Understanding, Modeling, and Managing Interdependent Complex Systems of Systems

20 OCTOBER 2017

Yacov Y. Haimes
Lawrence R. Quarles Professor of Systems & Information Engineering and of Civil & Environmental Engineering
Founding Director (1987), Center for Risk Management of Engineering Systems
University of Virginia

.

"The world is totally connected"

Jacob Bronowski [1978]

"Whatever explanation we invent at any moment is a partial connection, and its richness derives from the richness of such connections as we are able to make.

There is no nerve without the muscle and no muscle without the nerve in the total animal. This is the same statement as the one I made about the total connection of the world…"

What is the common denominator among the following?

(i) Universities;

(ii) Supply Chain;

(iii) Electricity and Communications;

(iv) Families and Communities

(v)Democracy and Free Press?

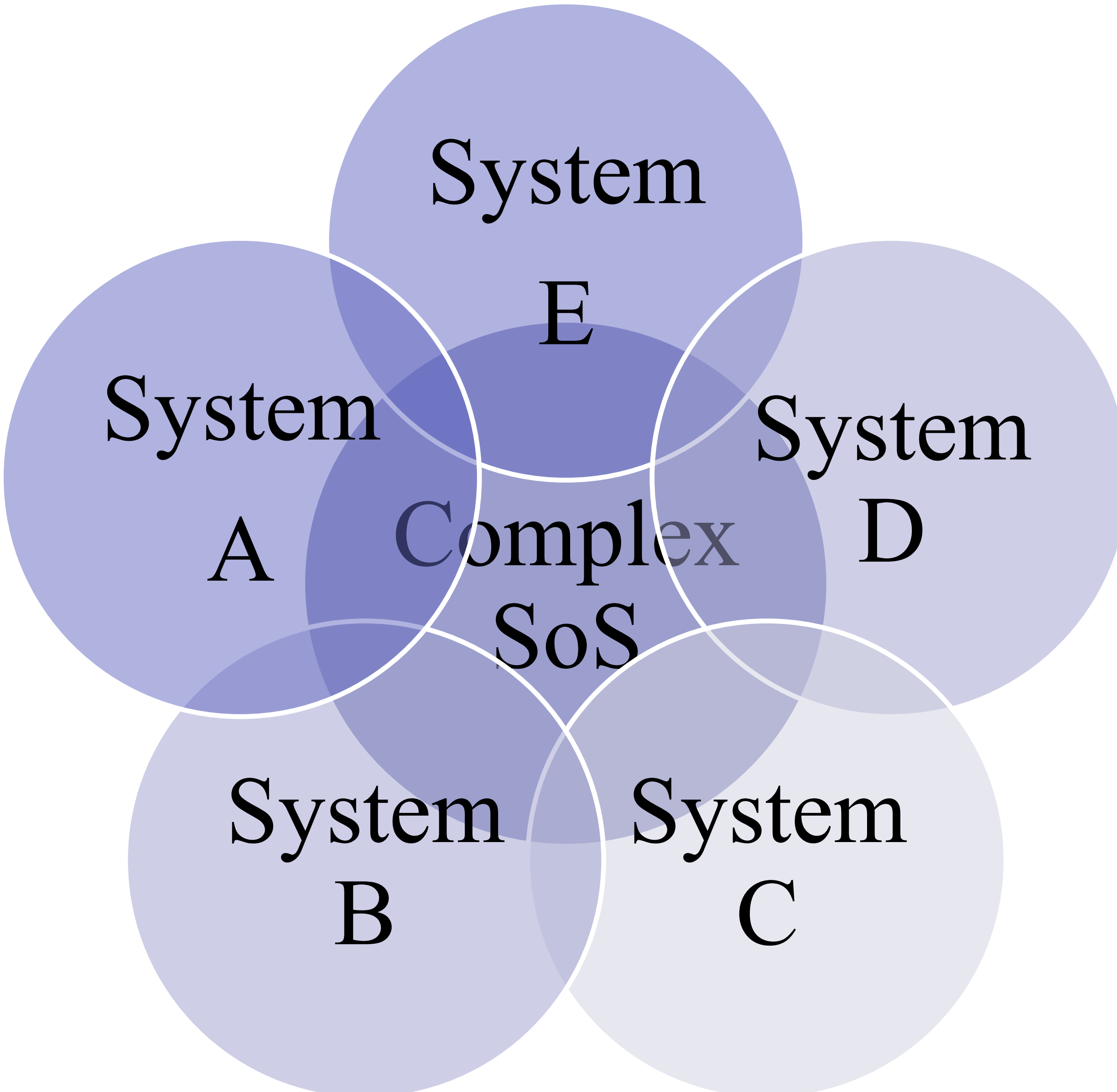
(vi) International Traveel; etc.

The growing interest in complexity by the professional community deserves a fresh reflection on its essence and on its evolving definitions and characterizations.

For systems modelers, the starting point begins by focusing on what constitutes complexity and how to understand, model and manage it.

This seminar offers an understanding of complexity through the discovery of its specific attributes, thereby enhancing our ability to effectively manage complexity with new analytical models.

We define and model complexity via the interconnectedness and interdependencies (I-I) within and among the systems characterizing complex systems of systems ("Complex SoS").


System
E
System
A
Complex
SoS
System
D
System
B
System
C

Current models for emergent complex SoS are insufficient because too often they fail to incorporate the complexity derived from the networks of interdependencies and interconnectedness (I-I) characterizing complex systems of systems.

This requires a reevaluation of the way we model, assess, manage, communicate, and analyze the risk thereto.

The key to modeling and managing Complex SoS lies in understanding the genesis of characterizing the interconnectedness & interdependencies manifested through shared:

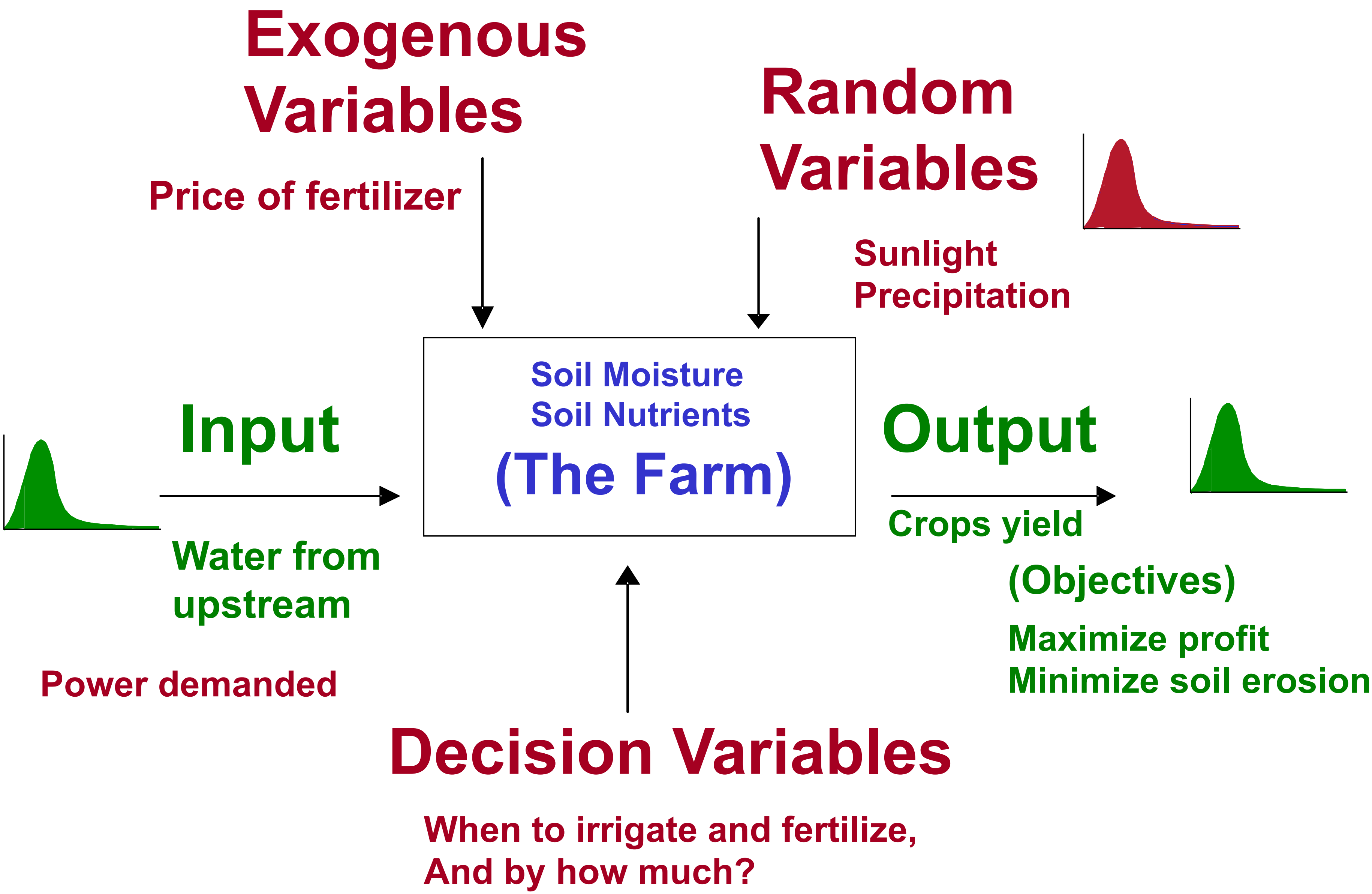
States, *decisions*, *resources*, *functions*, *policies*, *decisionmakers*, *stakeholders*, *organizational setups*, and others.

Why do farmers irrigate their crops in non-rainy seasons?

Why do farmers fertilize their crops?

Why do farmers irrigate their crops in non-rainy seasons?

The answer is fundamental to the role that *state space* plays in systems modeling;
and
to understanding the definitions of vulnerability and resilience of, and thus the risk to systems.


Exogenous Variables
Price of fertilizer
Random Variables
Sunlight
Precipitation
Input
Water from upstream
Power demanded
Soil Moisture
Soil Nutrients
(The Farm)
Output
Crops yield
(Objectives)
Maximize profit
Minimize soil erosion
Decision Variables
When to irrigate and fertilize,
And by how much?

States of the System

All decisions are made:

(i) to control (retain or change as appropriate) the levels of the essential states of the system;

(ii) to meet specific desired outputs (goals and objectives);

(iii) At acceptable tradeoffs; and

(iv) At acceptable time frame.

States of a System

Given a system's model, the states of a system are the smallest set of independent system variables such that the values of the members of the set at time t_0 along with known inputs, decisions, random and exogenous variables completely determine the value of all system variables for all

$t \geq t_0$ (under certain conditions).

Modeling I-I Complex Systems of Systems

(i) Models are built to answer specific questions;

(ii) They ought to be as simple as possible and as complex as required;

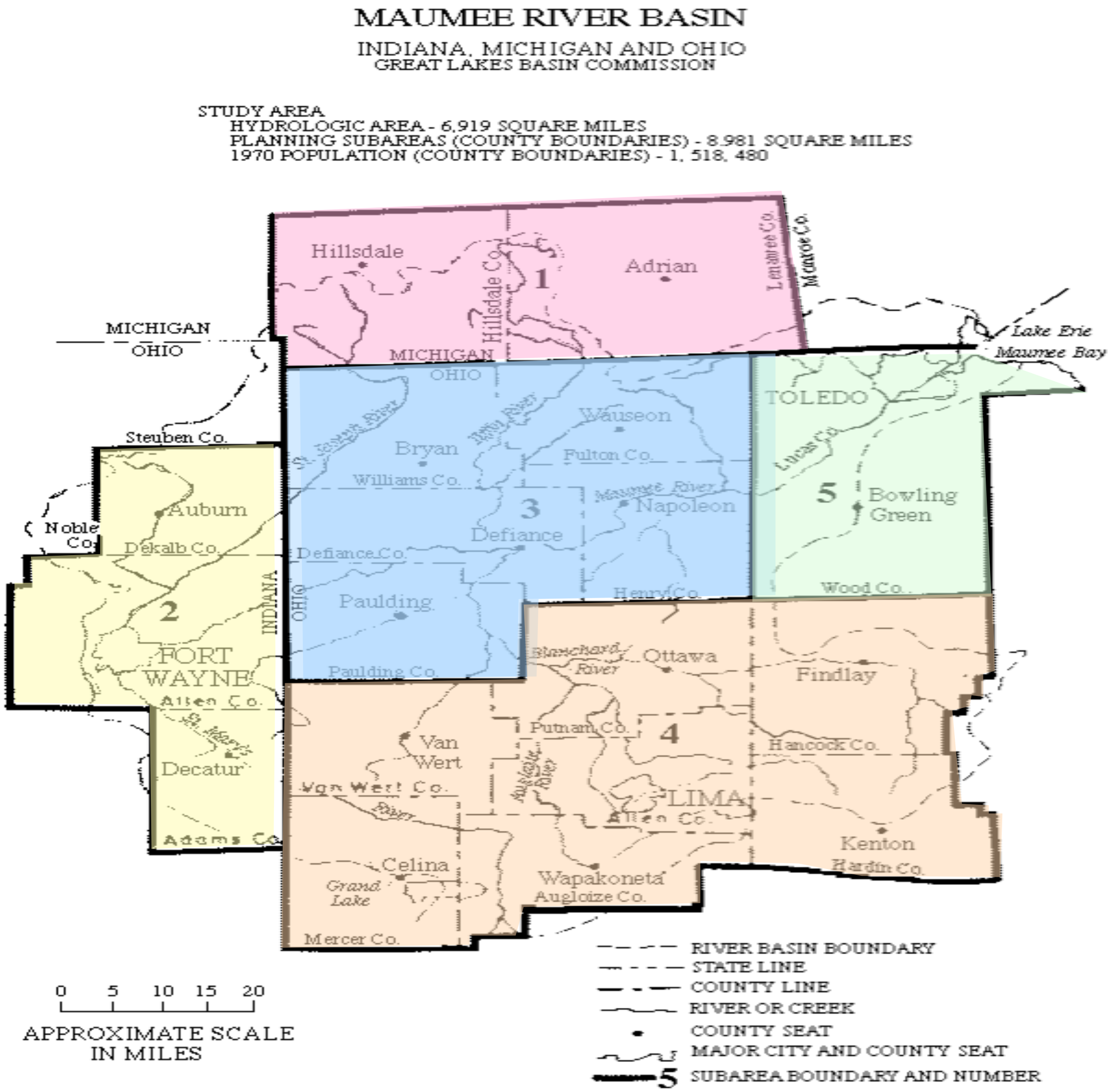
(iii) Modeling is an amalgamation and symbiosis of the arts and the sciences;

(iv) Artists reconstruct images and ideas, scenes, people and structures;

Similarly modelers of SoS decompose and restructure complex systems of systems.

Understanding and Modeling Complex Systems of Systems (Complex SoS) with Hierarchical Holographic Modeling (HHM)

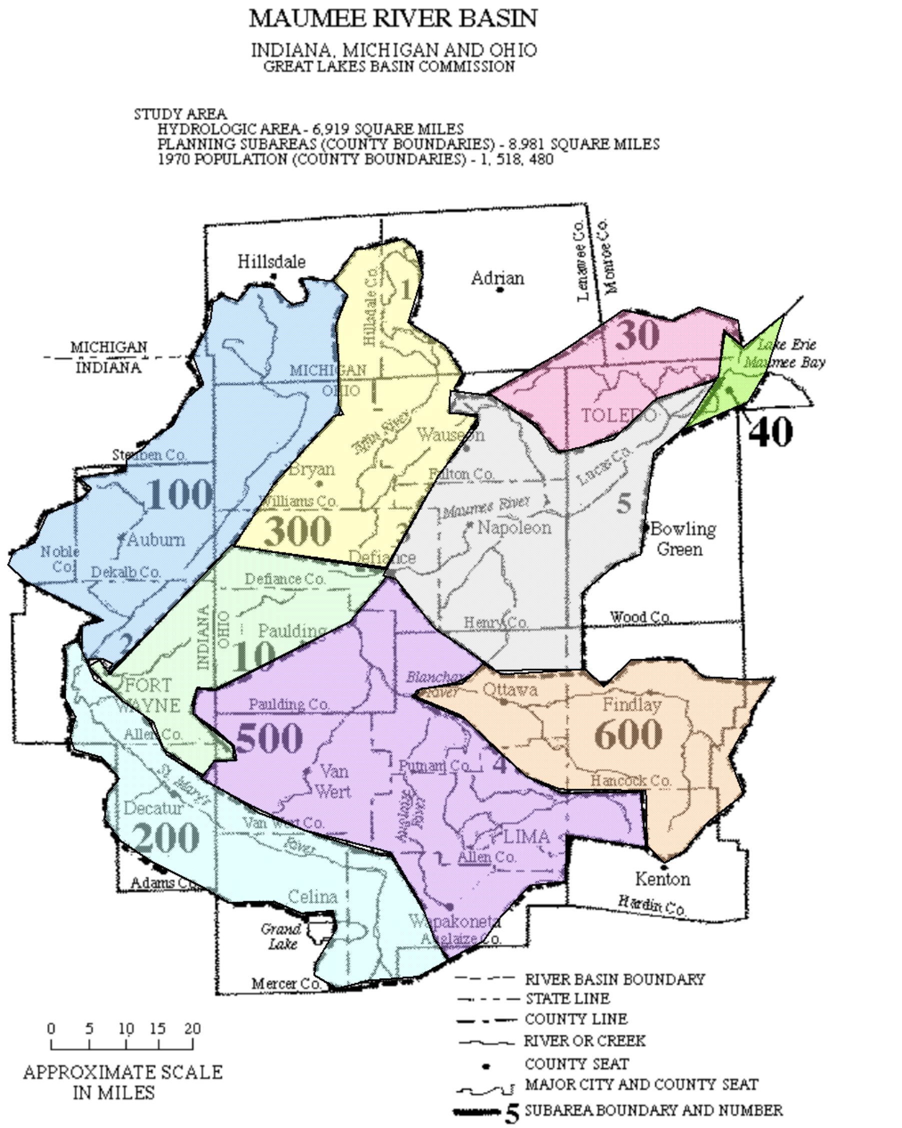
Hierarchical Holographic Modeling (HHM)



UNIVERSITY of VIRGINIA CENTER for RISK MANAGEMENT of ENGINEERING SYSTEMS EST. 1987

Political Decomposition

Hierarchical Holographic Modeling (HHM)

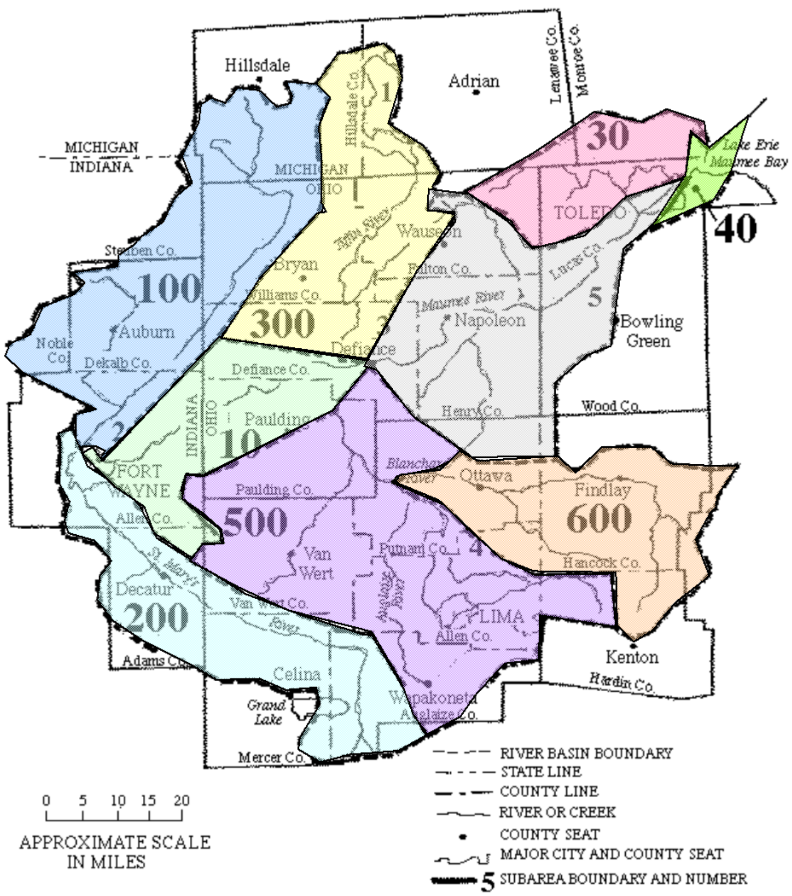


Hydrological Decomposition

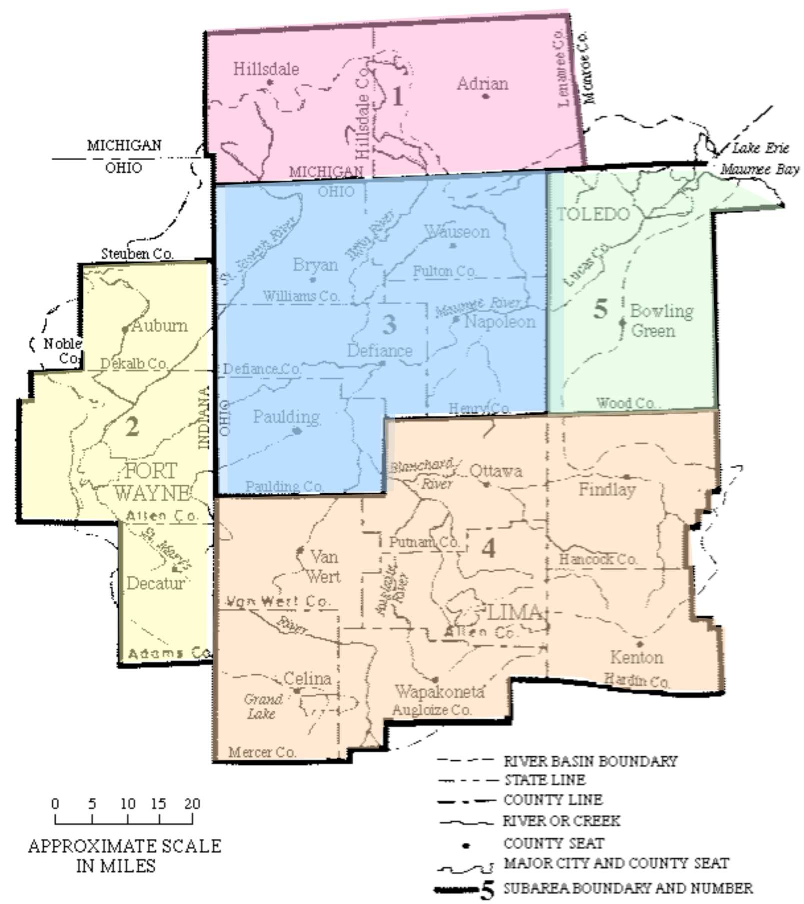
HHM Features

Flipping Perspectives

Hydrological Perspective



Geographic Perspective



Multiple perspectives allow for complete coordination

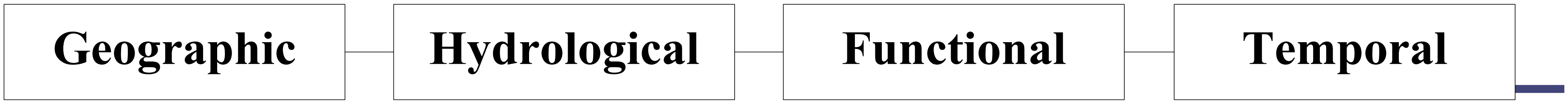
Flipping Perspectives Of Complex Systems of Systems

A key feature of HHM is the concept of “flipping,” or changing perspectives, to highlight interconnectedness and interdependencies characterizing complex systems of systems.

HHM Features: Flipping Perspectives

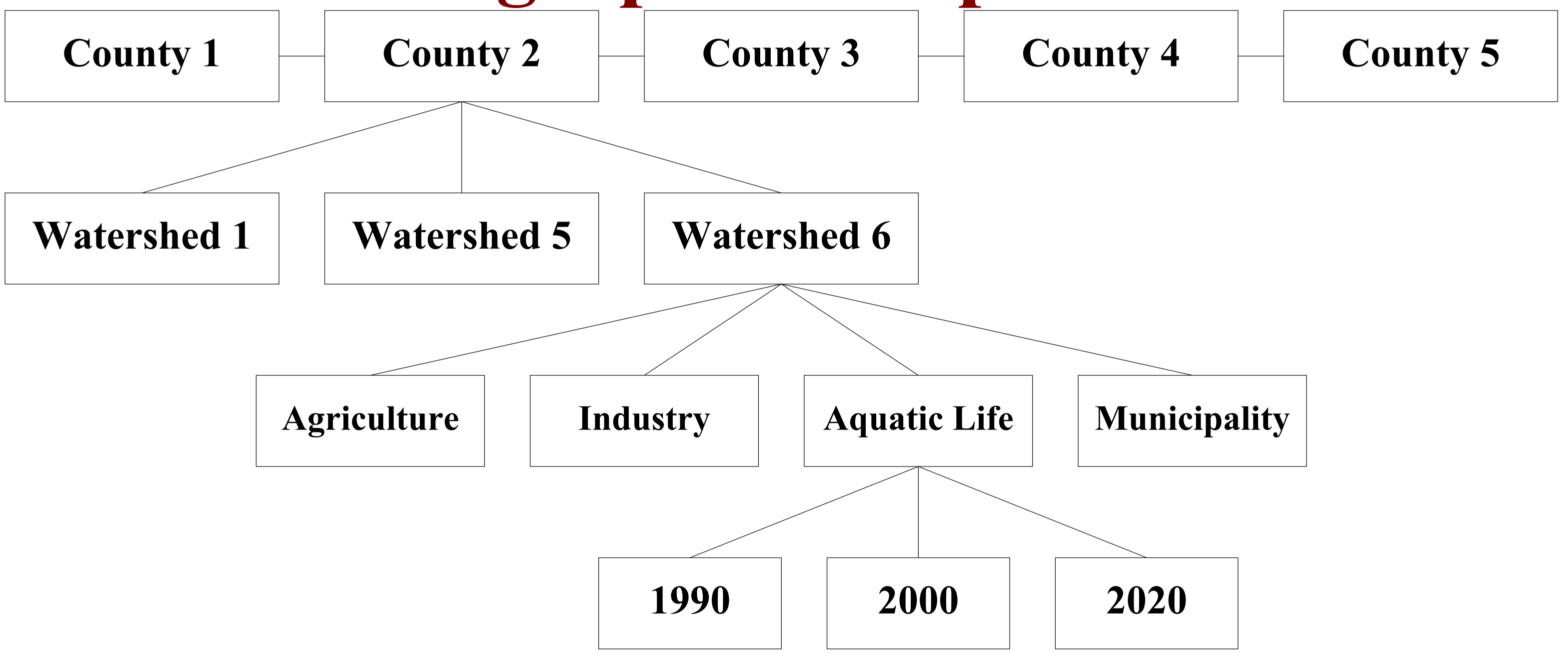
The Maumee River Basin is described by:

- **Five planning sub-areas each consisting of several counties**
  - **political/geographic decomposition**
- **Eight watersheds crossing state and county boundaries**
  - **hydrological decomposition**
- **Seven major objectives identified by an advisory group**
  - **functional decomposition**
- **Three planning time horizons**
  - **temporal decomposition**



Modeling Complexity: HHM Features: Flipping Perspectives

Geographic Perspective

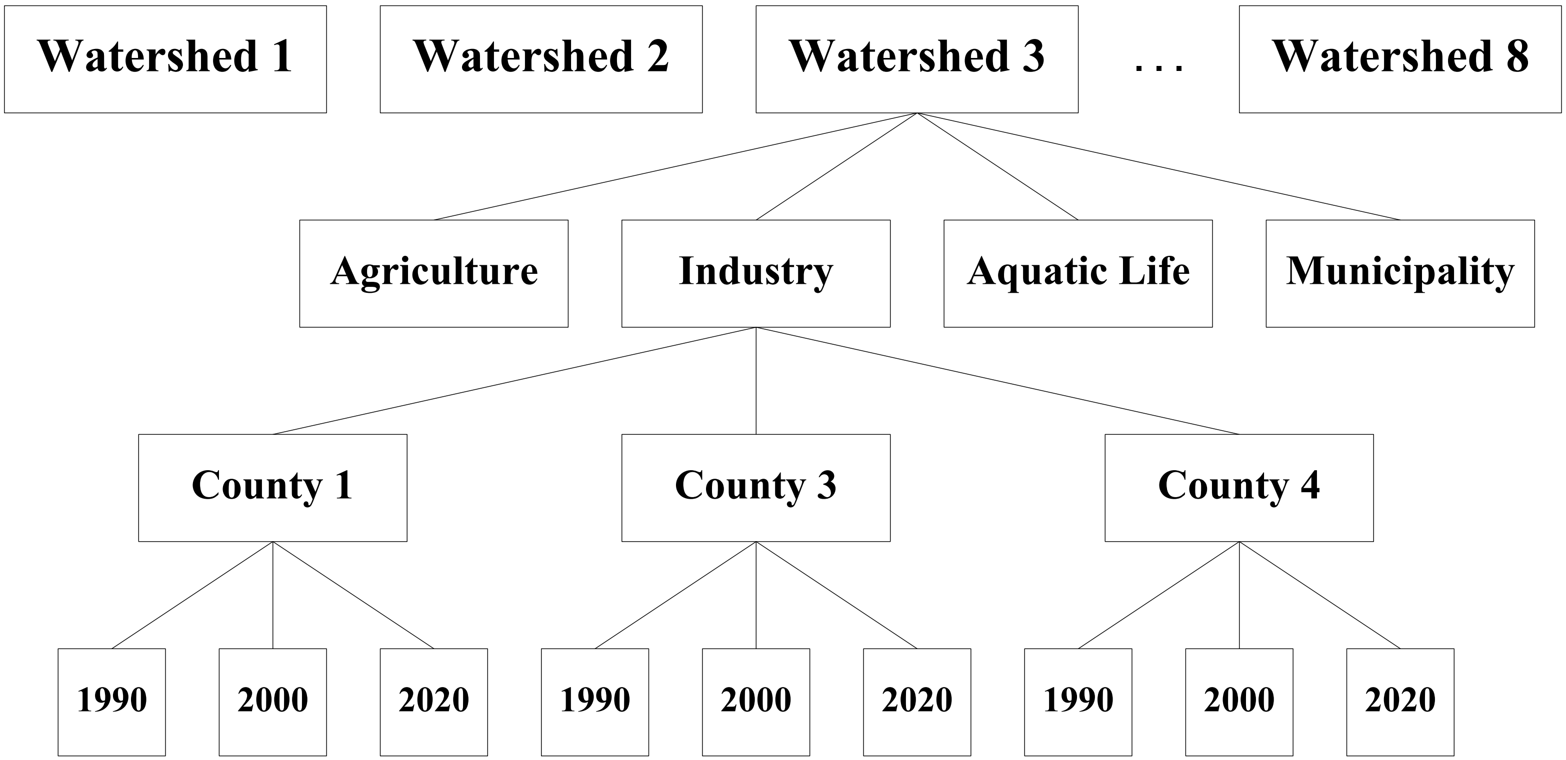


County 2 contains three watersheds

"Protecting fish and wildlife" may be of interest for the three planning periods

Modeling Complexity: HHM Features: Flipping Perspectives

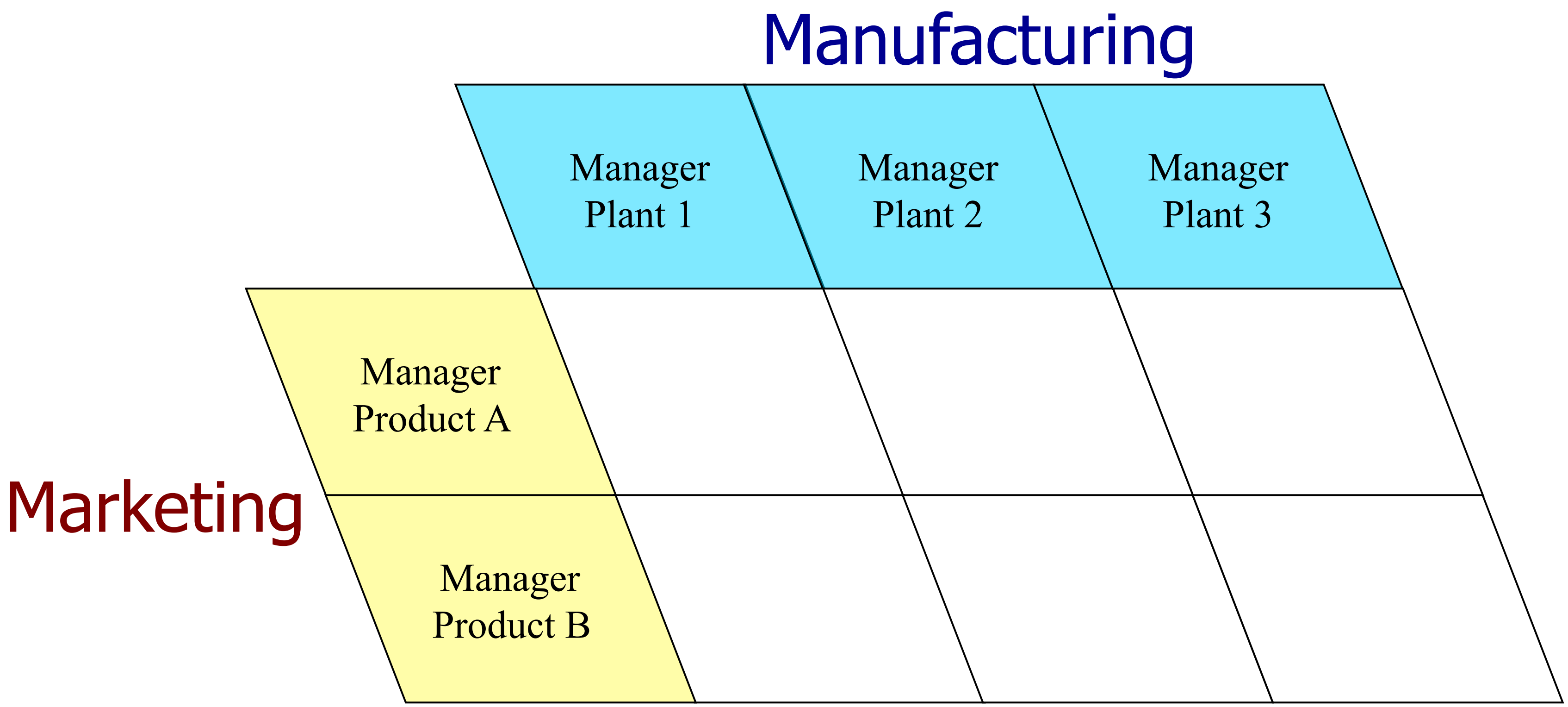
Hydrological Perspective



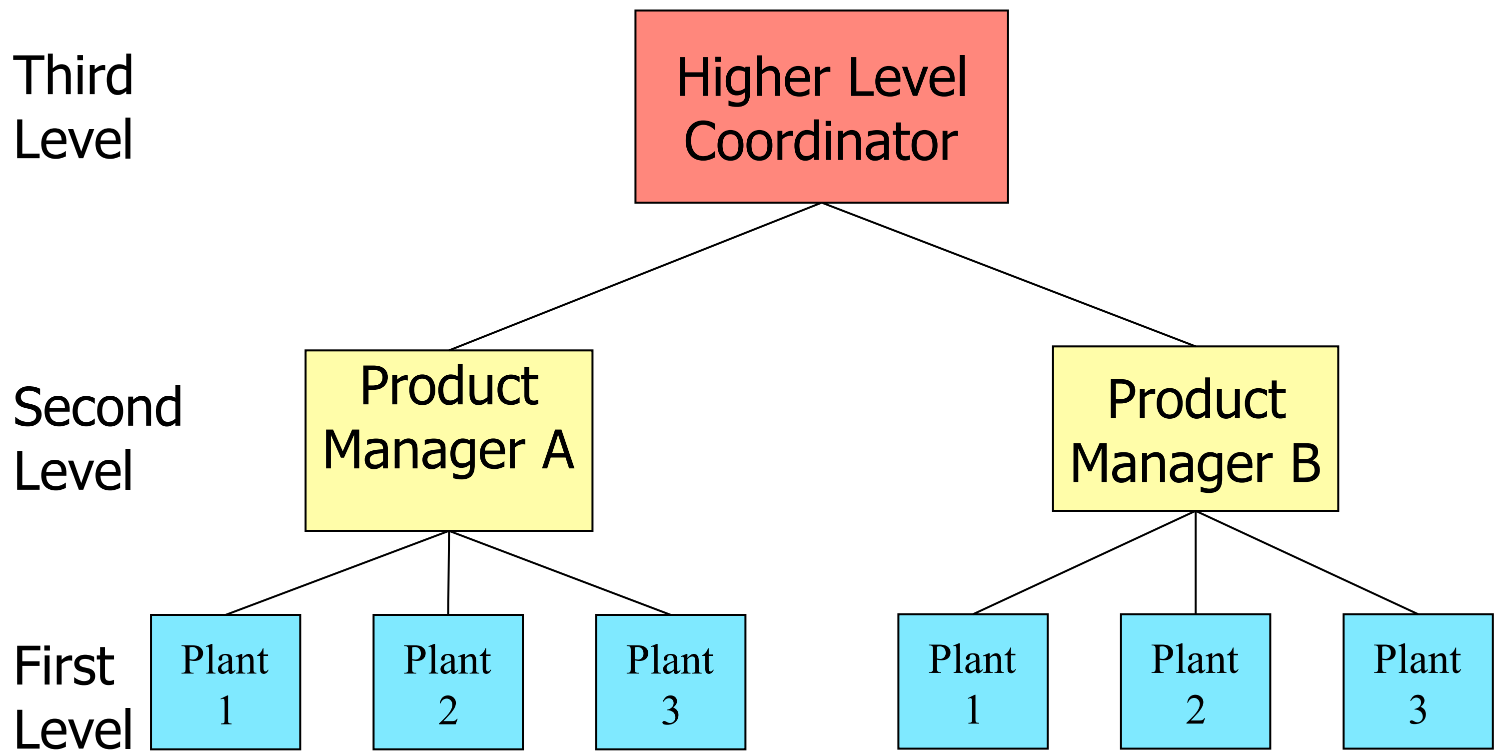
Watershed 3 has serves several large corporations and transcends three counties

Planning periods are considered for all three of those counties

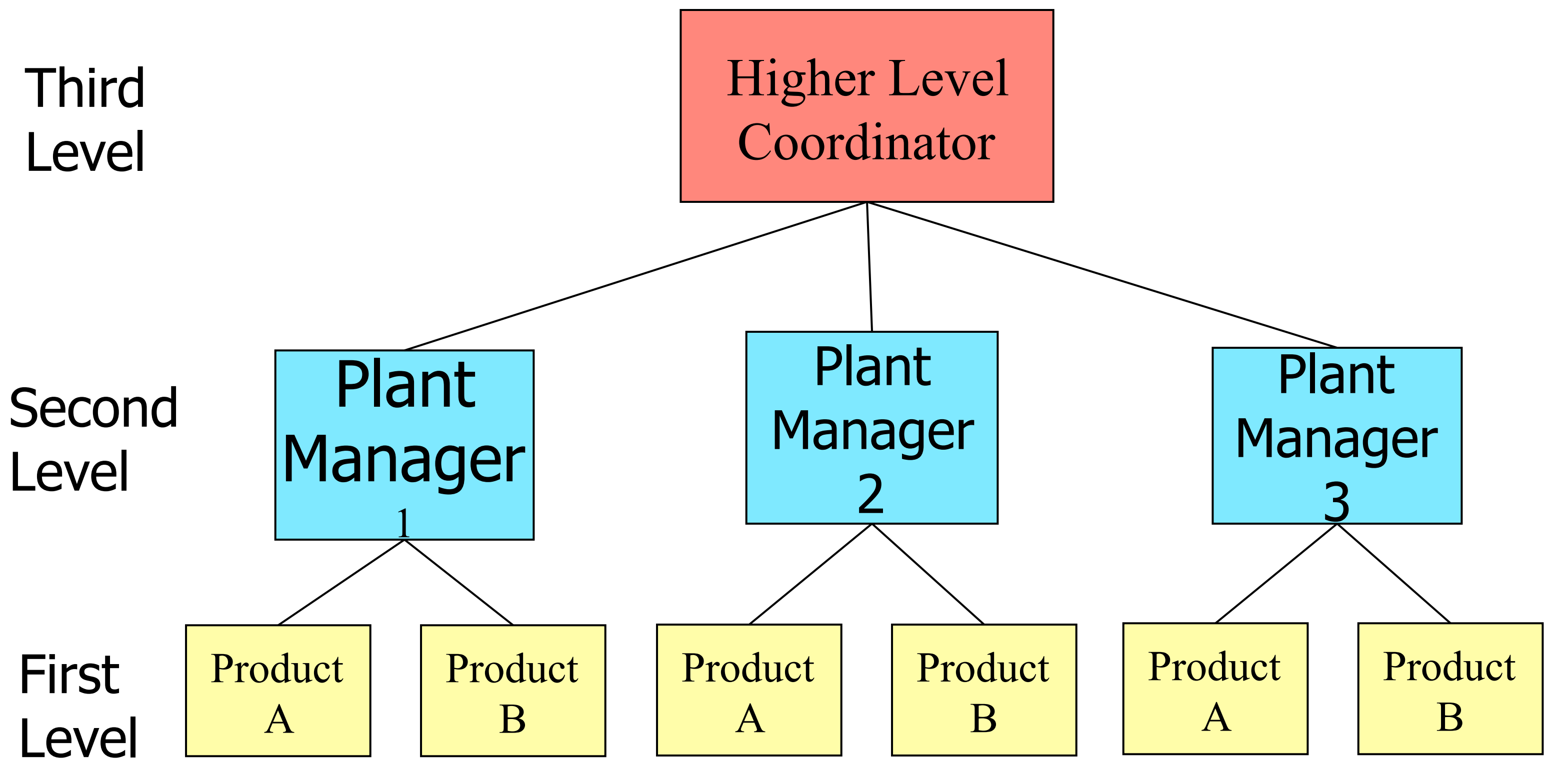
Matrix Organization of a Production System



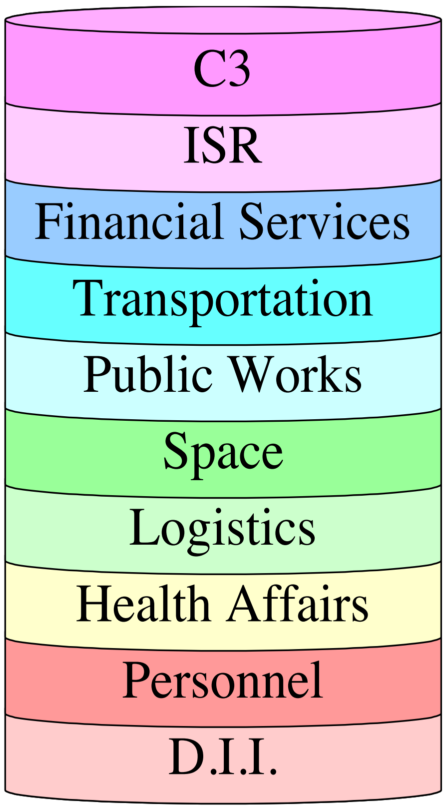
Product-Plant Decomposition



Plant-Product Decomposition

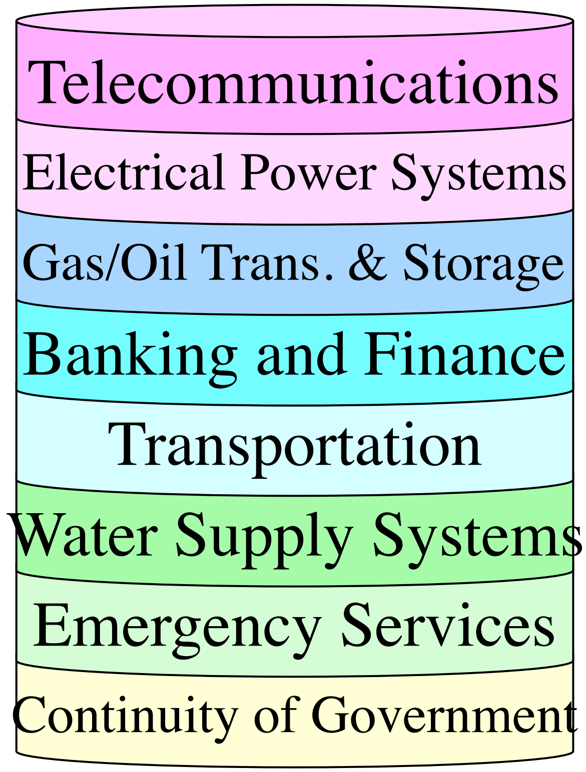


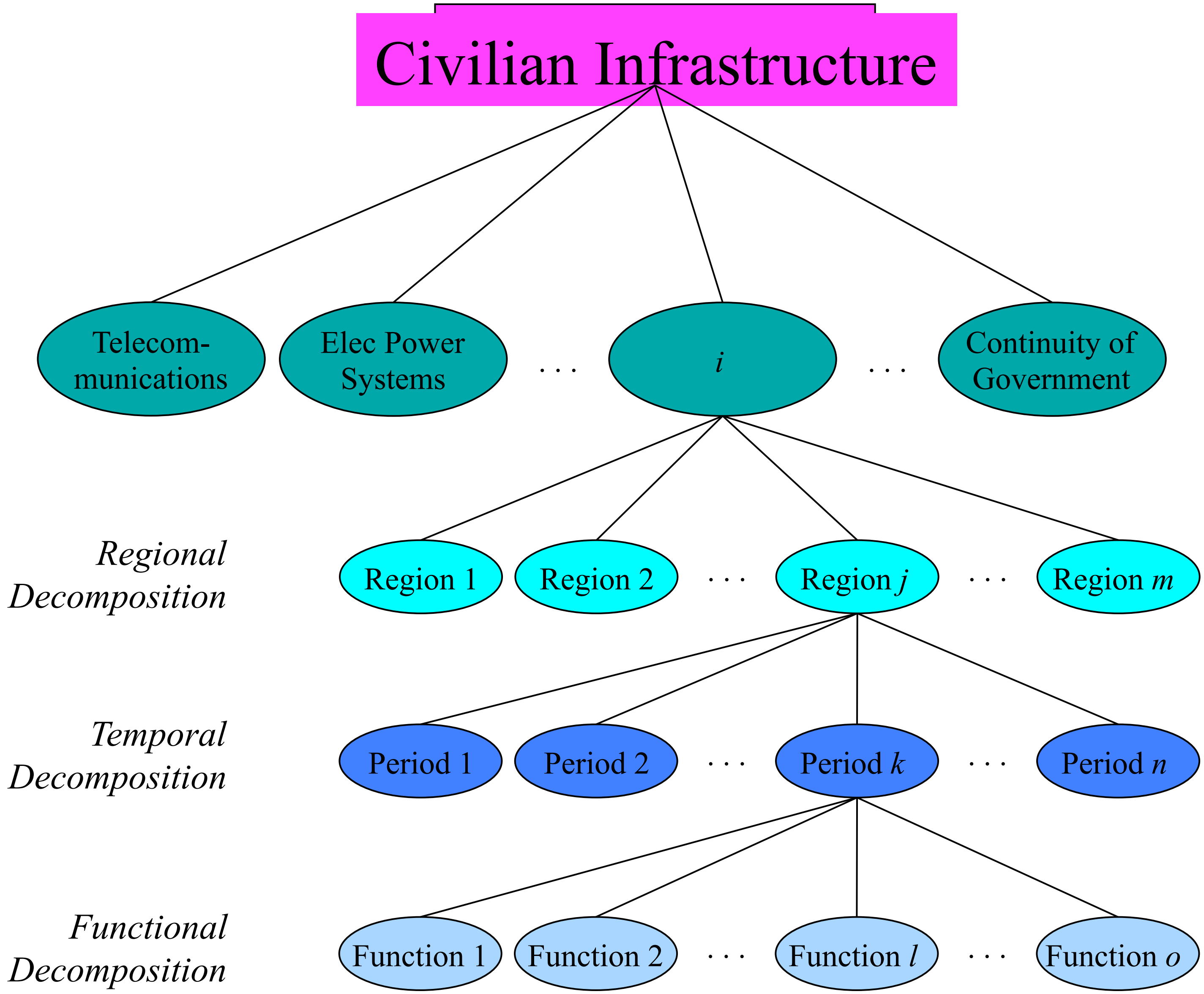
Defense Infrastructure Sectors

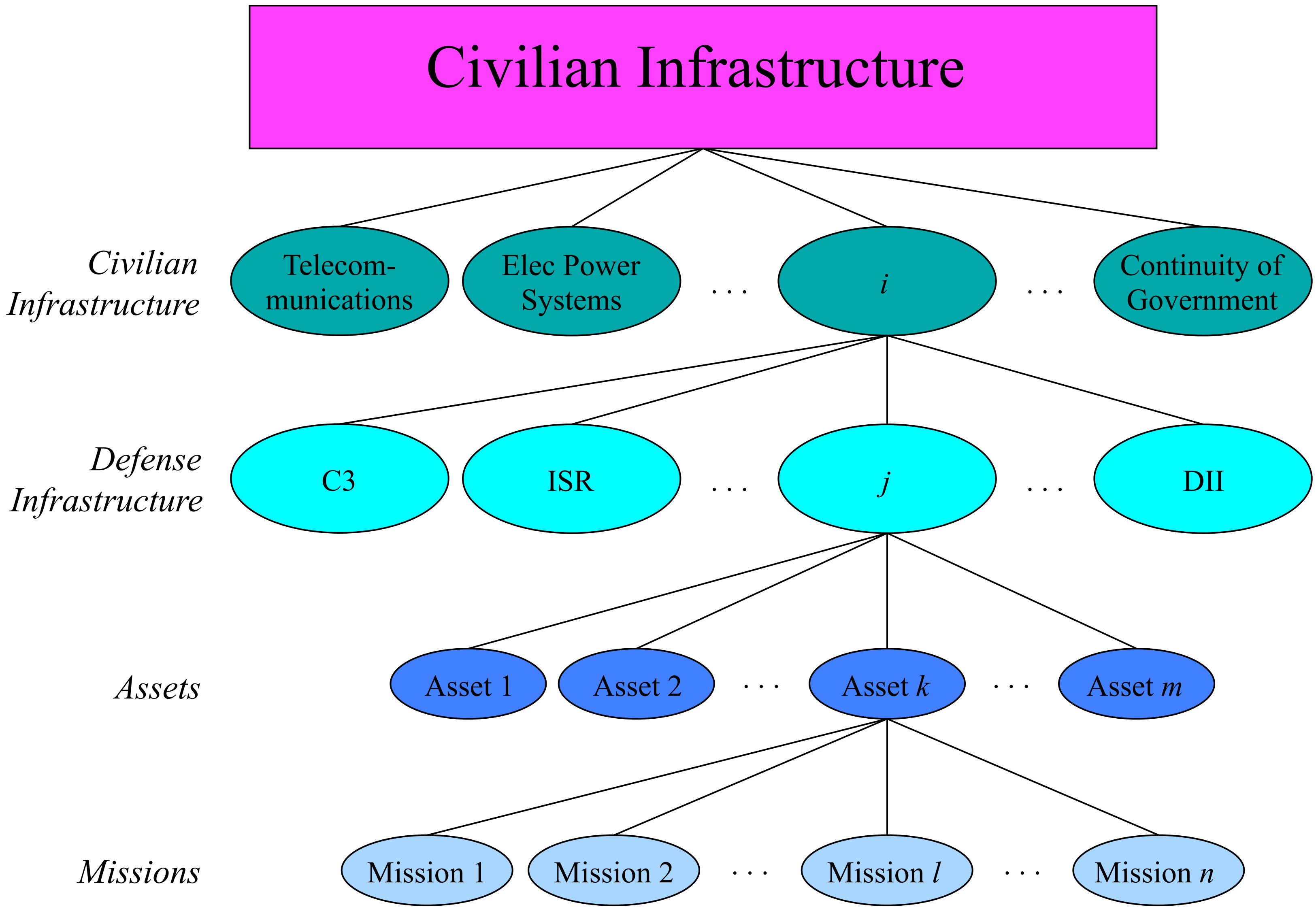


C3: *Command, Control, and Communications*
ISR: *Intelligence, Surveillance and Reconnaissance*
DII: *Defense Information Infrastructure*

Civilian Infrastructure Sectors




Civilian Infrastructure
Telecom-
munications
Elec Power
Systems
. . .
i
. . .
Continuity of
Government
Regional
Decomposition
Region 1
Region 2
. . .
Region j
. . .
Region m
Temporal
Decomposition
Period 1
Period 2
. . .
Period k
. . .
Period n
Functional
Decomposition
Function 1
Function 2
. . .
Function l
. . .
Function o


Civilian Infrastructure
Civilian Infrastructure
Telecom-munications
Elec Power Systems
. . .
i
. . .
Continuity of Government
Defense Infrastructure
C3
ISR
. . .
j
. . .
DII
Assets
Asset 1
Asset 2
. . .
Asset k
. . .
Asset m
Missions
Mission 1
Mission 2
. . .
Mission l
. . .
Mission n

Hierarchical Holographic Modeling of Complex Systems of Systems

The more we look
The more we find

The more we find
The more comprehensive is our modeling

Attributes of HHM

- Adds more realism to the entire modeling process by recognizing the limitations of modeling complex systems of systems via a single model;

- Provides more responsiveness to the inherent hierarchies of multiple objectives/sub-objectives and multiple decisionmakers.

Modeling Complex Systems of Systems via HHM

The more we look/model
The more we find/understand

The more we find/understand
The more comprehensive is our coverage

Risk Modeling, Assessment, Management, and Communication for Complex Systems of Systems:
We must answer the questions for each system and the SoS as a whole

Risk Assessment

1. What can go wrong?
2. What is the likelihood that it could go wrong?
3. What are the consequences?

4. What is the time frame?

Risk Modeling
Causal Relationships Among All State Variables

Risk Communication
Stakeholders and Knowledge Integration

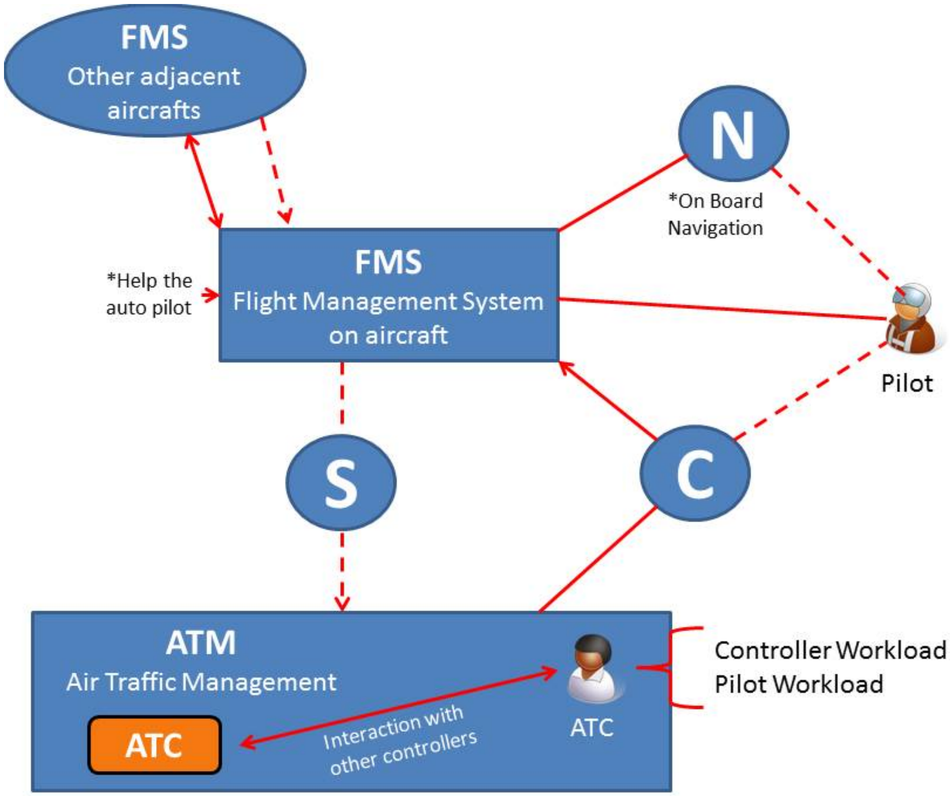
1. What can be done and what options are available?
2. What are the associated trade-offs in terms of all costs, benefits, and risks?
3. What are the impacts of current management decisions on future options?

Risk Management

Systems-Based Risk Analysis for the NextGen Integration of the Communication, Navigation, and Surveillance Complex System of Systems

A Case Study Performed for the U.S.federal Aviation Administration (FAA)

Technical Understanding of CNS as System of System (SoS)

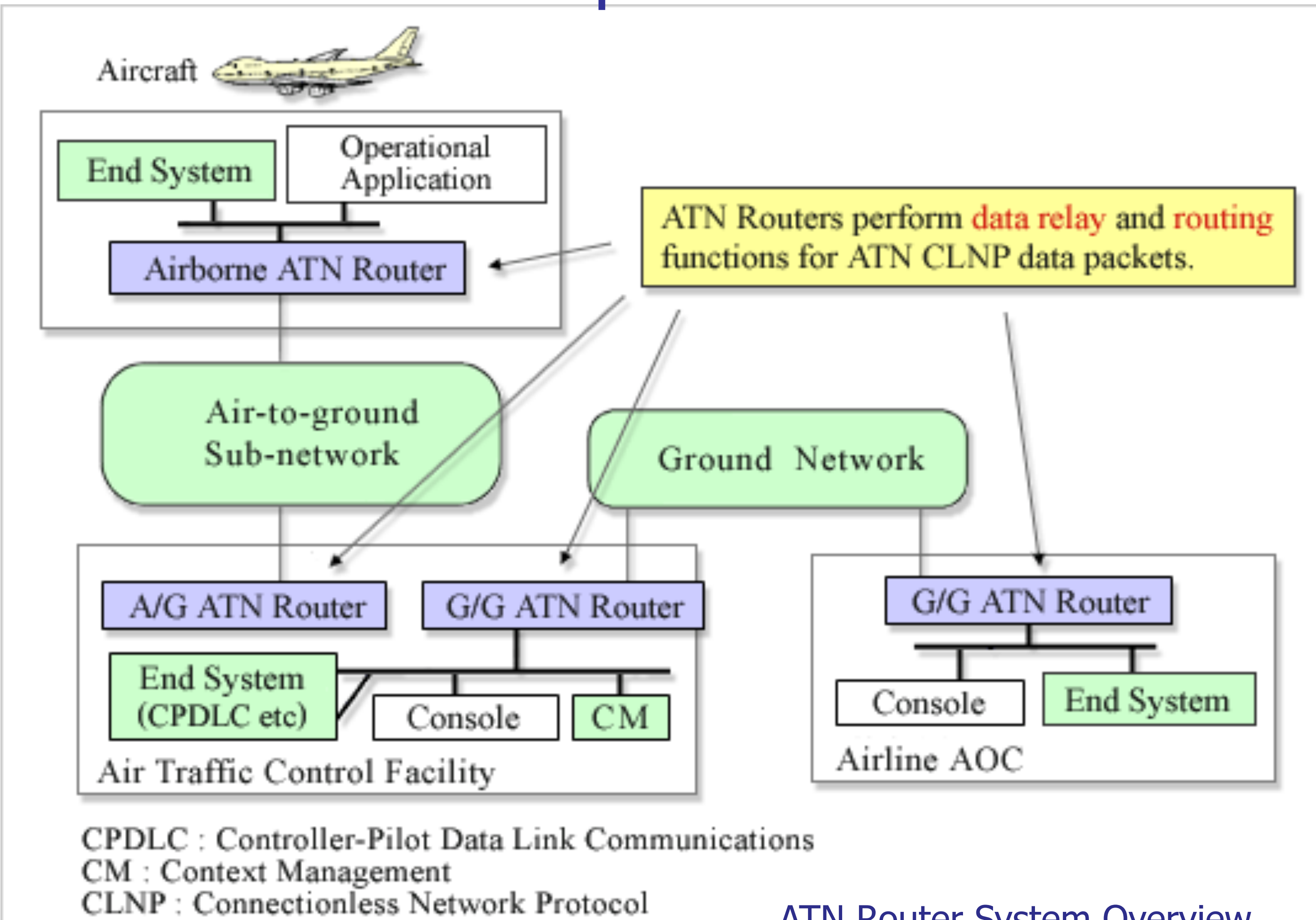


Flight Management System (FMS)

Air Traffic Controller's (ATC)

Required Navigational Performance (RNP)_

Technical Understanding of CNS as Complex SoS



ATN Router System Overview

RECALL:

The key to modeling and managing Complex SoS lies in understanding the genesis of characterizing the interconnectedness & interdependencies manifested through shared:

States, *decisions, resources, functions, policies, decisionmakers, stakeholders, organizational setups,* and others.

Shared States: Current Configuration

The shared states determined are highlighted in Red

States	Communication	Navigation	Surveillance
LF Signal Integrity		✓	
MF Signal Integrity		✓	
HF Signal Integrity	✓		
VHF Signal Integrity	✓	✓	
UHF Signal Integrity (Includes GPS)		✓	✓
SATCOM Signal Integrity	✓		
GPS Signal Integrity		✓	✓
GPS Signal Availability		✓	✓
GPS Signal Accuracy		✓	✓
Radar Signal Integrity			✓
Comprehension	✓		
Plane Authenticity/Identification	✓		✓
Signal Effective Range	✓	✓	✓
Station Authenticity/ Identification		✓	
Distance Calculation Accuracy		✓	
Position Drift		✓	
Detection Availability			✓
Navigation System Error - NSE		✓	
Flight Technical Error - FTE (Conformance)	✓	✓	✓

Shared States: Dynamic Required Navigational Performance (D-RNP) Configuration

States	Communication	Navigation	Surveillance
HF Signal Integrity	✓	✓	
VHF Signal Integrity	✓	✓	
UHF Signal Integrity		✓	✓
SATCOM Signal Integrity	✓	✓	
GPS Signal Integrity		✓	✓
GPS Signal Availability		✓	✓
GPS Signal Accuracy		✓	✓
Radar Signal Integrity			✓
Comprehension	✓		
Plane Authenticity/Identification	✓		✓
Signal Effective Range	✓	✓	✓
Station Authenticity/Identification		✓	
Distance Calculation Accuracy		✓	
Position Drift		✓	
Detection Availability			✓
Compliance	✓	✓	✓

Shared Decisions – Current Configuration

Shared Decisions			
Decision	**Communication**	**Navigation**	**Surveillance**
Tuning of Frequency	✓	✓	
Human Information Requests	✓		
System Use		✓	
INS Correction System		✓	
Call Sign Assignment	✓		✓
Flight Plan	✓	✓	
Altitude Adjustments	✓		✓
Weather Aversion	✓		✓

Shared Decision Makers – Current Configuration

Shared Decision Makers			
Decision Maker	Communication	Navigation	Surveillance
Pilot	✓	✓	
ATC	✓	✓	✓
Airport		✓	✓
FAA	✓	✓	✓
ICAO	✓	✓	
ARINC	✓		
AAC	✓		
AOC	✓		

Shared Resources- Current Configuration

Shared Factors			
Resource	**Communication**	**Navigation**	**Surveillance**
Radar Sites			✓
NAVAID Site		✓	
Air Traffic Controllers	✓		✓
Pilots	✓	✓	
Airplane	✓	✓	✓
Airport			
Satellites	✓	✓	✓
Navigation Charts (IAP, etc.)		✓	✓
Flight Plans		✓	
Weather Stations	✓	✓	✓
Runways		✓	✓
Flight Management Computer	✓	✓	

Shared Decisions/Decision Makers – Dynamic Required Navigational Performance (RNP) Configuration

Decision \ Decision Maker	Pilot	ATC	Airport
Type of Approach			
Instrument Flight Rules	✓	✓	
Visual Flight Rules	✓	✓	
Approach System			
ILS	✓	✓	✓
Vectored Approach	✓	✓	✓
GPS (RNAV) Approach	✓	✓	✓
VOR Approach	✓	✓	✓
NDB Approach	✓	✓	✓
Runway Clearance		✓	✓
Aircraft Separation		✓	
Approach Route	✓	✓	
Holding Pattern		✓	

Shared Decisions

Required Navigational Performance (RNP) Configuration

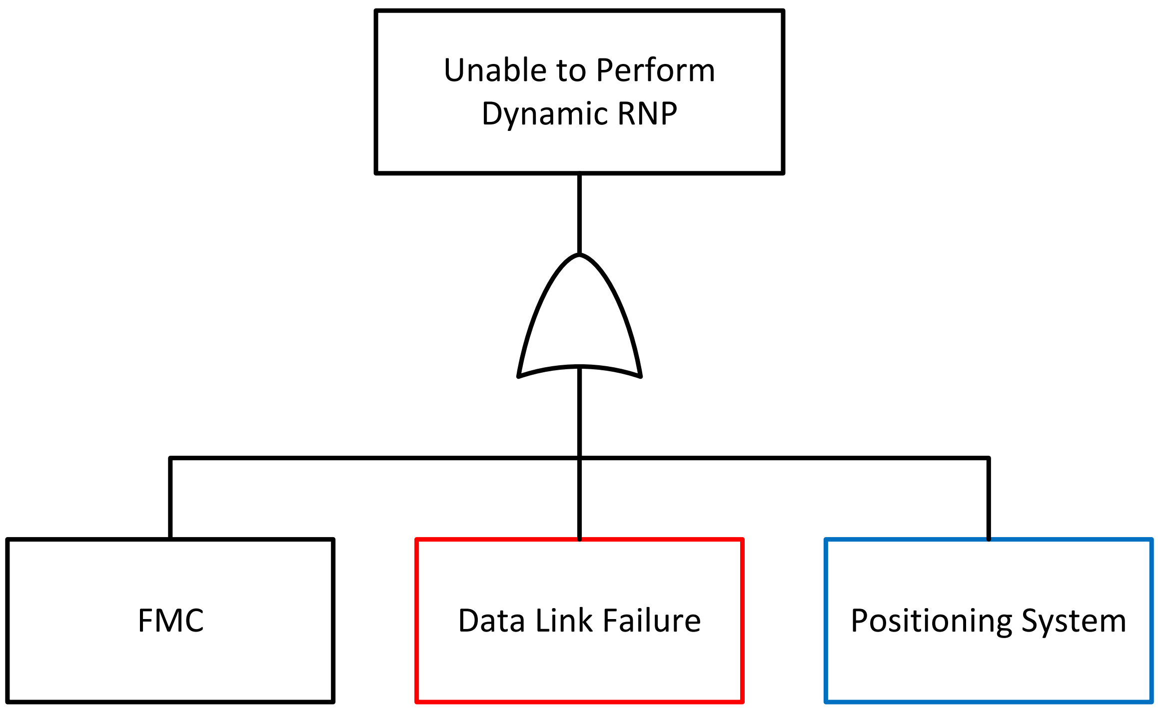
Decision	Communication	Navigation	Surveillance
Type of Approach			
Instrument Flight Rules	✓	✓	✓
Visual Flight Rules	✓	✓	
Approach System			
ILS		✓	
Vectored Approach	✓		✓
GPS (RNAV) Approach		✓	
VOR Approach		✓	
NDB Approach		✓	
Runway Clearance	✓		
Aircraft Separation	✓		✓
Approach Route	✓	✓	
Holding Pattern	✓	✓	

Shared Resources –
Dynamic RNP Configuration

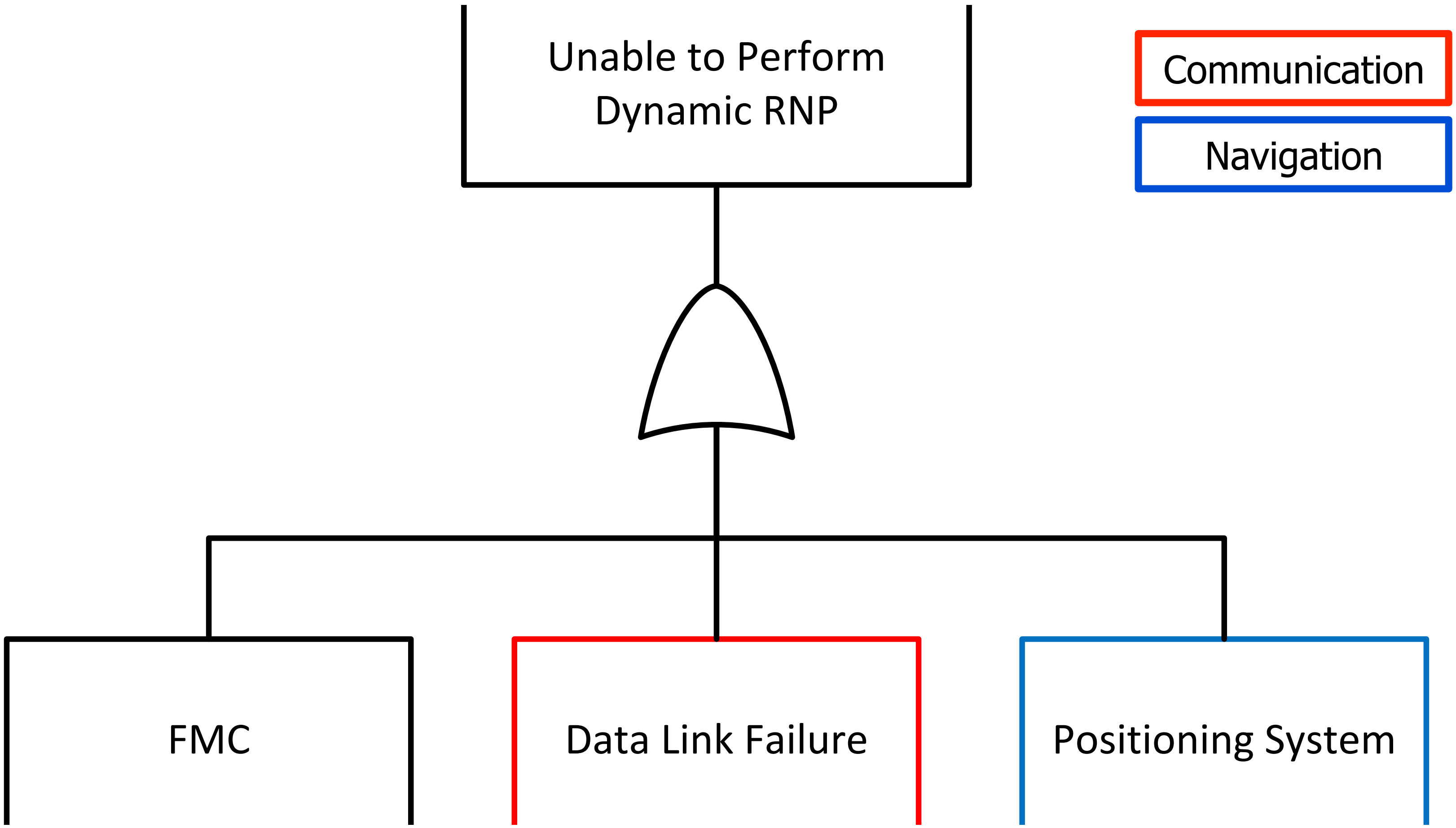
Resource	Communication	Navigation	Surveillance
Radar Sites			✓
DME Substations		✓	
Satellites	✓	✓	
Air Traffic Controllers	✓		✓
Pilots	✓	✓	
Airplane	✓	✓	✓
NACO Charts	✓	✓	✓
Flight Management Computer	✓	✓	
ATN – B2 Receiver/Transceiver	✓		
NAVAID Receiver		✓	

Fault Tree Analysis

1. Flight Management Control (FMC) Failure
2. Data Link Failure
3. Positioning System Failure



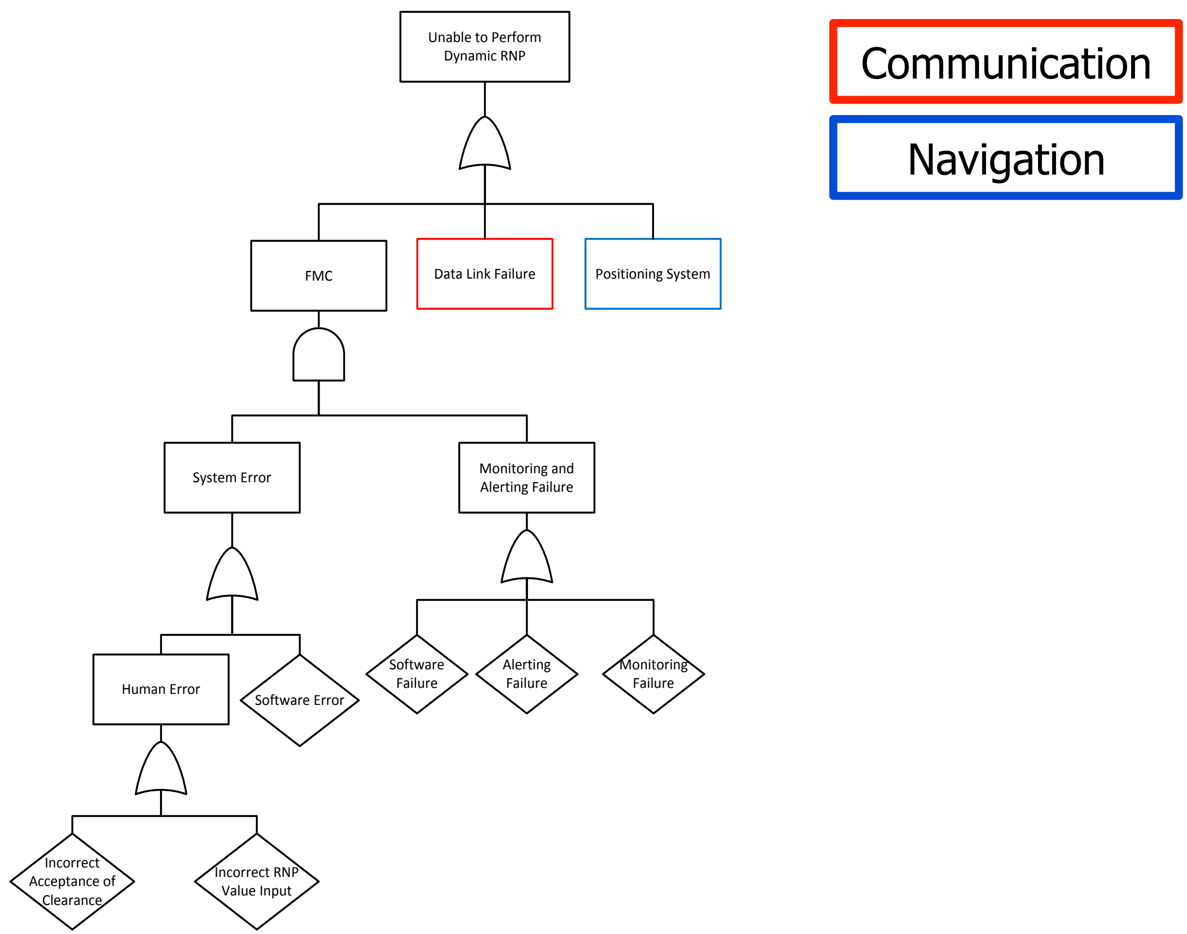
Fault Tree Analysis Continued



Fault Tree Analysis Cont.'d

Flight Management Control

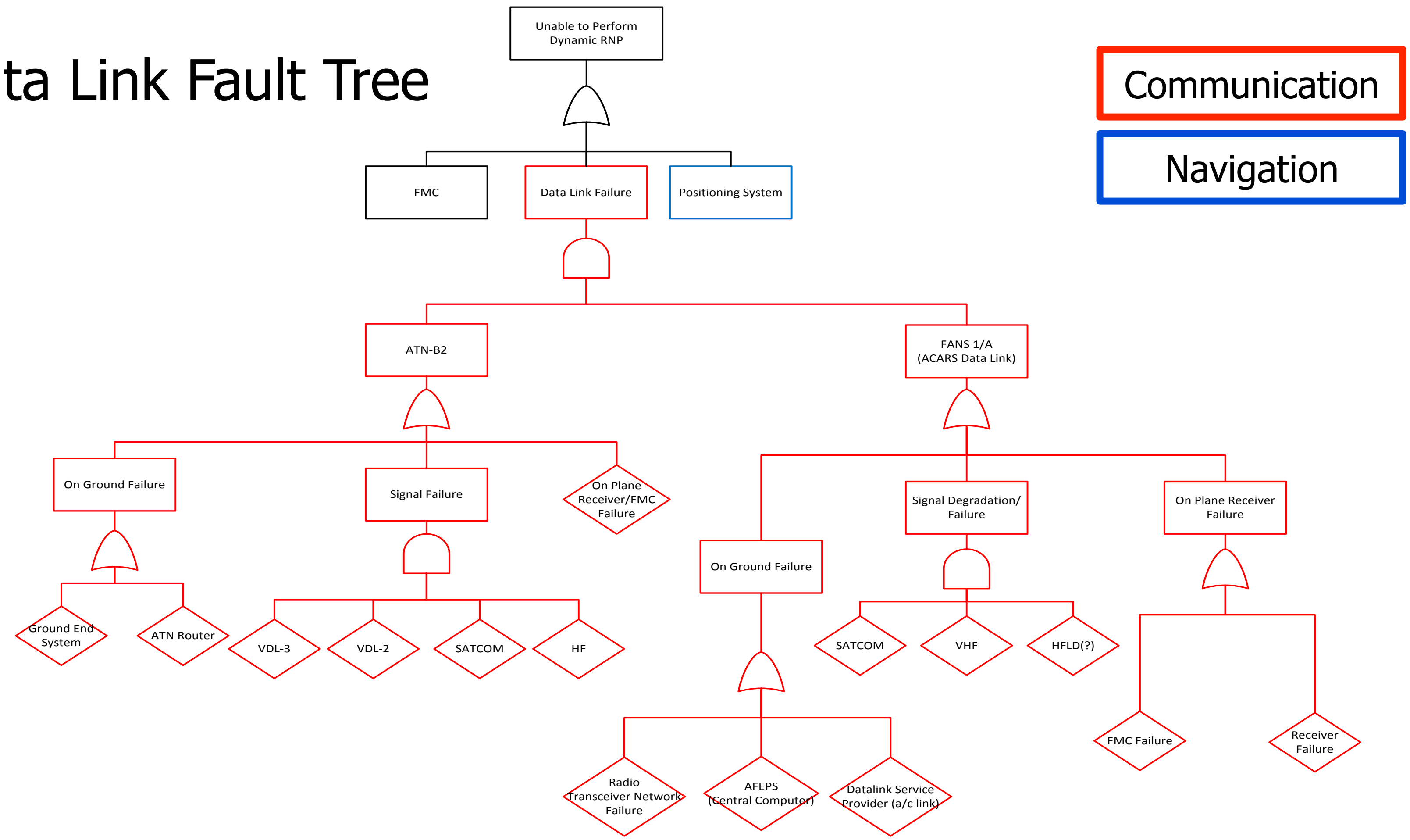
Fault Tree



Expanded Fault Tree with Failure Modes Caused by FMC Failure

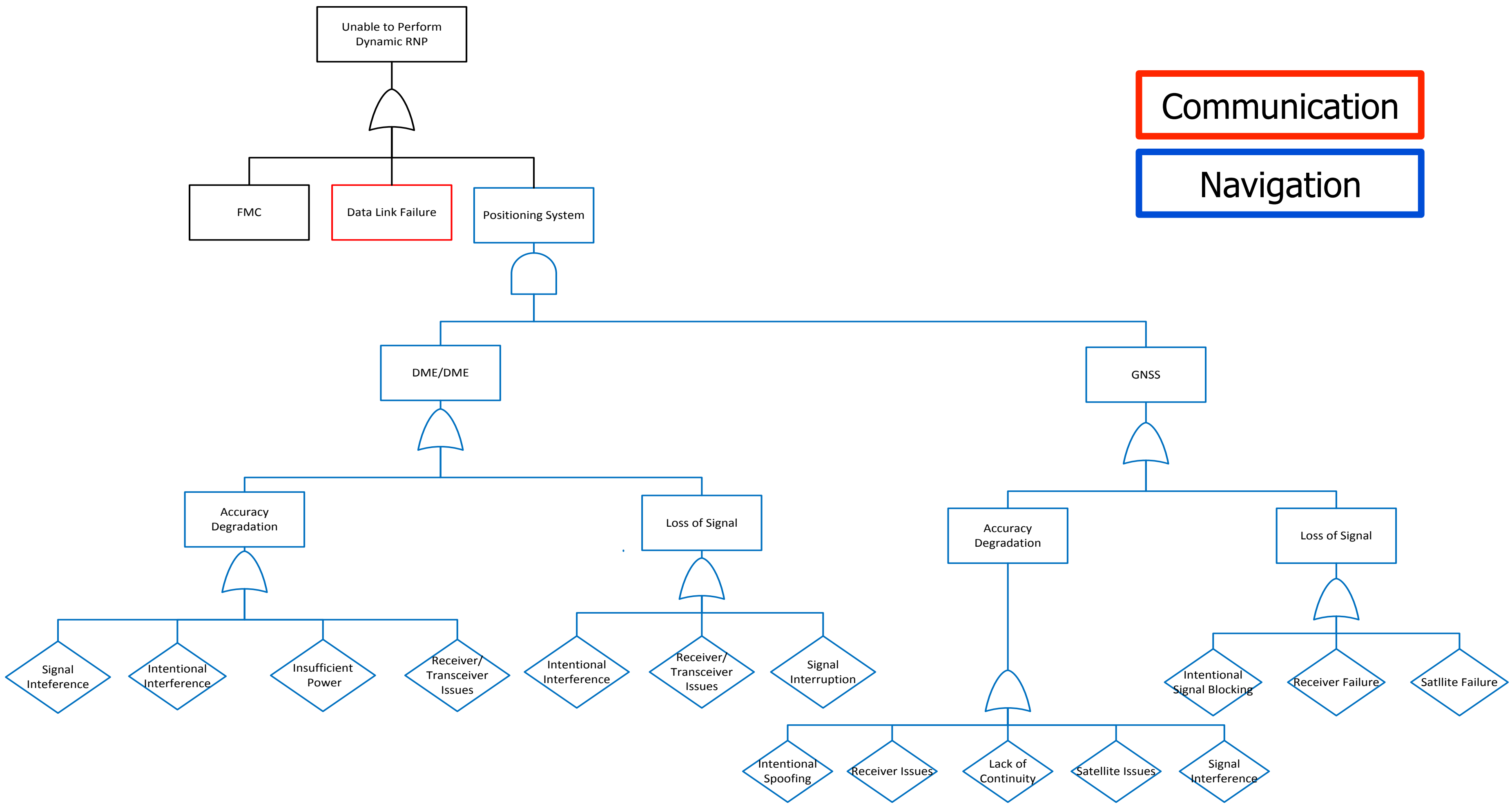
Fault Tree Analysis Contued

Data Link Fault Tree



Expanded Fault Tree with Failure Modes Caused by DataLink Failure

Positioning System Fault Tree



Expanded Fault Tree with Failure Modes Caused by DataLink Failure

What Have We Learned?

Throughout this seminar we defined and modeled complexity via the interconnectedness and interdependencies (I-I) characterizing complex systems of systems (SoS).

We further modeled and quantified the I-I by building on the shared/ common:

(i) States; (ii) *Decisions*; (iii) *Resources*; and (iv) *Decisionmakers*.