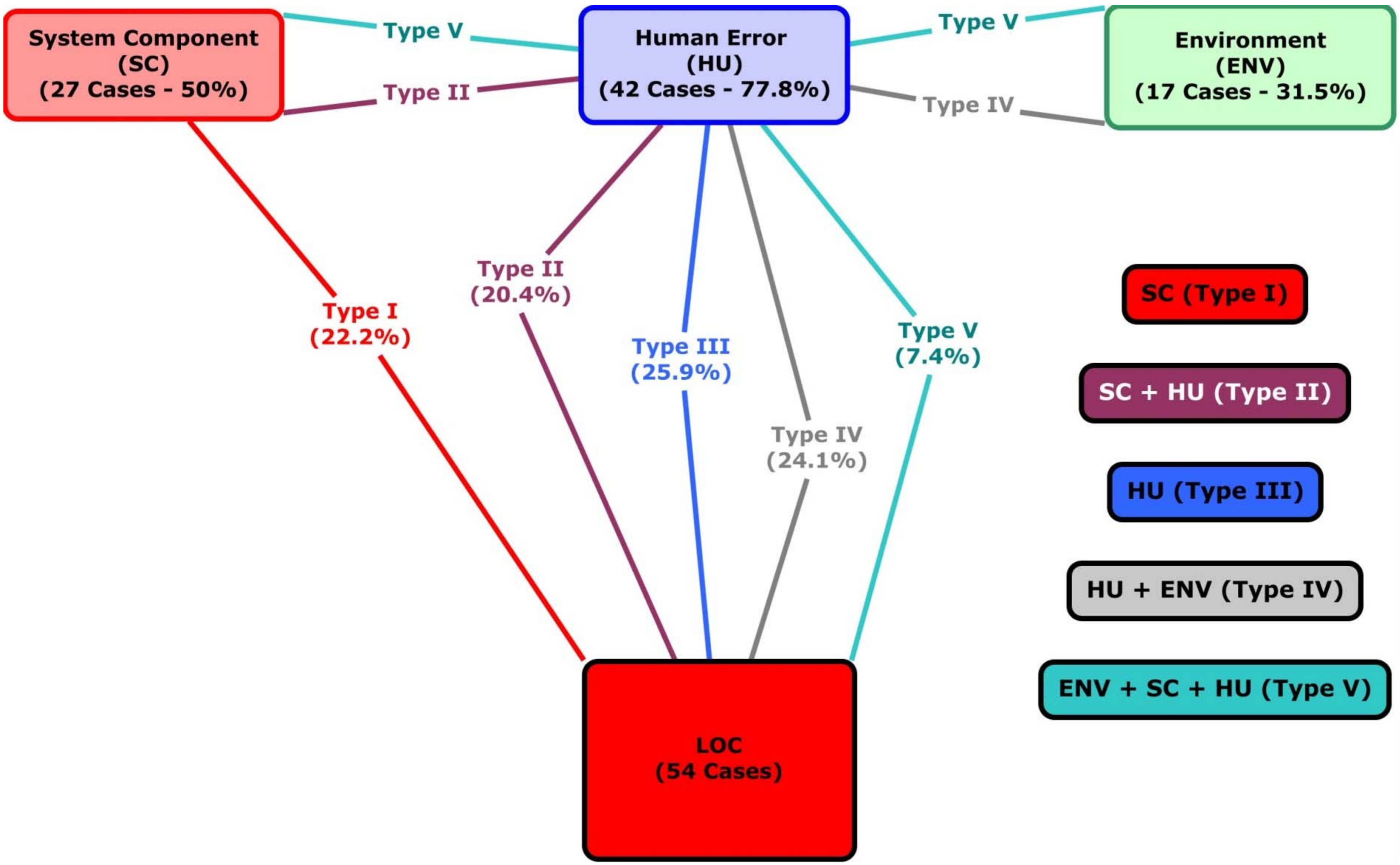
Assumptions and ground rules

- US accidents
- Aircraft take-off-weight > 5700kg (12500 lbs)
- Security-related accidents are excluded
- Excluded LOC accidents with DC-3 aircraft due to its age and limited use (all system component related)

Total # of LOC accidents on the final list: 54

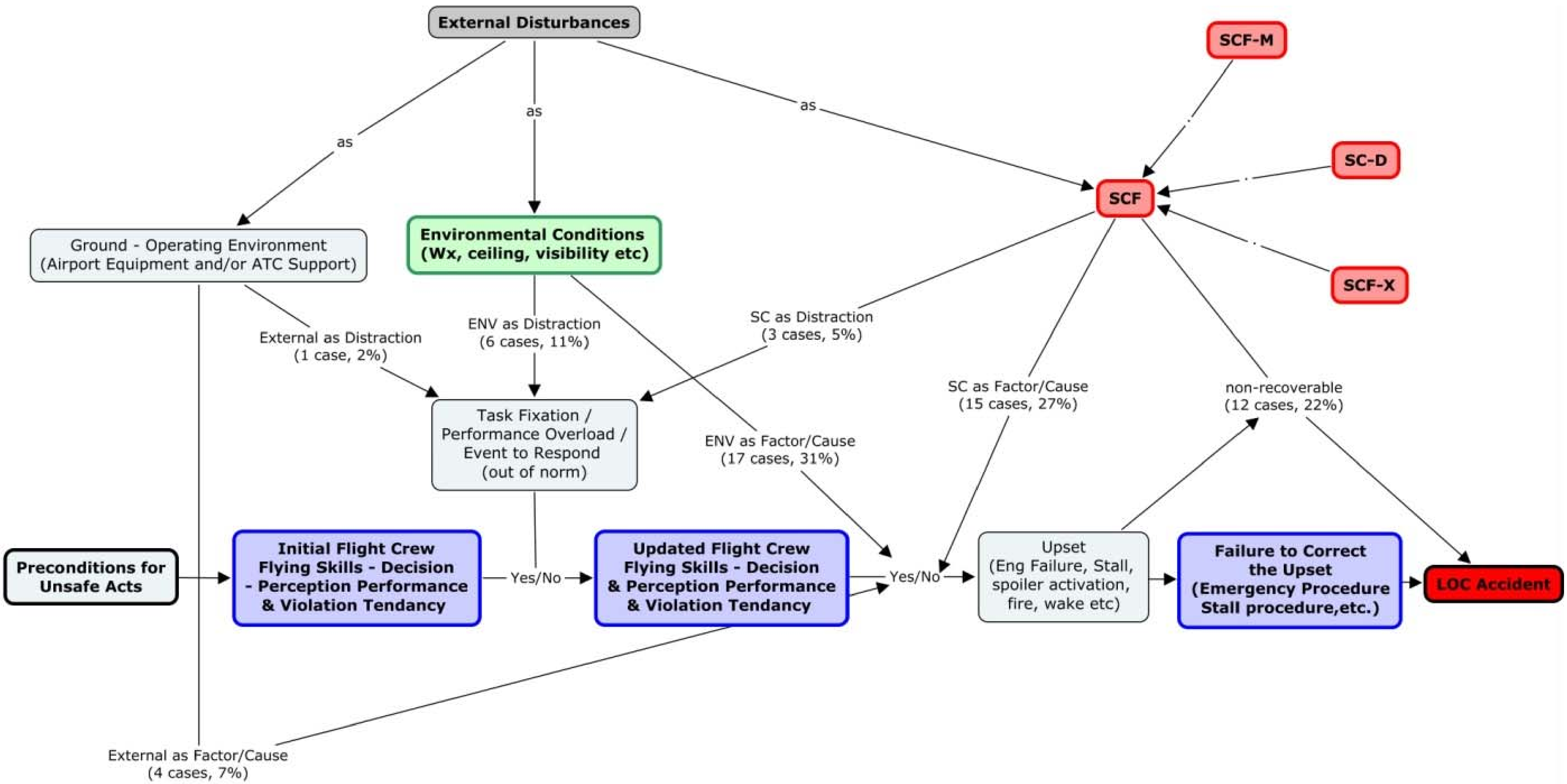
Loss of Control Accident Framework
Development of the Generalized Framework

- Identify the event sequence for 54 LOC accident cases
- Categorize five generalized LOC accident types based on LOC primary causes



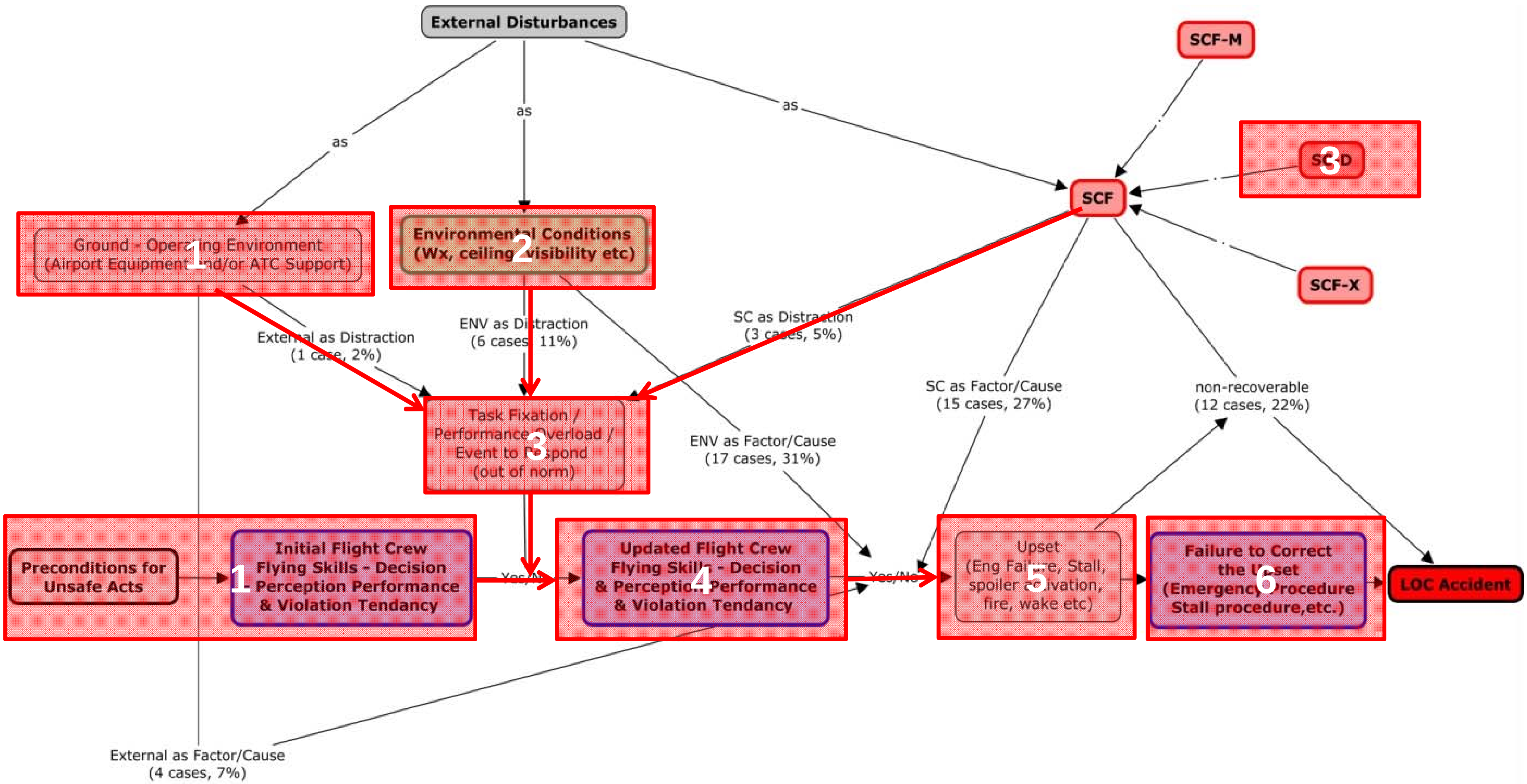
Loss of Control Accident Framework
Development of the Generalized Framework (cont'd)

- **LOCAF configuration**



Loss of Control Accident Framework
Development of the Generalized Framework (cont'd)

- **LOCAF mapping example: Colgan 3407 accident (Buffalo, NY, 2009)**



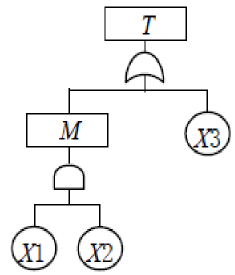
Systems Modeling

System Safety Risk Modeling Methods Criteria

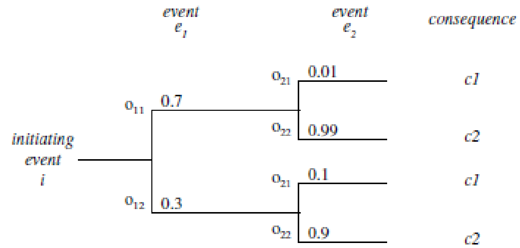
- Probabilistic model
- Causal relationships/networks
- Inference and reasoning and updates
- Decision-making
- Large complex integrated system model

Systems Modeling
Popular Modeling Techniques

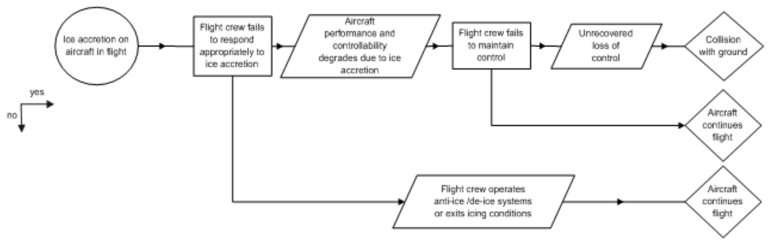
Fault Tree (FT):
Failure analysis
- Top-down approach
- AND, OR gate
- Binary logic
- For risk & reliability study of (sub)systems



Event Tree (ET): Consequence analysis
- Forward method
- Initiating event with chronological sequence of events/consequences
- Linear sequence dependencies
- For multiple safeguards to mitigate risk

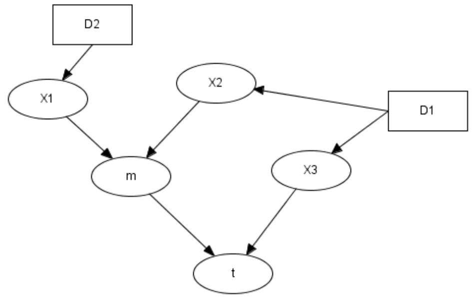


Event Sequence Diagram (ESD): Scenario analysis
- Similar to ET, but at a broader level
- Risk scenarios from an initiating event
- Pivotal events
- End state for each scenario path



* ESD by Alfred Roelen

Bayesian Belief Network (BBN): Causal analysis
- Reasoning under uncertainty
- Bayes' Theorem - Conditional probabilities
- Multi-dependencies between causal factors
- Decision-support tool - Influence Diagram (ID)



Systems Modeling
Review of Existing Aviation Safety Risk Models

- **Safety Methods Database***
  - Maintained by the National Aerospace Laboratory of the Netherlands (NLR)
  - Contains over 600 techniques, methods, models, and frameworks
  - Over 160 methods are related to air transportation (ATM, aviation) and 60 related to aircraft and avionics
  - Also covers techniques used in domains like nuclear and chemical industries, telecommunications, health, as well as rail/road/water transportation and logistics
- **Models evaluated**
  - Aviation Safety Risk Model (ASRM) - BBN
  - Causal model for Air Transport Safety (CATS) - ESD, FT, BBN
  - Quantitative Risk Assessment System (QRAS) - ESD, FT
- *Note: FT and ESD can be represented by BBN*

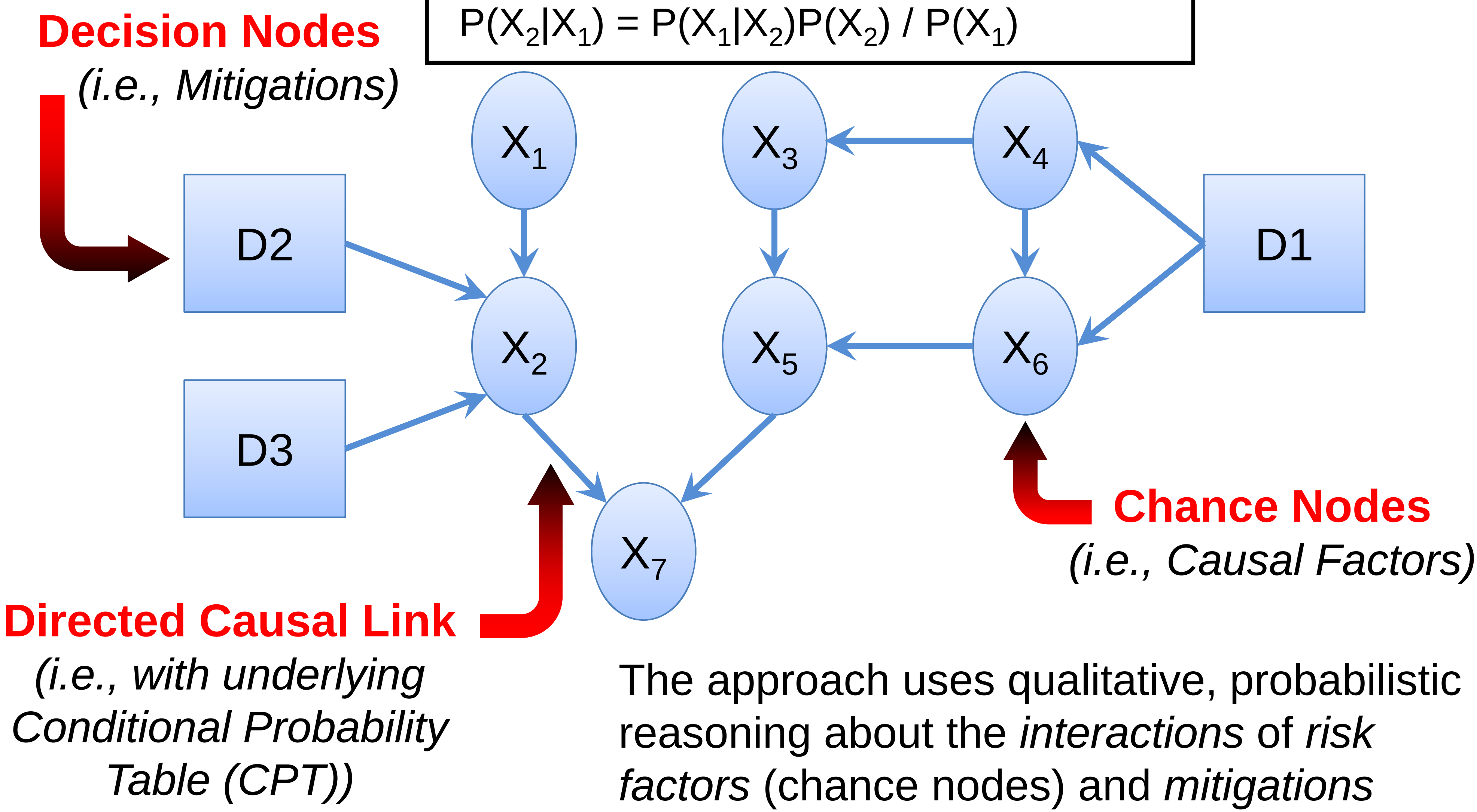
*A copy of the database can be accessed from: http://www.nlr.nl/downloads/safety-methods-database.pdf

Loss of Control Accident Framework

Bayesian Belief Networks – Terminology and Definitions

Bayes Theorem:

$P(X_2|X_1) = P(X_1|X_2)P(X_2) / P(X_1)$



The approach uses qualitative, probabilistic reasoning about the *interactions* of *risk factors* (chance nodes) and *mitigations* (decision nodes) to make inferences.

Loss of Control Accident Framework

BBN Software Selection Criteria*

- Influence diagrams (ID) capability
- Modular and hierarchical capability
- Computational efficiency/performance
- Maturity
- Application Program Interface (API)
- Software maintenance and technical support
- Cost for multiple licenses at different user locations

*Publication: Shih, A. T., Ancel, E., Jones, S. M., "Object-Oriented Bayesian Networks (OOBN) for Aviation Accident Modeling and Technology Portfolio Impact Assessment" *Proceedings of the American Society for Engineering Management (ASEM) 33rd International Annual Conference*, Virginia Beach, VA, October 17-20, 2012

Loss of Control Accident Framework

BBN Software Options*

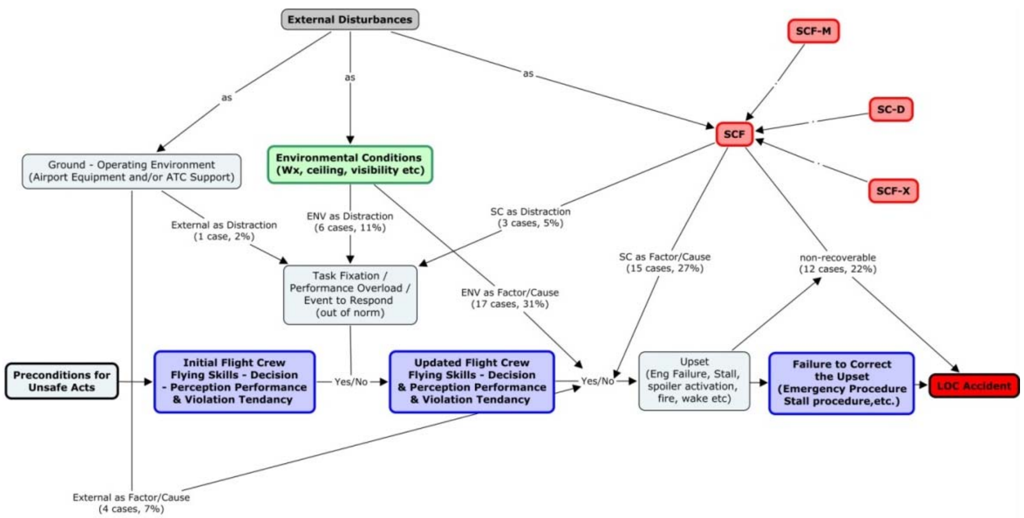
Name	Authors	Src	API	Exec	Cts	GUI	Params	Struct	Utility	Free	Undir	Inference	Comments
AgenaRisk	Agena	N	Y	W,U	Cx	Y	Y	N	N	$	D	JTree	Simulation by Dynamic discretisation
Analytica	Lumina	N	Y	W,M	G	Y	N	N	Y	$	D	sampling	spread sheet compatible
Banjo	Hartemink	Java	Y	W,U,M	Cd	N	N	Y	N	0	D	none	structure learning of static or dynamic networks of discrete variables
Bassist	U. Helsinki	C++	Y	U	G	N	Y	N	N	0	D	MH	Generates C++ for MCMC. (No longer maintained)
gR	Lauritzen et al.	R	-	-	-	-	-	-	-	0	-	-	Various packages
Grappa	Green (Bristol)	R	-	-	D	N	N)	N	N	0	D	Jtree	-
HdBCS	Dobra et al (Washington)	C++	-	-	G	N	Y	Y	N	0	U	SL	stochastic search for structure learning of GGMs
Hugin Expert	Hugin	N	Y	W	G	W	Y	CI	Y	$	CG	Jtree	-
Hydra	Warnes	Java	-	-	Cs	Y	Y	N	N	0	U,D	MCMC	-
IBAyes	Artificial Intelligence Lab @ IBA (Pakistan)	N	N	W	D	Y	N	N	N	0	D	Junction Tree, Sampling	-
Infer.NET	John Winn, Tom Minka	C#	Y	Y	Y	N	Y	N	N	0	Y	VMP, EP, Gibbs	Bayesian parameter estimation as well
JAGS	Martyn Plummer	Java	Y	-	Y	N	Y	N	N	0	Y	Gibbs	Similar to BUGS
Java Bayes	Cozman (CMU)	Java	Y	WUM	D	Y	N	N	Y	0	D	Varelim, jtree	-
LibB	Friedman (Hebrew U)	N	Y	W	D	N	Y	Y	N	0	D	SL	Structure learning
libDAI	Mooij et al.	C++	Y	-	D	N	Y	N	N	0	Fgraph	JTree,VarElim,G,VMP	also supports GBP,HAK,LCBP,TreeEP,TRWBP
MIM	HyperGraph Software	N	N	W	G	Y	Y	Y	N	$	CG	Jtree	Up to 52 variables.
Mocapy++	U. Copenhagen	C++	Y	W,U,M	G	N	Y	N	N	0	D	Gibbs sampling	Support for directional statistics
MSBNx	Microsoft	N	Y	W	D	W	N	N	Y	0	D	Jtree	-
Netica	Norsys	N	WUM	W	G	W	Y	N	Y	$	D	jtree	-
Bayes net learner	Moore, Wong (CMU)	N	N	W,U	D	N	Y	Y	N	0	D	SL	optimal reinsertion algorithm

Reference: Murphy, Kevin, “Software Packages for Graphical Models / Bayesian Networks,” http://www.cs.ubc.ca/~murphyk/Software/bnsoft.html

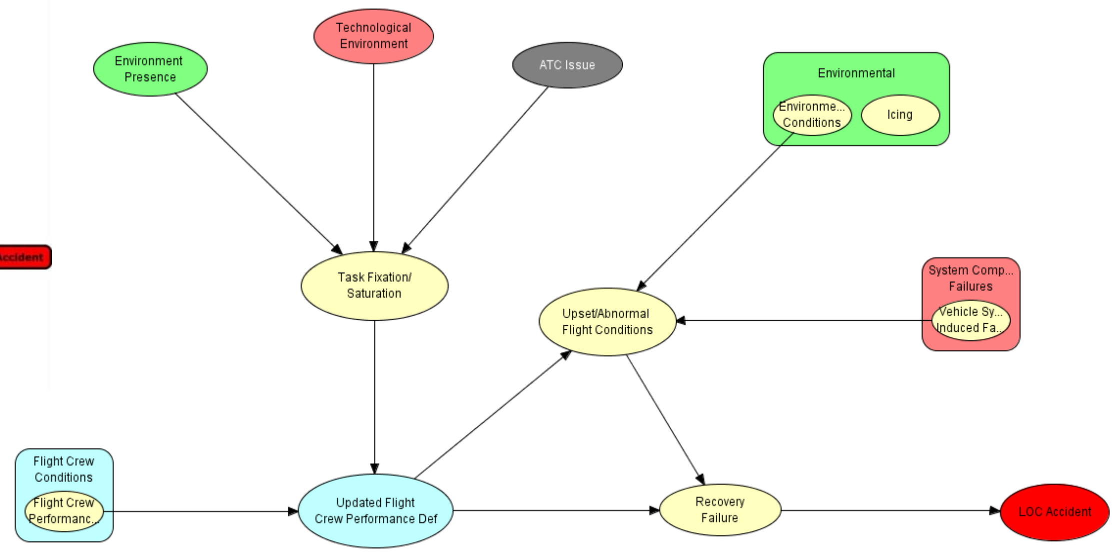
Loss of Control Accident Framework

Conversion to Integrated Systems Model

LOCAF



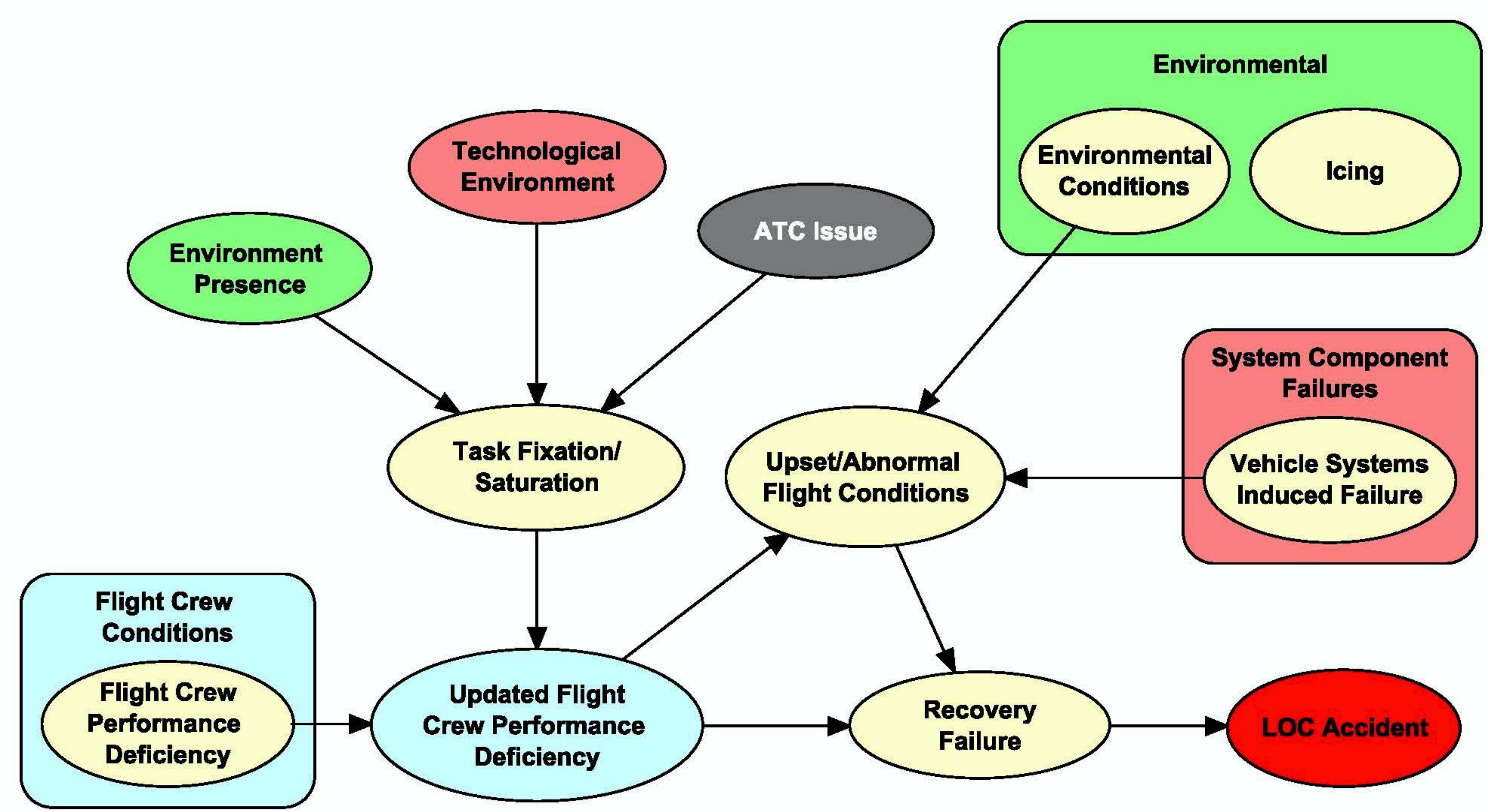
Systems Model of LOCAF



*Publication: Ancel, E., Shih, A.T., 2012, The analysis of the contribution of human factors to the in-flight loss of control accidents. *Proceedings of the 12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Indianapolis, IN, Sept 17-19.

Loss of Control Accident Framework

Top-level Baseline LOCAF Model in Hugin®



Loss of Control Accident Framework
Knowledge Elicitation Sessions*

Knowledge Elicitation Sessions for:

- Reviewing the baseline model structures (ontology and terminology) – Nodes and links in LOCAF model
- Eliciting the conditional probabilities (CP) from LOC accident perspective (not overall aviation accident perspective) in the National Air Space (NAS) for time frame 1990 to 2010
- Inserting AvSP safety technology products from AEST, SSAT, and VSST projects into the LOCAF model for portfolio assessment
- Updating the CPs with the presence of AvSP products in the model
- Reviewing the LOCAF model structures with products inserted

* Publication: Luxhoj, J. T., Shih, A. T., Jones, S. M., Ancel, E. and Reveley, M. S., "Safety Risk Knowledge Elicitation in Support of Aeronautical R&D Portfolio Management: A Case Study," *Proceedings of the American Society for Engineering Management (ASEM) 33rd International Annual Conference*, Virginia Beach, VA, October 17-20, 2012

Loss of Control Accident Framework

Knowledge Elicitation and Subject Matter Expert Review Sessions

Knowledge Elicitation (KE) Sessions

The five elicitation stages of motivating, structuring, conditioning, encoding and verifying were followed.

Session 1.0
Baseline Model
May 8-9, 2012
Hampton, VA
Operational SMEs (3)
- Pilot
- ATC
- Accident Investigator

Session 2.0
Product Insertions
July 31 - August 1, 2012
Hampton, VA
Operational SMEs (3)
- Pilot
- ATC
- Accident Investigator

Session 4.0
Product Insertions Review
June 19-20, 2013
Hampton, VA
Operational SMEs (3)
- Pilot
- ATC
- Accident Investigator

Session 1.5
July 19, 2012
Product SMEs
- Researcher/Academia
- Aero Industry
- Airline/End User

** Product SMEs only reviewed the model's structure and identified any missing causal factors.*

Session 3.0
External Review
September 12, 2012
Washington, DC
External SMEs (3)
- Safety Analyst
- Accident Investigator
- LOC Specialist

AvSP Projects
Feb.-April 2013
WebEx Meetings
Project Personnel
Product Leads or POCs
** Product leads provided feedback comments on products insertion.*

Loss of Control Accident Framework

Degree of Belief (DOB) Approach

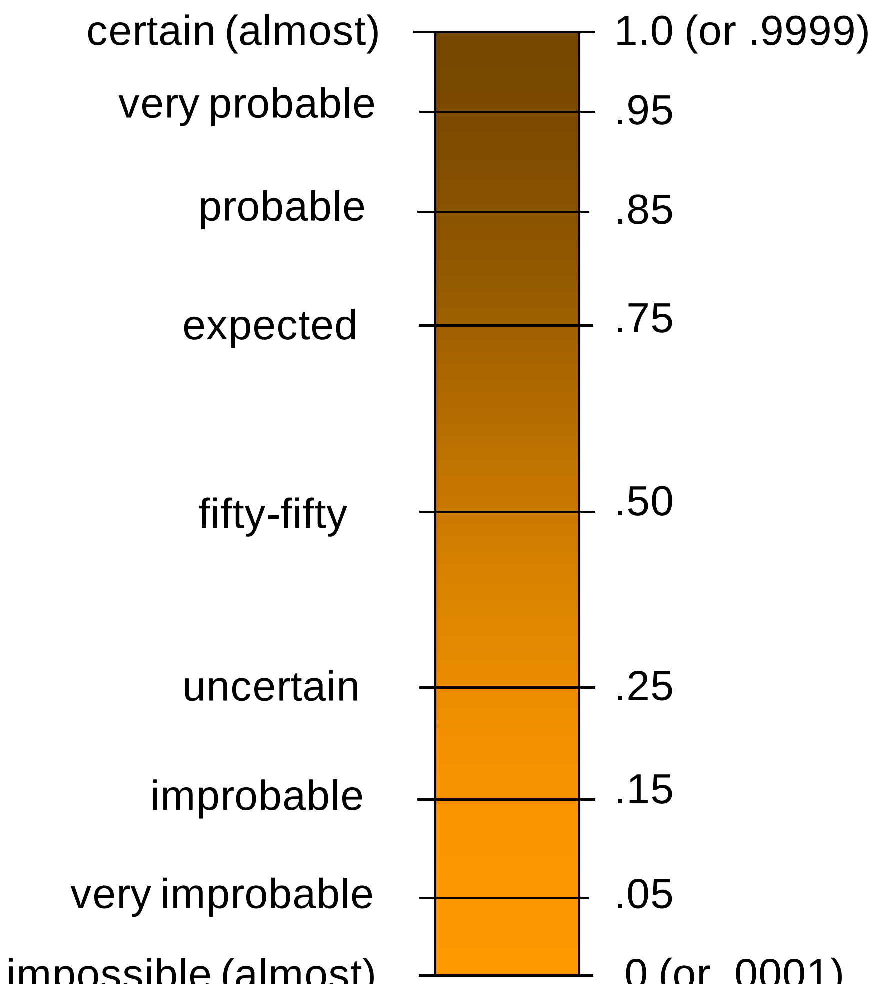
Renooij & Witteman (1999) Verbal Descriptor	Probability	Ang & Buttery (1997) Verbal Descriptor
(almost) certain	1	
	0.9999	extremely likely (i.e., almost certain)
	0.9	very likely
probable	0.85	
expected	0.75	
	0.7	likely
fifty-fifty	0.5	indeterminate
uncertain	0.25	
improbable	0.15	
	0.1	probable (i.e., credible)
	0.01	unlikely
	0.001	very unlikely
	0.0001	extremely unlikely
(almost) impossible	0	

Loss of Control Accident Framework

KE Probability Scale – Verbal/Numerical Equivalents

"The purpose of computing is insight, not numbers."

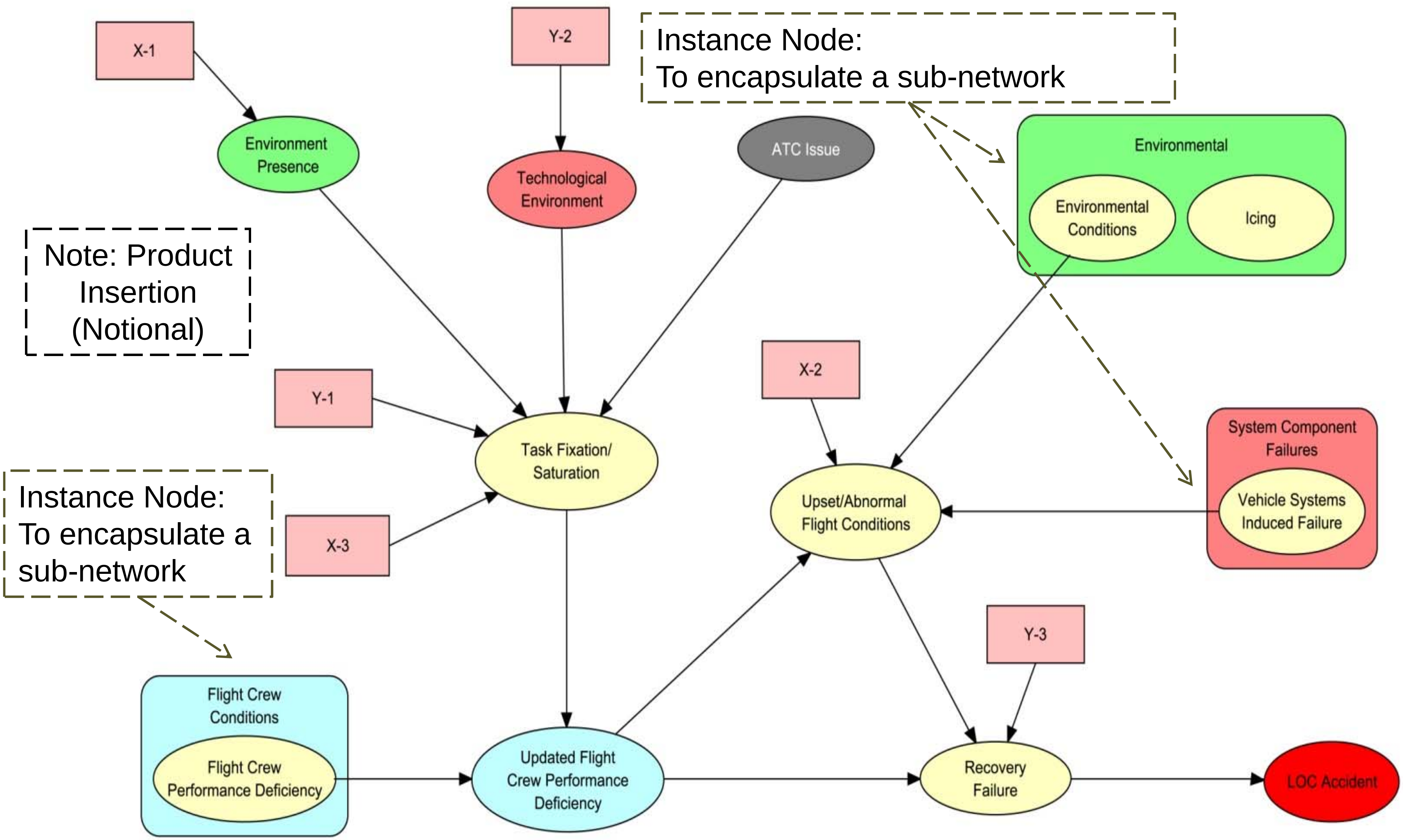
-Richard Wesley Hamming



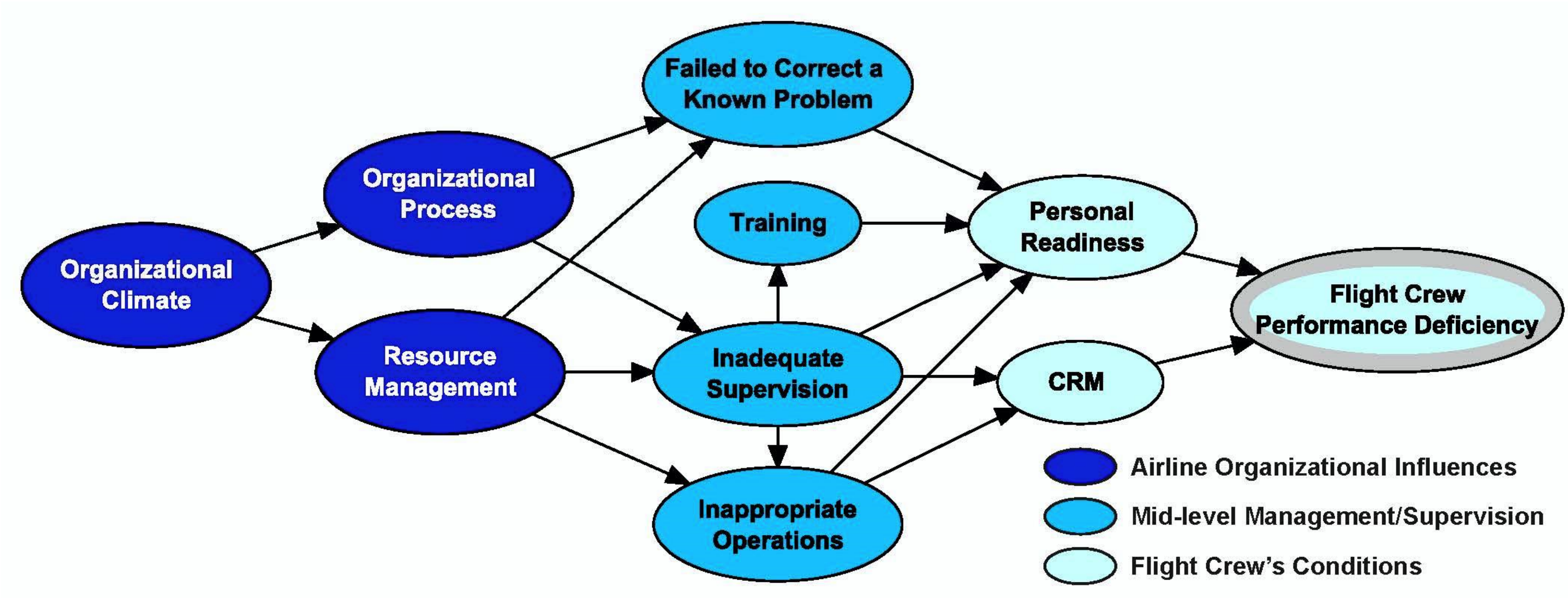
Adapted from Druzdel and van der Gaag, 2000; Renooij and Witteman, 1999

Loss of Control Accident Framework

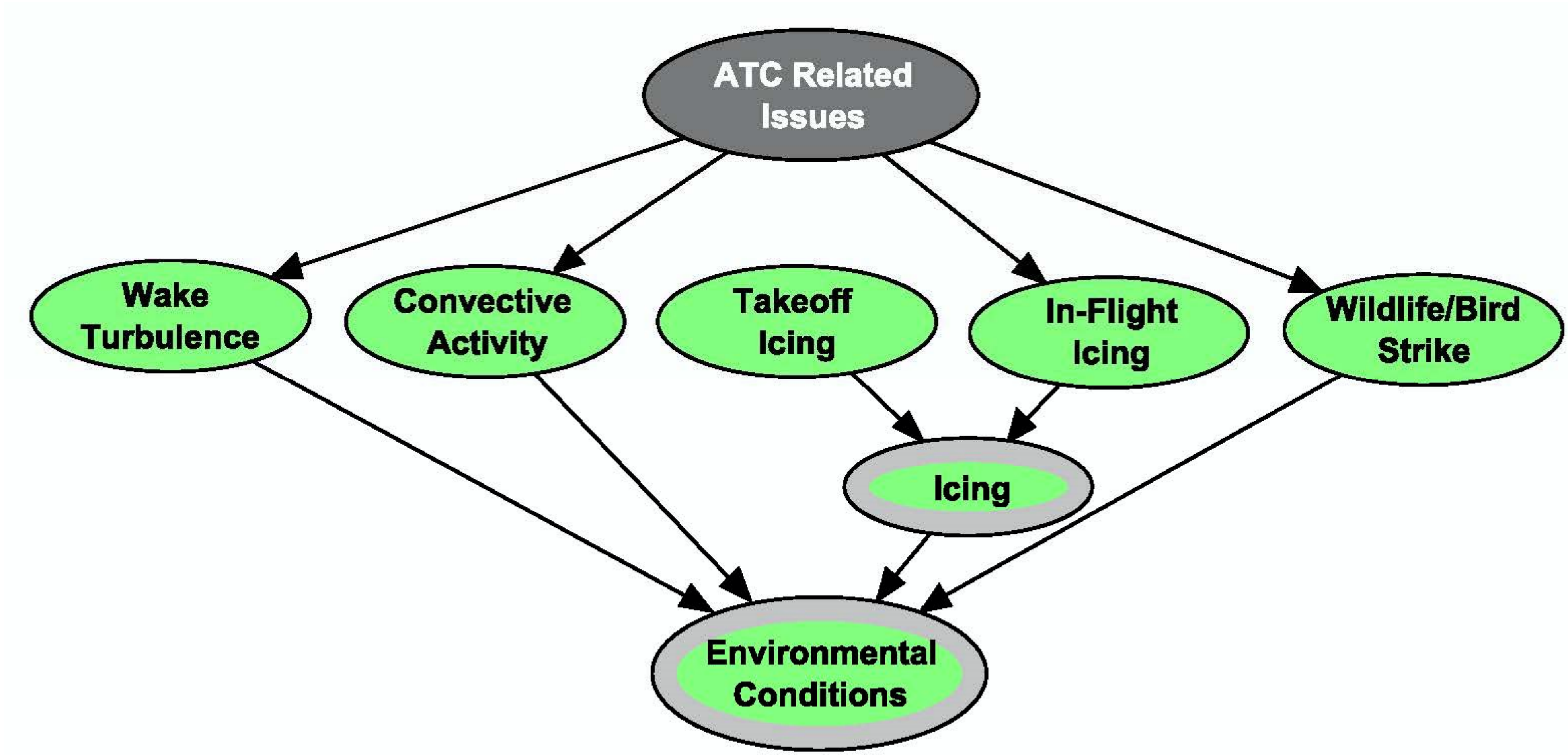
Top Level LOCAF Model



Loss of Control Accident Framework
Flight Crew Performance Sub-Network

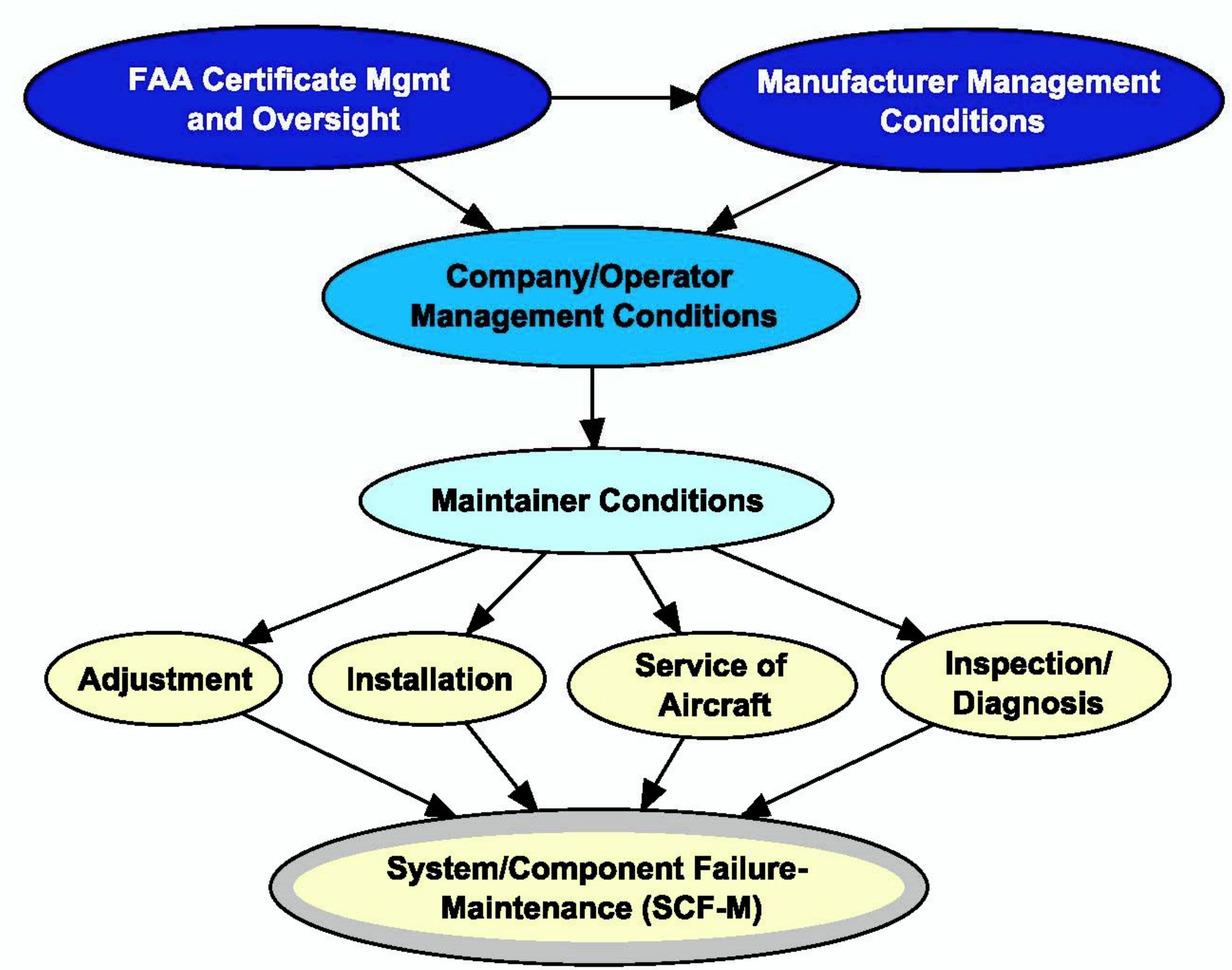


Loss of Control Accident Framework
Environment (ENV) Sub-Network



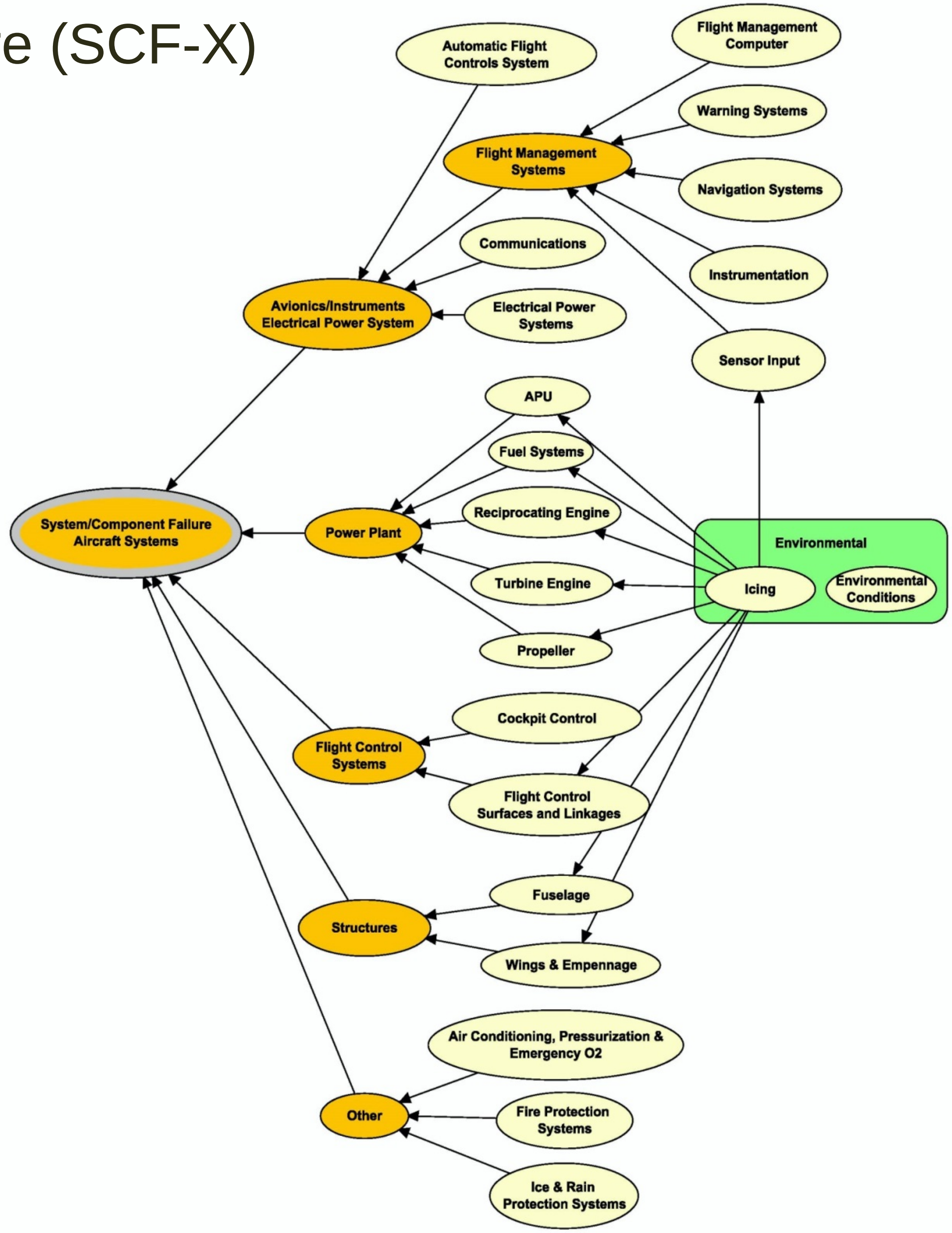
Loss of Control Accident Framework

System/Component Failure – Maintenance (SCF-M) Sub-Network



Loss of Control Accident Framework

System/Component Failure (SCF-X) Sub-Network



Modeling Results

- Likelihood/probability calculation of concerned aviation risks (e.g. LOC, etc.)
- Direct risk mitigation assessment on the safety technologies/products
- Portfolio gap analysis
- Sensitivity analysis for risk drivers

Loss of Control Accident Framework

Baseline LOCAF Model – Likelihood Probability

LOC Likelihood Results Comparison:

Data from historical database

54 Cases ('87-'09):

SCF: 50%

ENV: 31.5%

LOC: 13.81%

Historical Data '88-'04:

SCF: 20.8%

ENV: 14.37%

LOC: 12.84%

LOCAF model results

For This Study (54 Cases), '87-'09:

SCF: 50%

ENV: 31.5%

LOCAF LOC: 15.92% (+2.11%)

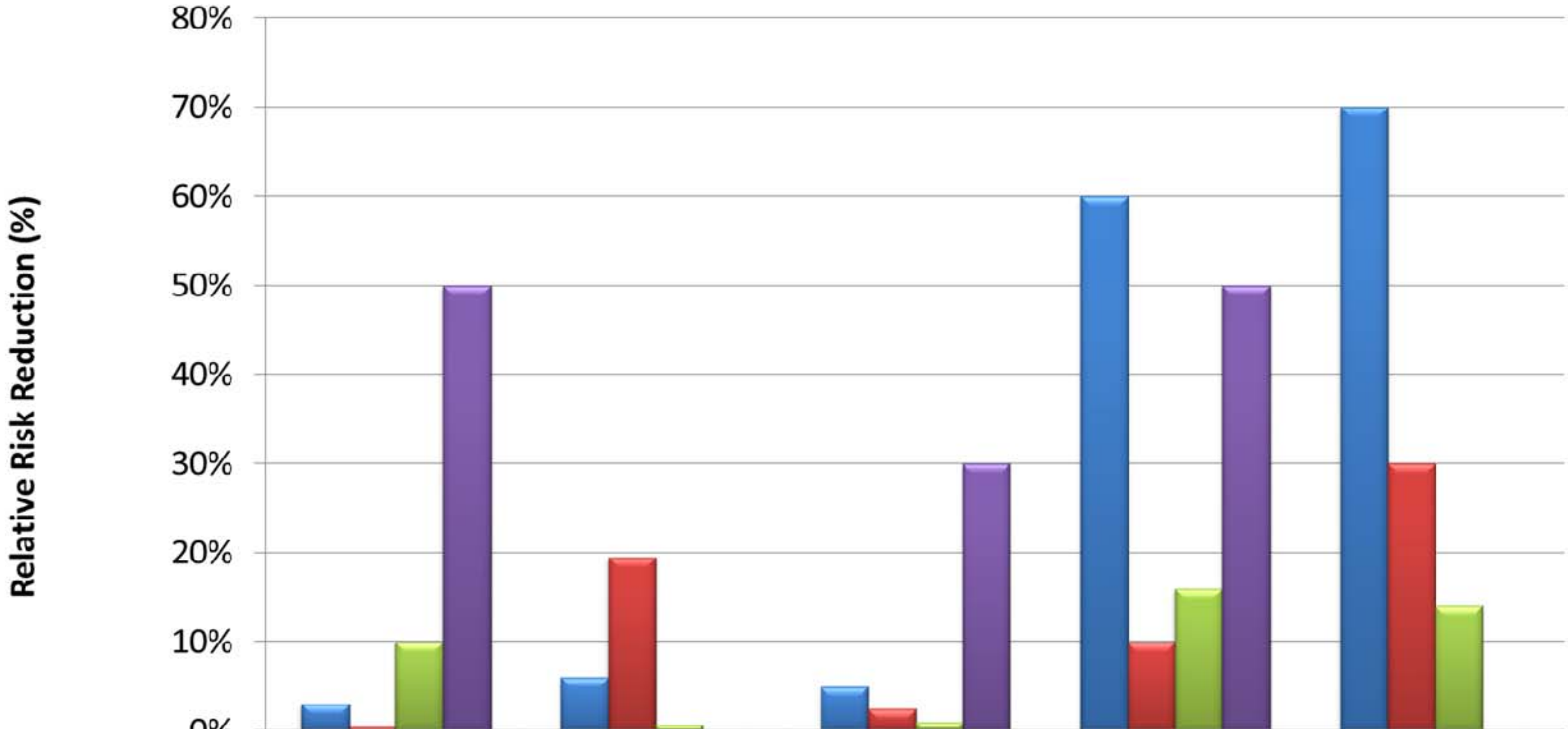
For Historical Data (1962 Cases), '88-'04:

SCF: 20.8%

ENV: 14.37%

LOCAF LOC: 10.11% (-2.73%)

Loss of Control Accident Framework
Risk Mitigation Assessment (Notional)

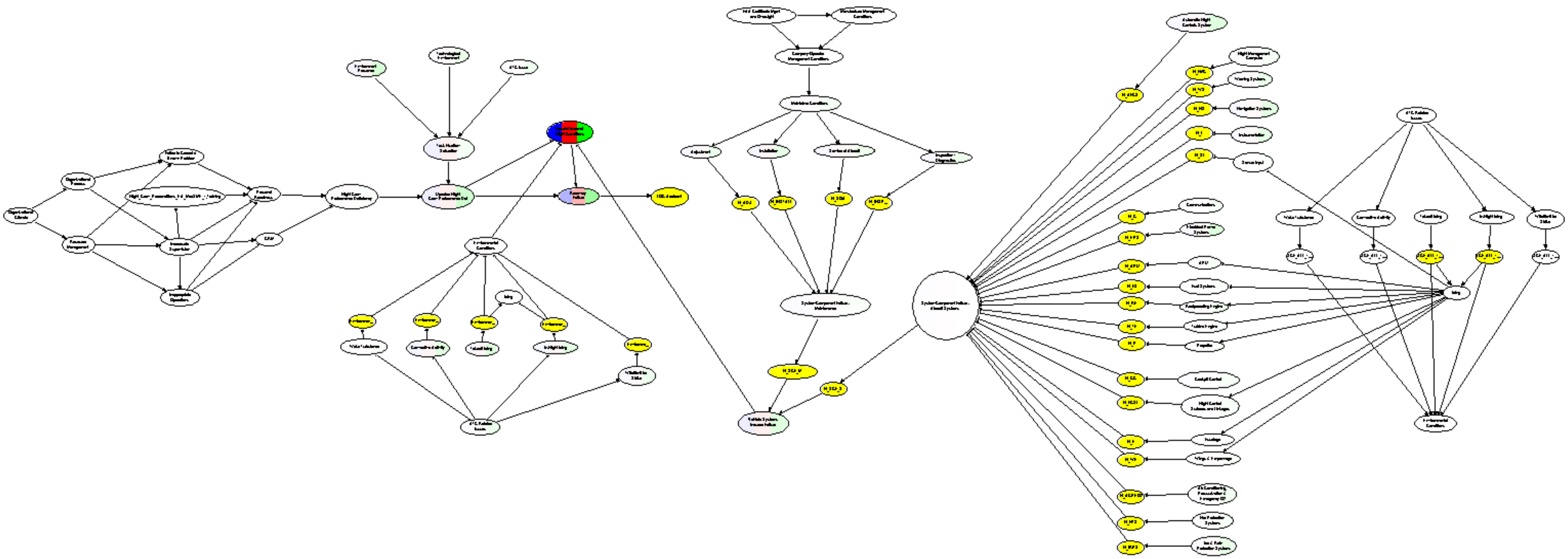


	Product Group 1	Product Group 2	Product Group 3	Product Group 4	Product Group 5
Loss of Control	Y	Y	Y	G	G
System Component Failure	R	G	Y	Y	G
Flight Crew Decision Failure	Y	R	Y	G	Y
Environment Related Failure	G	R	G	G	R

Red < X%
X% ≤ Yellow ≤ Y%
Green >Y%

Loss of Control Accident Framework

Hugin® Sensitivity Graph at Top Level



Loss of Control Accident Framework
Conclusions

- Papers describing results of LOCAF development have been presented to several different technical communities
  - Aeronautics (AIAA ATIO)
  - Systems engineering/operations research/engineering management
  - FAA risk analysis personnel
- Results of LOCAF were used to compute “relative safety risk reduction” metric for September 2013 Aviation Safety Program Portfolio Assessment milestone
- Two additional models are currently in development:
  - Runway Safety
  - Increasing Complexity and Reliance on Automation
- Current model is based on historical accidents, the next version of LOCAF will reflect future NextGen operating environment

Thank you

QUESTIONS?