A Model Based Systems Engineering Methodology for Employing Architecture in System Analysis: Developing Simulation Models Using Systems Modeling Language Products to Link Architecture and Analysis

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Agenda

- Introduction
- Relevance
- Methodology Presentation
- Methodology Demonstration
- Analysis
- Conclusions

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Motivation

- In April 2013 Secretary of Defense Chuck Hagel stated[1]:
  - DOD systems are often more expensive and technologically risky than originally planned
  - Systems must be defined, planned, analyzed, and constructed to ensure that systems "do not continue to take longer, cost more, and deliver less than initially planned and promised."
- DOD systems necessary have long development times, high costs, and high levels of complexity, which prompts a reliance on modeling and simulation
- This dissertation develops an analysis methodology that ***establishes a clear linkage between systems architecture models and systems analysis models***
- The methodology is tailored for implementation early in the system lifecycle, when the majority of system decisions ***must utilize system models and simulations***
- The dissertation integrates with current MBSE efforts to support system development

1. Hagel, Charles T. "Speech Delivered to National Defense University." Speech, Washington, DC, April 3 2013

Intended Benefits of MBSE[1]

1. **Improved communications** among the development stakeholders
2. **Increased ability to manage system complexity** by enabling a system model to be viewed from multiple perspectives, and to analyze the impact of changes
3. **Improved product quality** by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness
4. **Enhanced knowledge capture and reuse of information** by capturing information in more standardized ways and leveraging built in abstraction mechanisms inherent in model driven approaches. This in-turn can result in reduced cycle time and lower maintenance costs to modify the design
5. **Improved ability to teach and learn systems engineering fundamentals** by providing a clear and unambiguous representations of concepts

1. Friedenthal, Sanford., Regina Griego, and Mark Sampson. "INCOSE Model Based Systems Engineering (MBSE) Initiative." Presented at the INCOSE 2007 Symposium, San Diego, CA, June 2007.

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Building Criteria Based on the Intended Benefits of MBSE

1. **<u>Improved communications</u>** among the development stakeholders
   1. Does the MBSE MEASA explicitly incorporate stakeholder input?
2. **<u>Increased ability to manage system complexity</u>** by enabling a system model to be viewed from multiple perspectives, and to analyze the impact of changes
   1. Does the MBSE MEASA allow the system model to be viewed from multiple perspectives?
   2. Does the MBSE MEASA incorporate a method for analyzing the impact of changes to the system design?
3. **<u>Improved product quality</u>** by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness
   1. Does the MBSE MEASA provide an unambiguous and precise model of the system?
   2. Can the models developed in the context of the MBSE MEASA be evaluated for consistency, correctness, and completeness?
4. **<u>Enhanced knowledge capture and reuse of information</u>** by capturing information in more standardized ways and leveraging built in abstraction mechanisms inherent in model driven approaches. This in-turn can result in reduced cycle time and lower maintenance costs to modify the design
   1. Does the MBSE MEASA capture information in standard ways?
   2. Does the MBSE MEASA enable reduced cycle time and lower maintenance costs to modify system designs?

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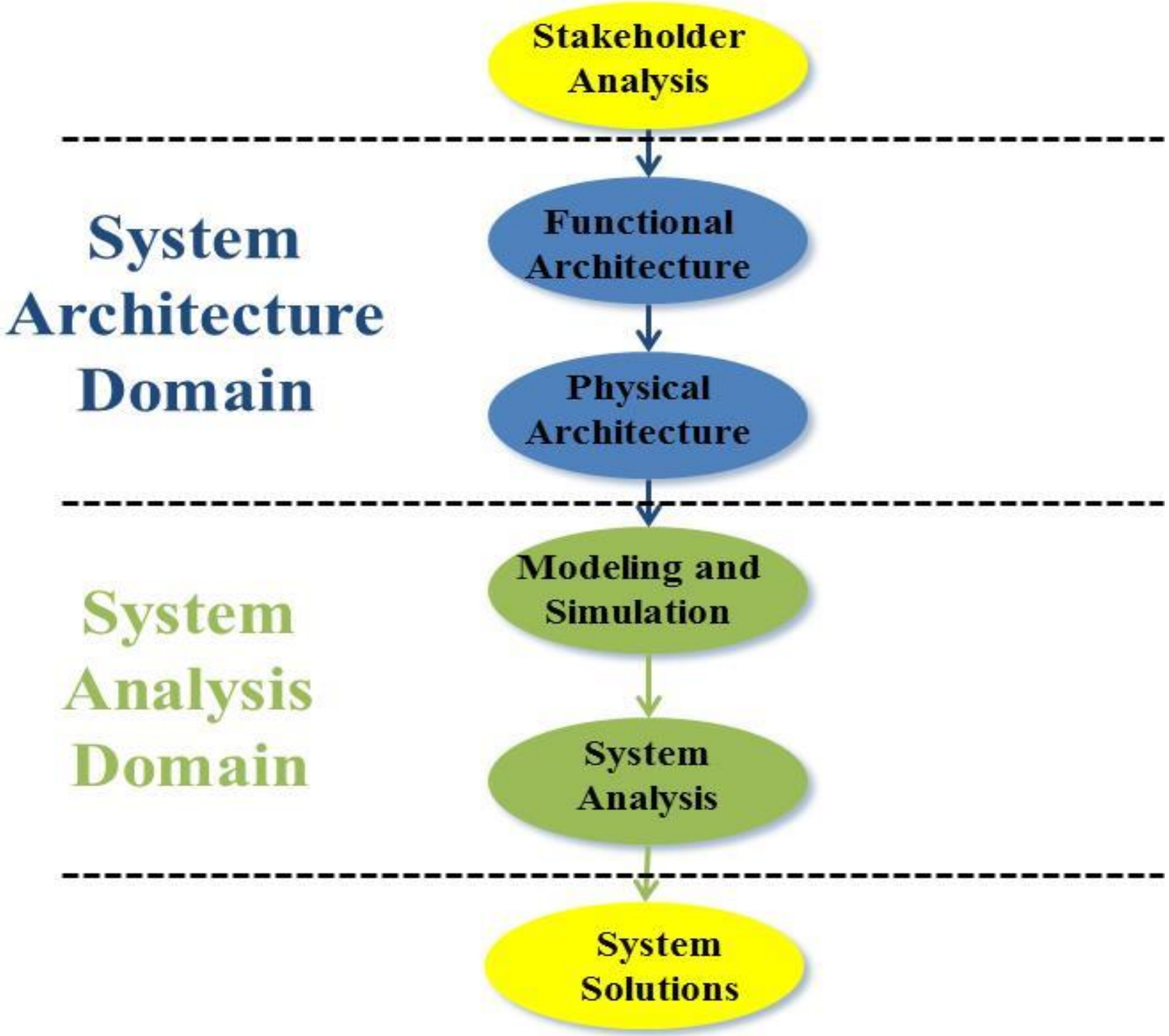
SE Process Conceptualization

Intended Utility of the Systems Engineering Process

- One potential representation of the general systems engineering process
- Focuses on decomposition of system requirements (System Architecture) and integration of system components (System Analysis)
- Systems Architecture is used to capture a set of Functions and Physical Elements, based on a Stakeholder Analysis
- System Analysis is then used to conduct Modeling and Simulation and System Analysis
- The final system solution should be traceable back to the original stakeholder analysis



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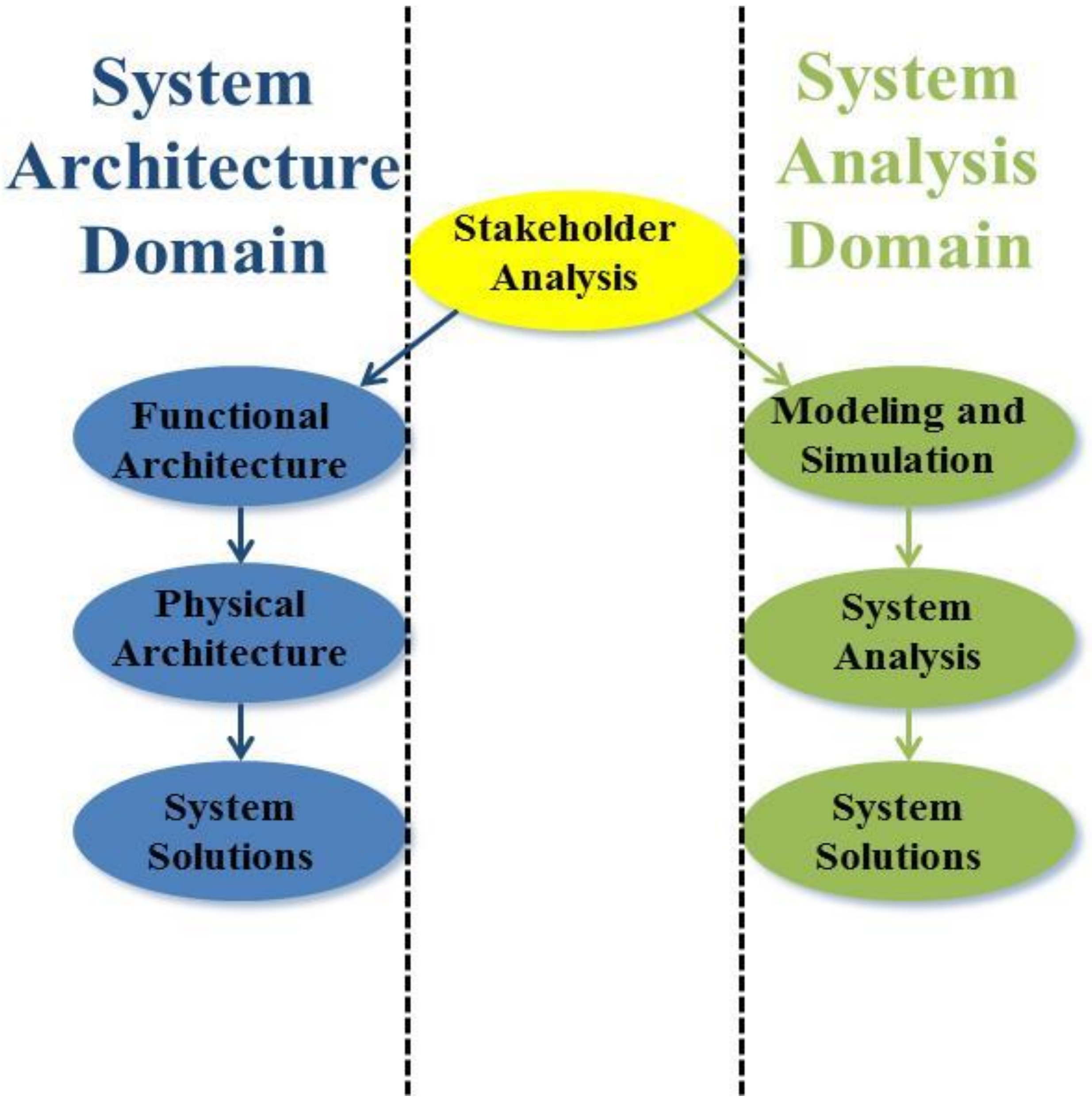
SE Process Reality

Reality of the Systems Engineering Process

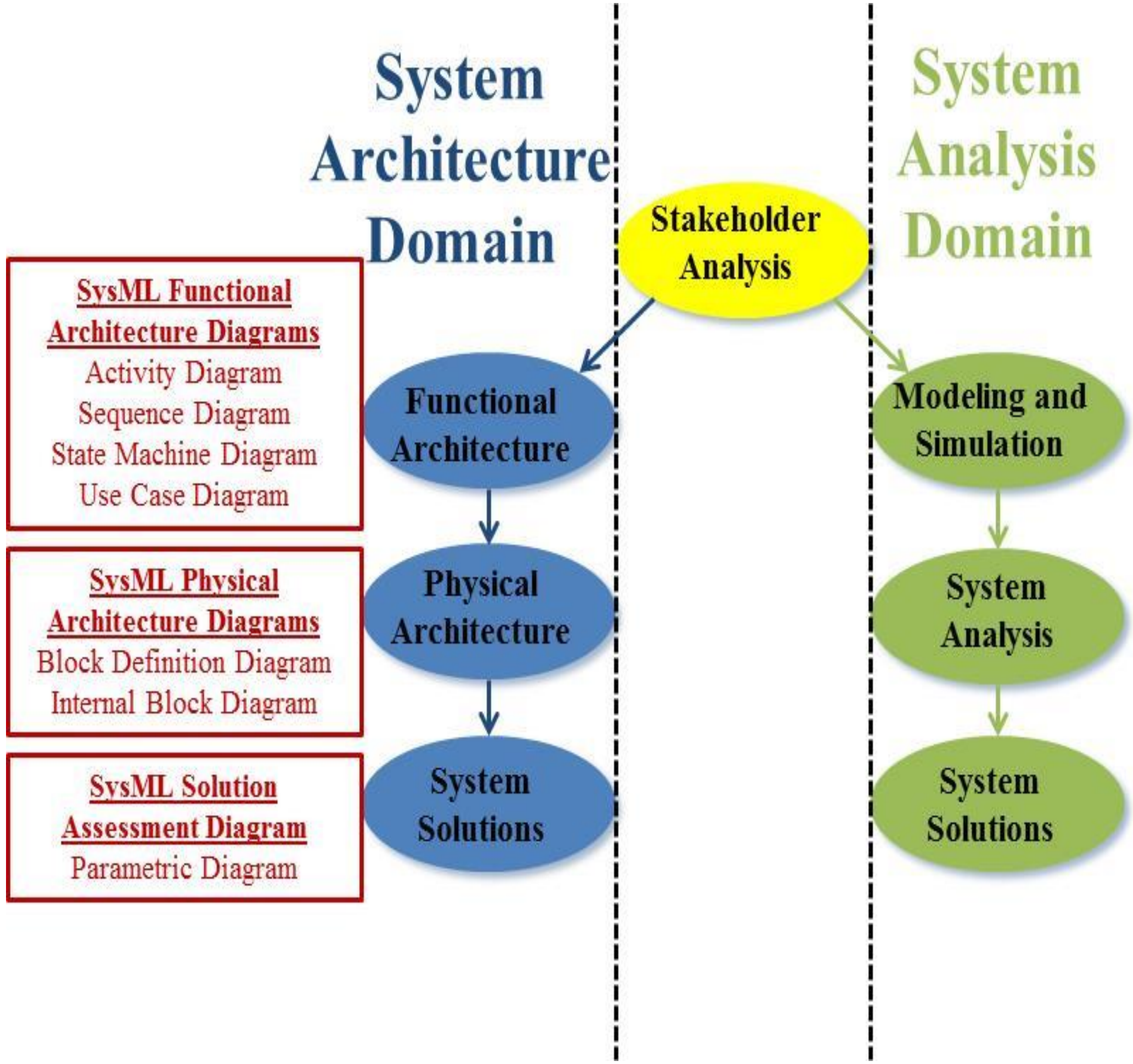
- Systems Architecture and System Analysis are conducted by different sets of people
- Substantial expertise is required in each area, and communication is difficult
- Adherence to a common set of system requirements is difficult
- There is no mechanism that ensure any behaviors represented in models and simulations are the functions prescribed by the system architecture
- There is no mechanism to ensure that the performance standards established in the physical architecture are consistent with models and simulations



Current MBSE Research

SysML Focused Development

- Recent MBSE research has focused on appropriate definition and execution of SysML Diagrams
- SysML Diagrams can generally be grouped into functional, physical, and solution analysis diagrams (groupings are mine)
- Functional and Physical Diagrams generally provide a comprehensive, integrated system description
- Parametric Diagrams are incapable of analyzing system performance in detail
- SysML products CAN be used as the basis for the development of external models and simulations



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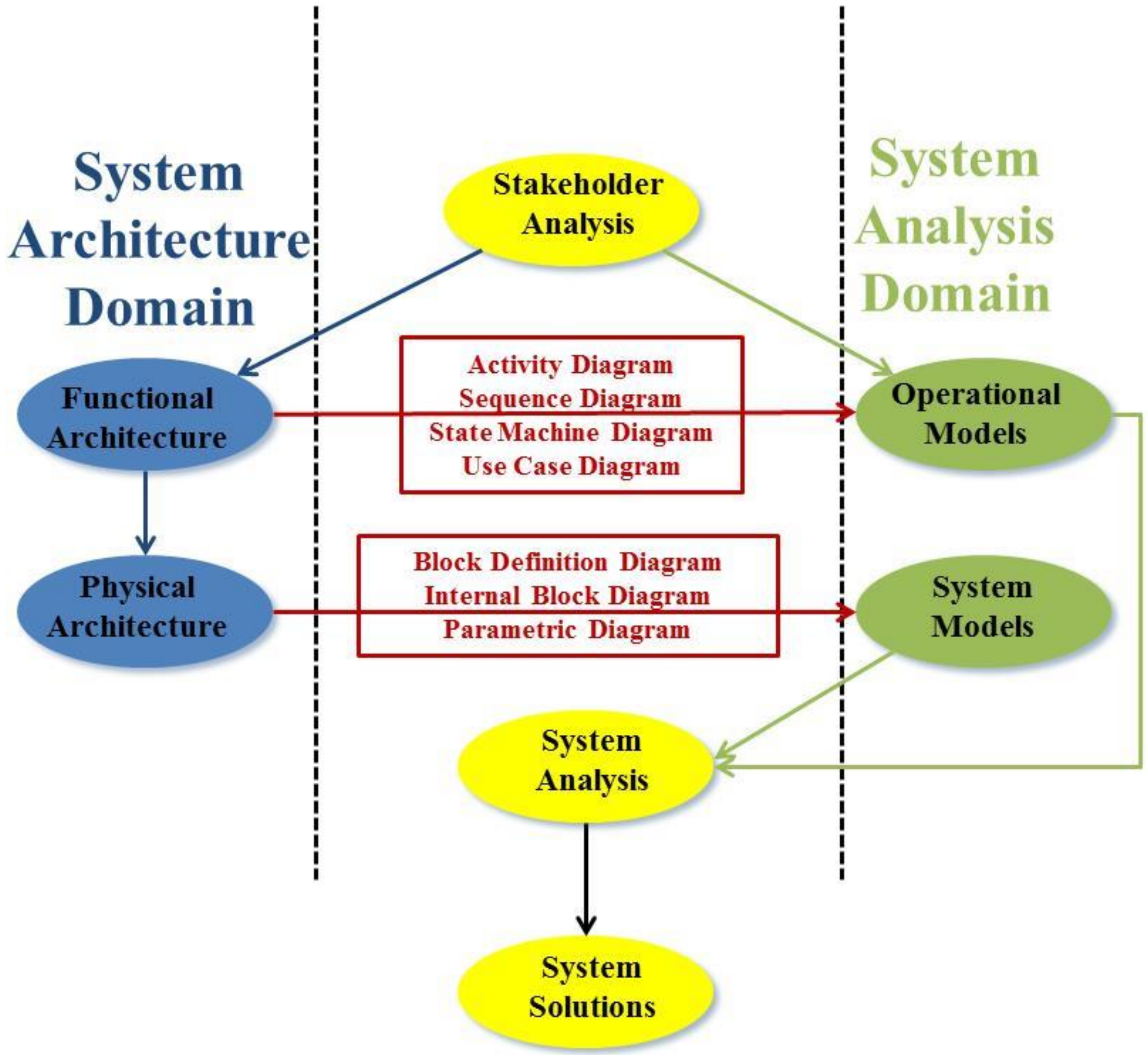
Contribution Implementation

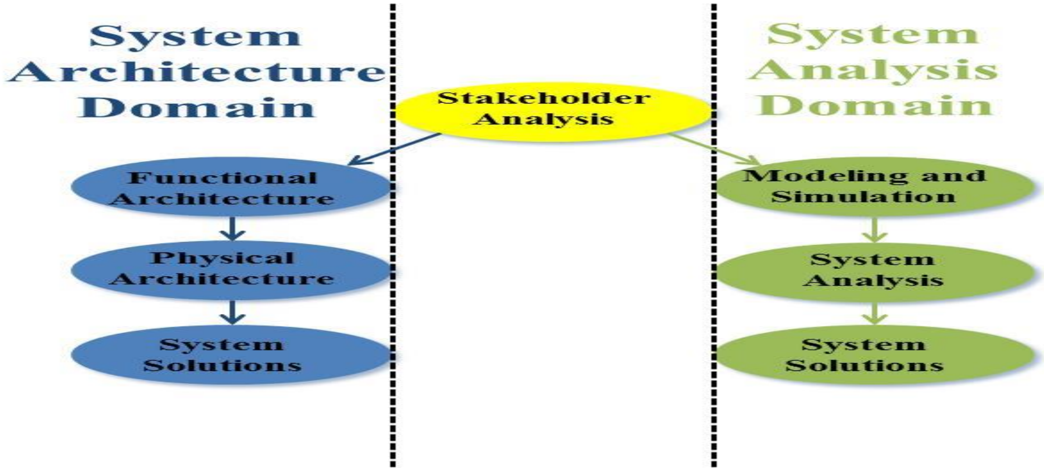
MBSE MEASA Utility

- Systems Architecture and System Analysis are not independent domains
- System development can be viewed from a functional perspective, where the Functional Architecture informs Operational Models
- System development can be viewed from a system perspective, where the Physical Architecture informs System Models (which may be physical synthesis models or cost models)
- There MBSE MEASA ensures any behaviors/elements represented in external models and simulations are the functions and physical elements prescribed by the system architecture



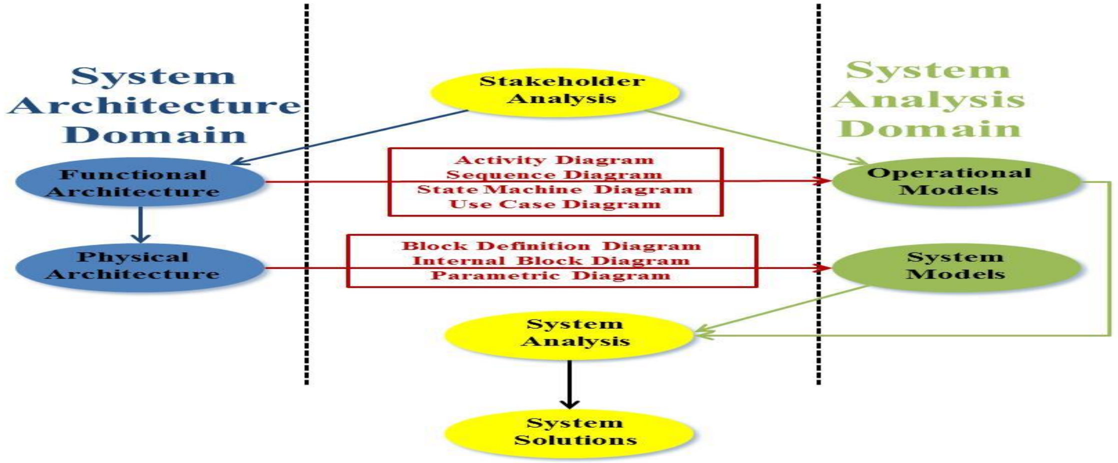
MBSE MEASA Benefits

Current Engineering Approach



- Development of architecture products and modeling/analysis products are stove-piped
- Architecture developers and modeling and simulation developers rarely get actionable feedback from analysts and engineers
- The segmented, independent processes produce solutions that may not adequately address the real problem

MBSE MEASA



- Development of architecture products is conducted to directly support development of modeling/analysis products
- Architecture developers and modeling and simulation developers interact continuously to clearly link products with the defined problem as the focus
- The connected, interdependent processes product solutions that are explicitly linked to a defined problem

The MBSE MEASA establishes an explicit linkage between architecture products and external models and simulations

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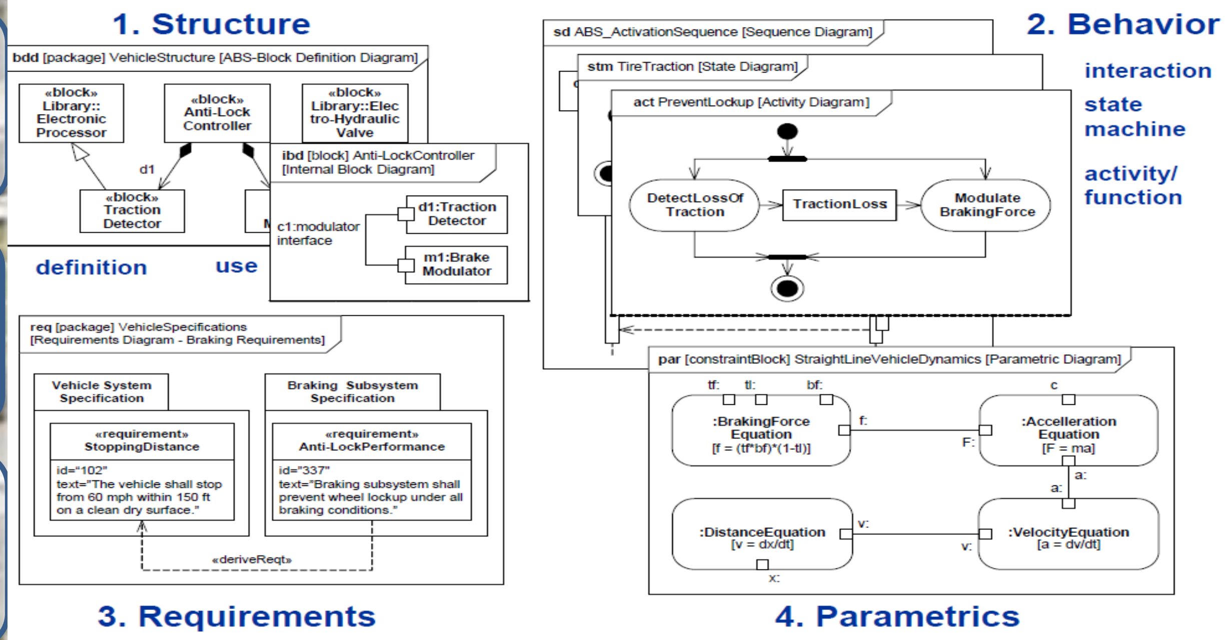
Current SysML Conceptualization

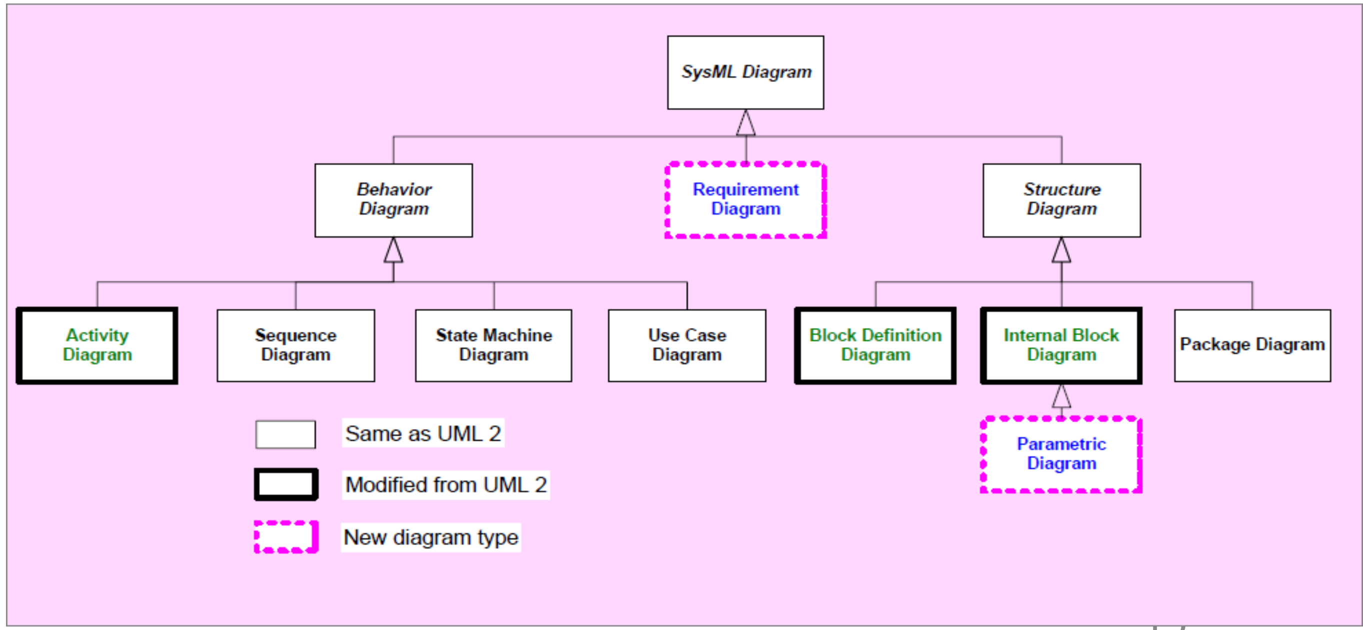
Pillars of SysML

- Customized from UML:
  - Capture system information
  - Analyze system requirements
  - Communicate system information
- Analysis is conducted through execution of Parametric Diagrams

SysML Diagram Taxonomy

- Diagrams are classified as:
  - Structure Diagrams
  - Behavior Diagrams
  - Requirements Diagrams
  - Parametric Diagrams





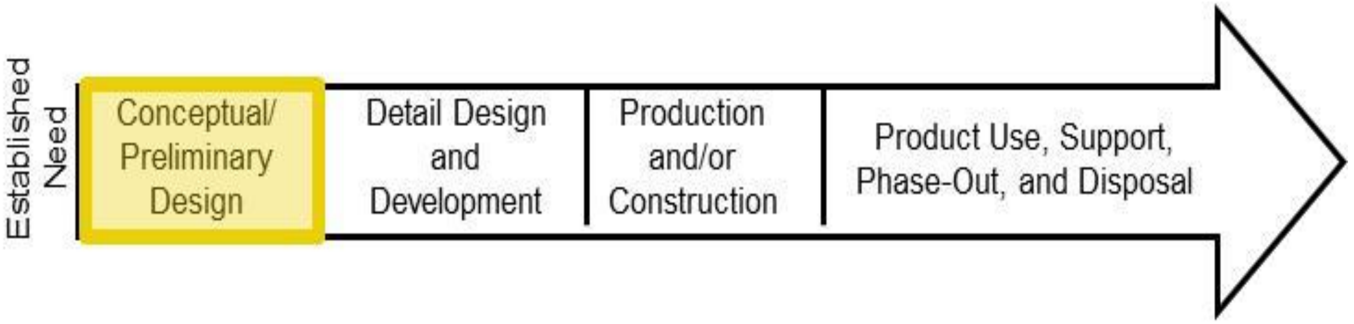
The Importance of Requirements Identification

1. *Problem Definition*
   1. *Stakeholder (Customer Analysis)*
   2. *Requirements Identification*
2. ***System Design***
   1. ***Functional Analysis***
   2. ***Physical Analysis***
   3. ***Design Generation***
   4. ***Modeling & Simulation***
3. ***System Analysis***
   1. ***Performance Analysis***
   2. ***Cost and Risk Analysis***

Assume This is Complete…

Because We Assume We Have Requirements … But Do Not Assume We Have "Good" Requirements

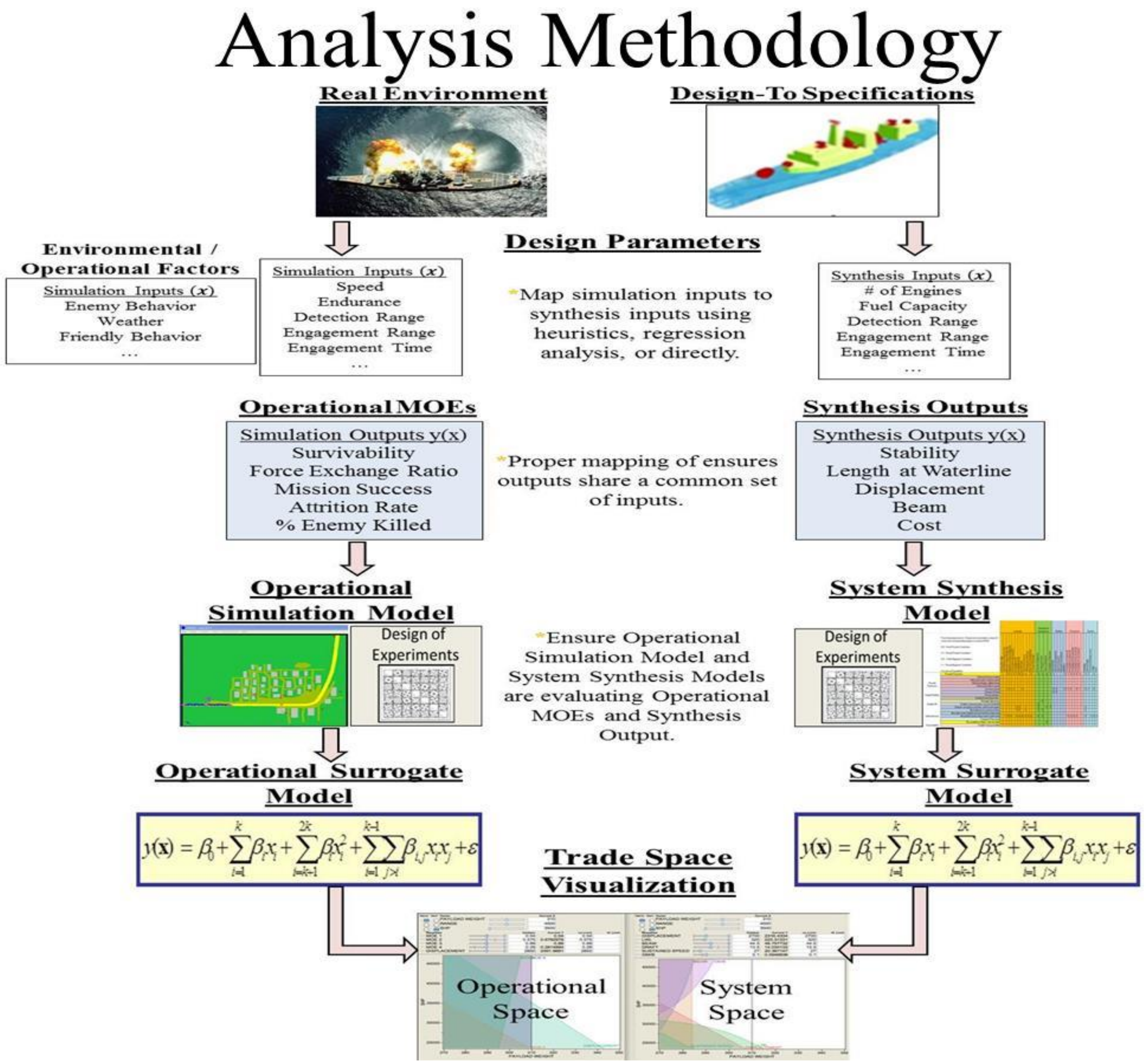
Limited to Conceptual Design



"The MBSE MEASA effectually assumes that all requirements are non-fixed ("soft") and systematically varies those requirements to better specify system design parameter configuration that perform best with respect to a set of operational effectiveness measures"

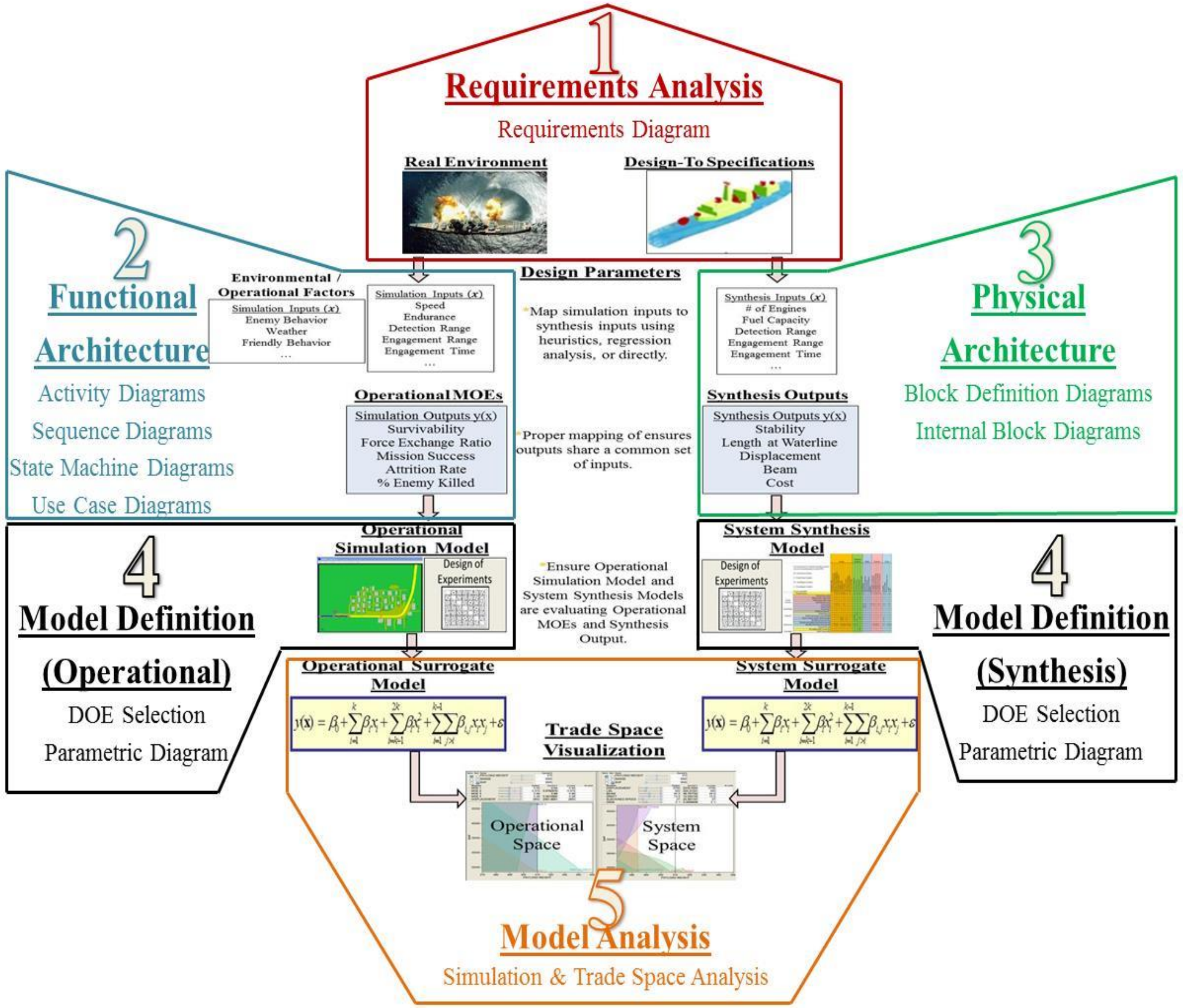
Analysis Methodology

- Model an operation to gain insight on how results vary based on changes to design parameters, environmental factors, and operational implementation
- Operational Effectiveness Modeling
  - Design Parameters are evaluated along with environmental and operational factors
  - Establishes a linkage between the characteristics of a system (Design Parameters) and the performance of that system (Operational MOEs)
- System Synthesis Modeling
  - Utilize the same set of Design Parameters (with potential mapping) as Operational Effectiveness Models
  - Establishes a linkage between the characteristics of a system (Design Parameters) and the system form (Synthesis Outputs)
- Trade Space Visualization
  - Sharing of Design Parameters allows for simultaneous exploration of Operational Space and System Space



MBSE MEASA

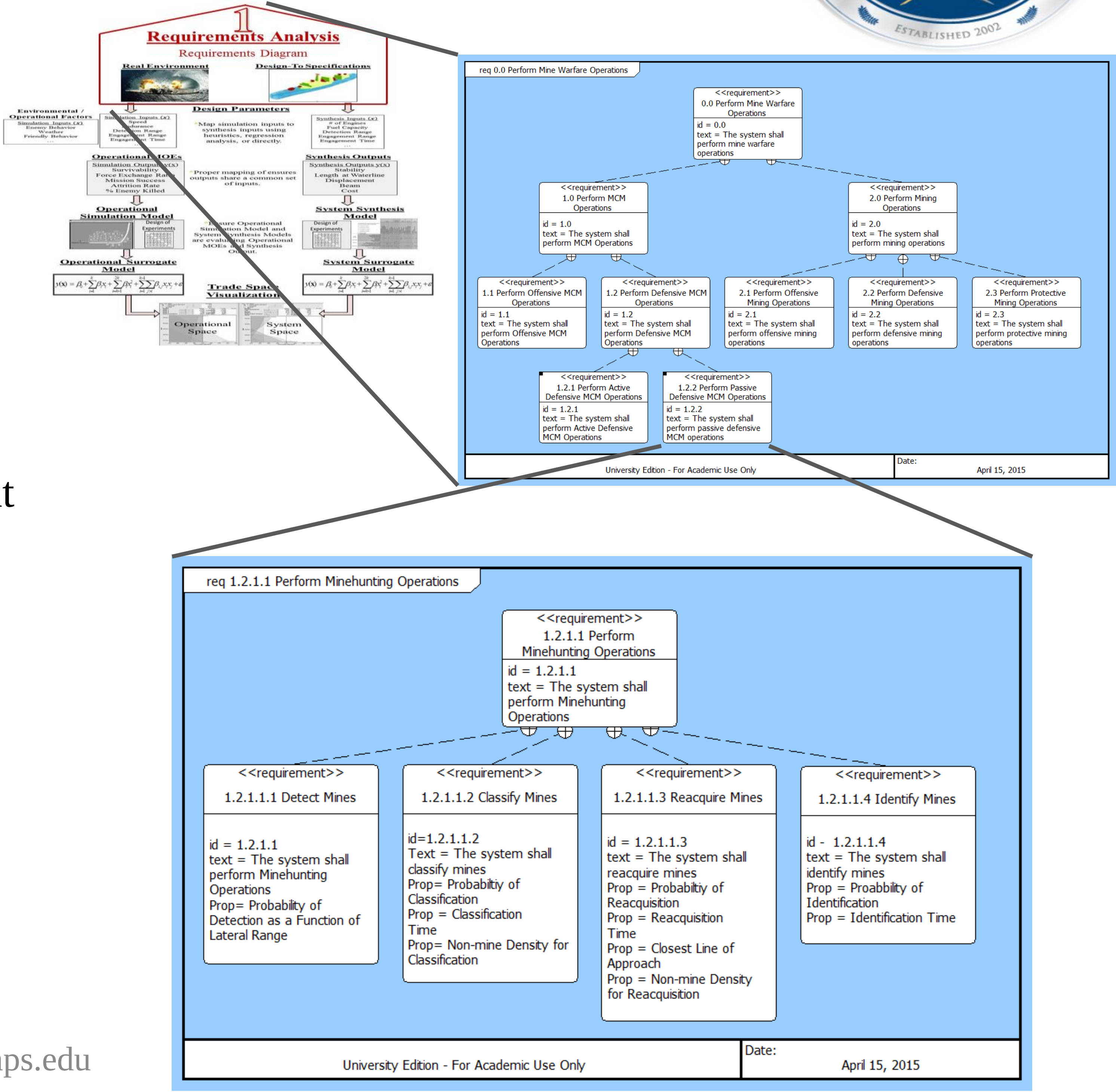
- First three steps are supported by SysML modeling
- The final two steps are supported by experimental design selection, simulation analysis, and trade space analysis
- Methodology identifies the SysML products and simulation analysis products that support each step of the process
- Methodology expands the scope of SysML modeling by specifying support for external model development and analysis
- Ensures that SysML architecture products are directly linked to an analysis approach
- Requirements Diagram captures the environment and design specifications, SysML products capture functional and physical architectures, external models and simulations support detailed system analysis



MBSE MEASA (Step 1)

Step 1: Requirements Analysis

- Define a set of requirements that capture both the intended operational environment and design specifications
- Specifies intended capabilities, expected functions, and performance capabilities
  - Leads to quantifiable performance metrics
- Establishes a common operating model that can be supplemented with increased detail
- Perform Mine Warfare Operations →
- Perform MCM Operations →
- Perform Defensive MCM Operations →
- Perform Active Defensive MCM Ops →
- Perform Minehunting Operations →
- Identify Mines
  - Describe with: ID, text description, Properties



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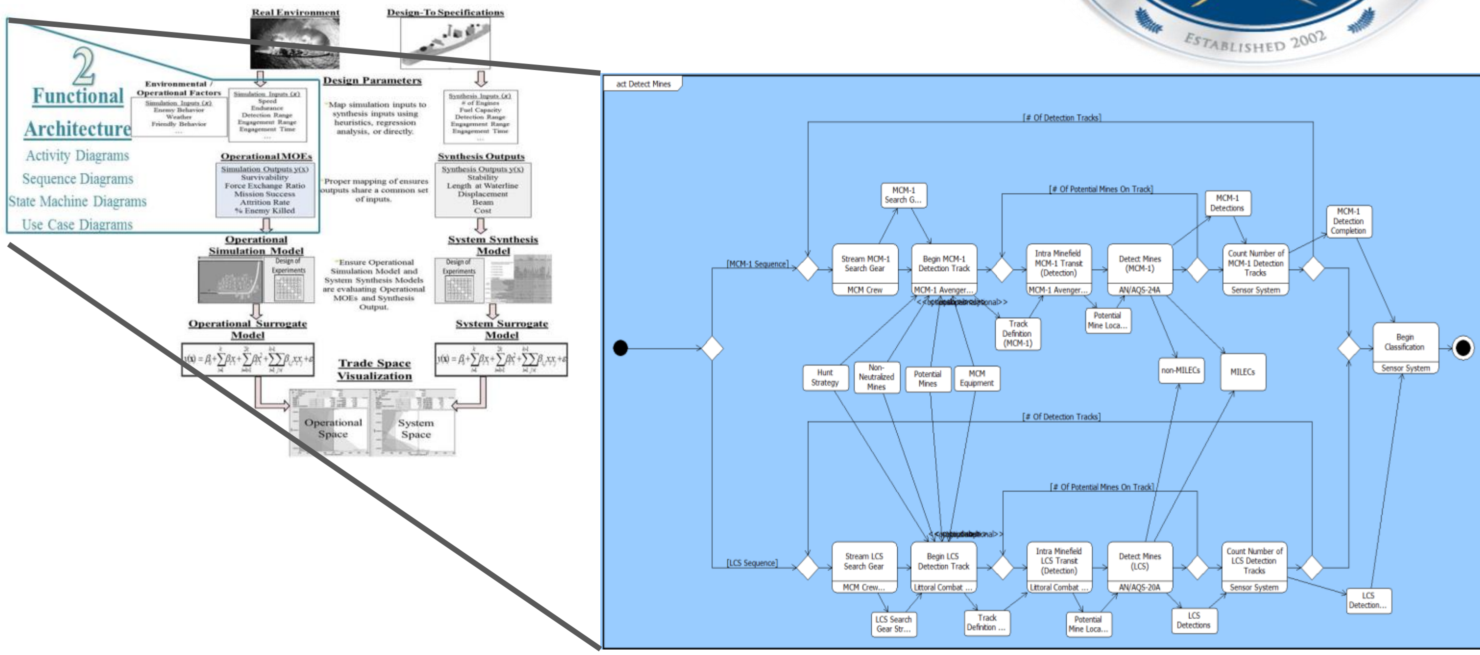
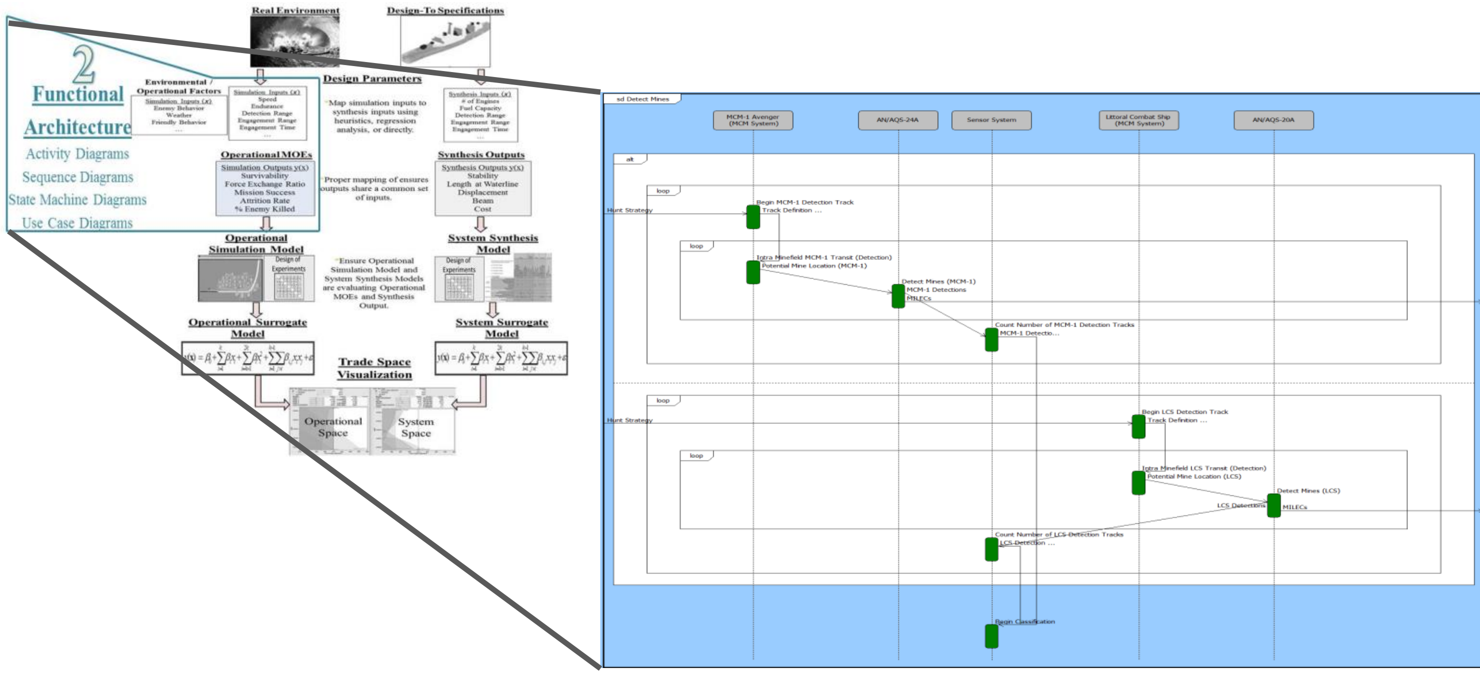
MBSE MEASA (Step 2a)

Step 2a: Activity & Sequence Diagrams

- Functional Architectures specify how a system will behave
- Activity Diagrams specify what a system must do in order to satisfy requirements
  - Also describes the external objects necessary to complete or trigger each activity
  - May also model parallel operations, loops, interactions, and replications of activities
  - Activities may be grouped into partitions (swim lanes)
- Sequence Diagrams provide additional information regarding interactions between elements and the internal stricture of activities
  - Provides detail regarding the ordering of activities
  - Alerts users to conflicts that may result from expecting an activity to commence prior to creation of external information necessary to support the activity

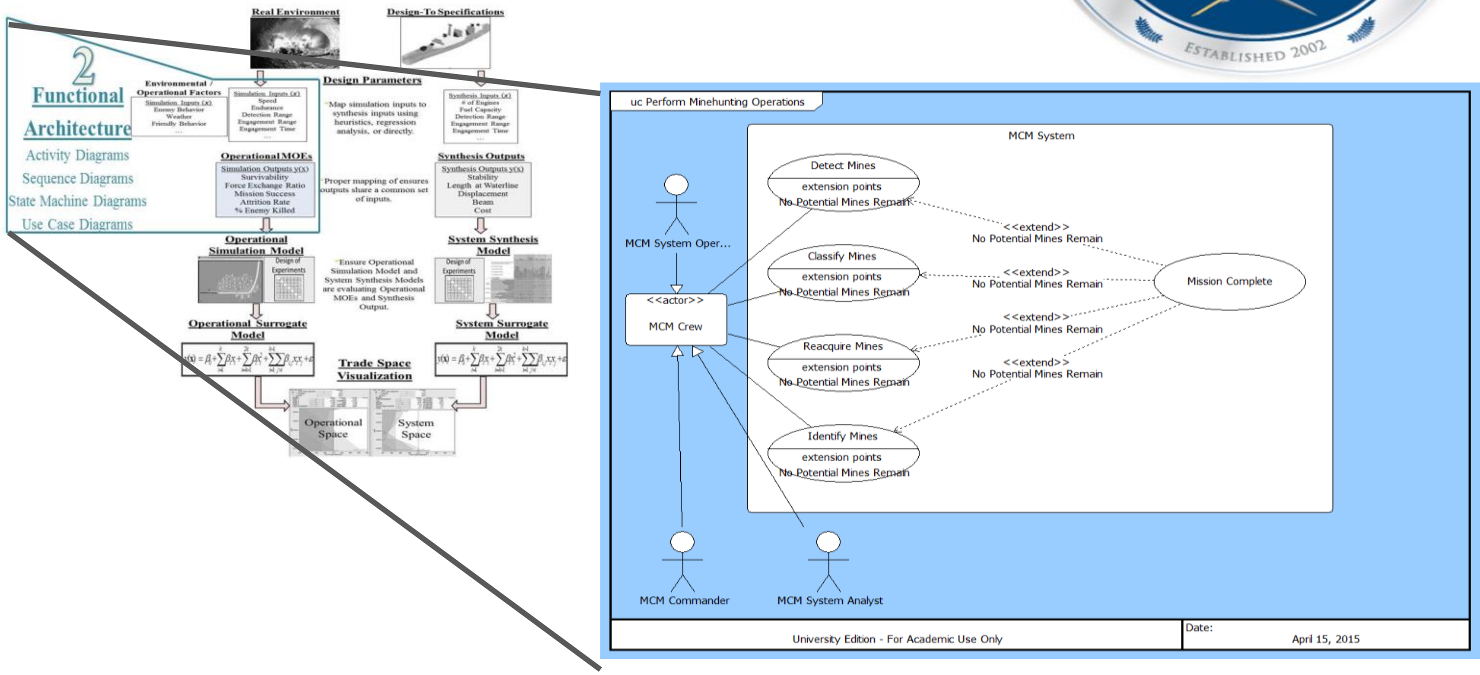


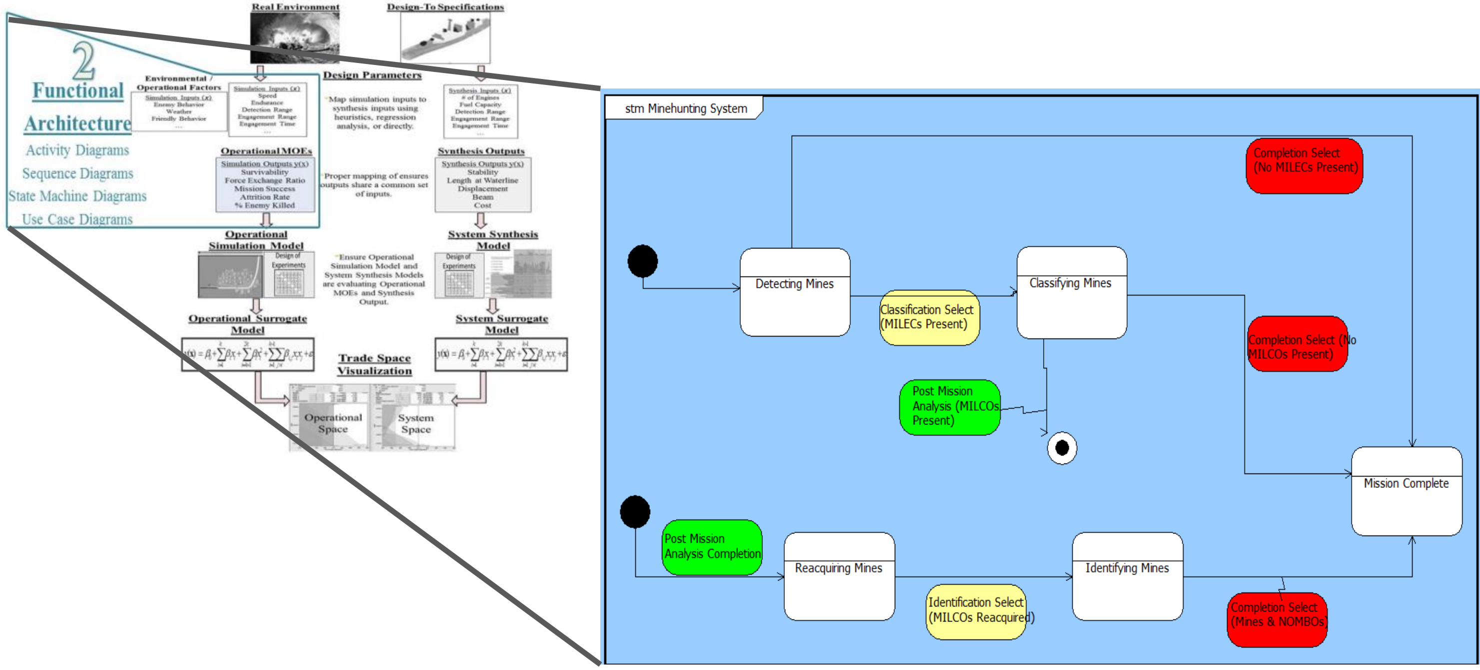


MBSE MEASA (Step 2b)

Step 2b: Use Case & State Machine Diagrams

- Functional Architectures specify how a system will behave
- Use Case Diagrams define the relationships between system activities and external actors
  - Particularly useful for multi-purpose systems
  - Identify conflicts in terms of system control and system implementation
  - Beneficial to remain solution neutral in terms of physical components
- State Machine Diagrams provide additional clarity regarding control systems and the range of potential system behaviors
  - Describe state dependent behaviors of physical components
  - Define entry and exit conditions for each potential system state
  - Define capabilities and limitations on system behaviors related to current system status





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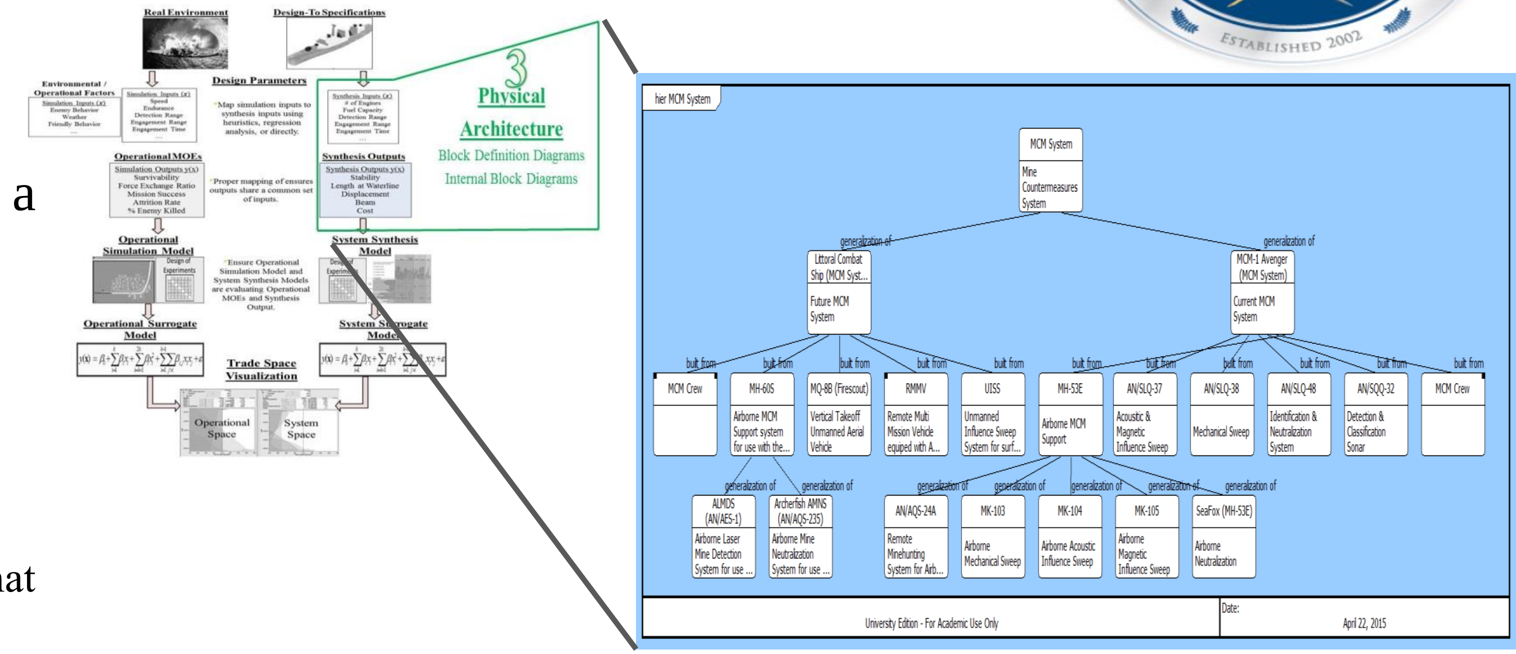
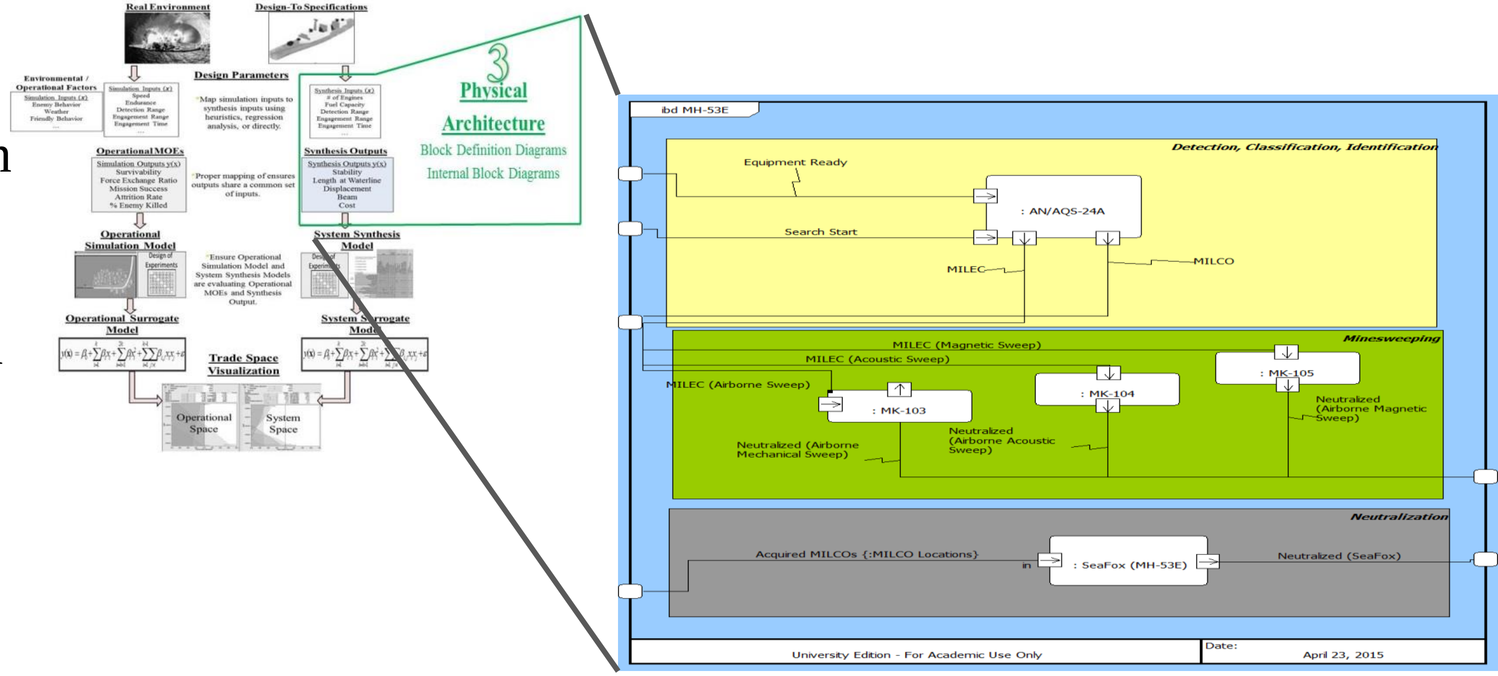
MBSE MEASA (Step 3)

Step 3: Block Definition and Internal Block Diagrams

- Physical Architectures specify the structure of a system
- Block Definition Diagrams describe the set of physical components that define a system
  - Define what physical systems exist in each potential system configuration
  - “Built from” relationships specify subcomponents that exist for each configuration of a given component
  - “Generalization of” relationships specify subcomponents that completely a component (mutually exclusive)
- Internal Block Diagrams establish a connection between Block Definition and Activity Diagrams by specifying what blocks (system components) are necessary to achieve intended system functionality
  - View activities/functions from a physical/structural perspective
  - Defines boundaries for each system component
  - Identifies links between subcomponents and between external components

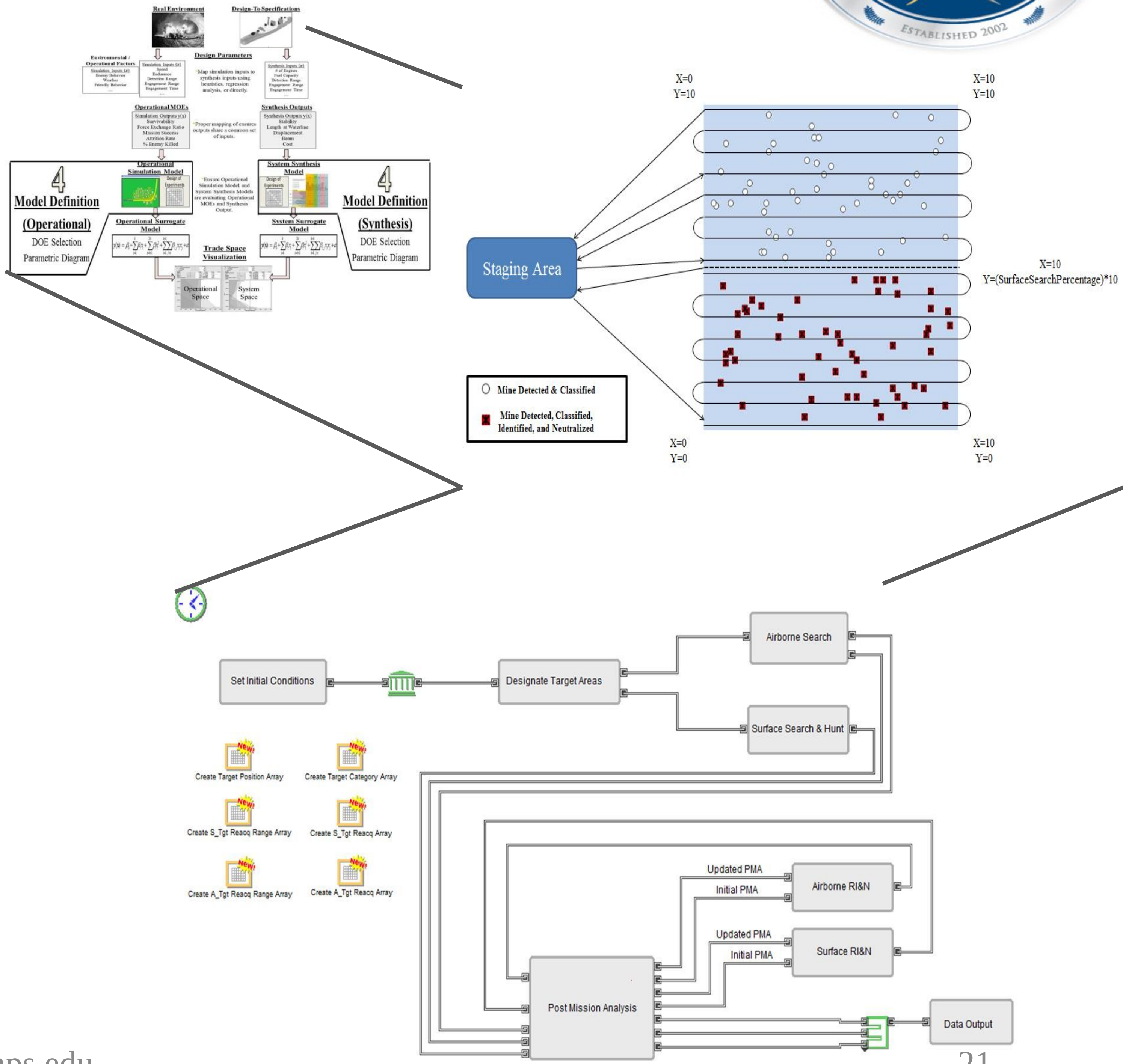




MBSE MEASA (Step 4)

Step 4: Model Definition

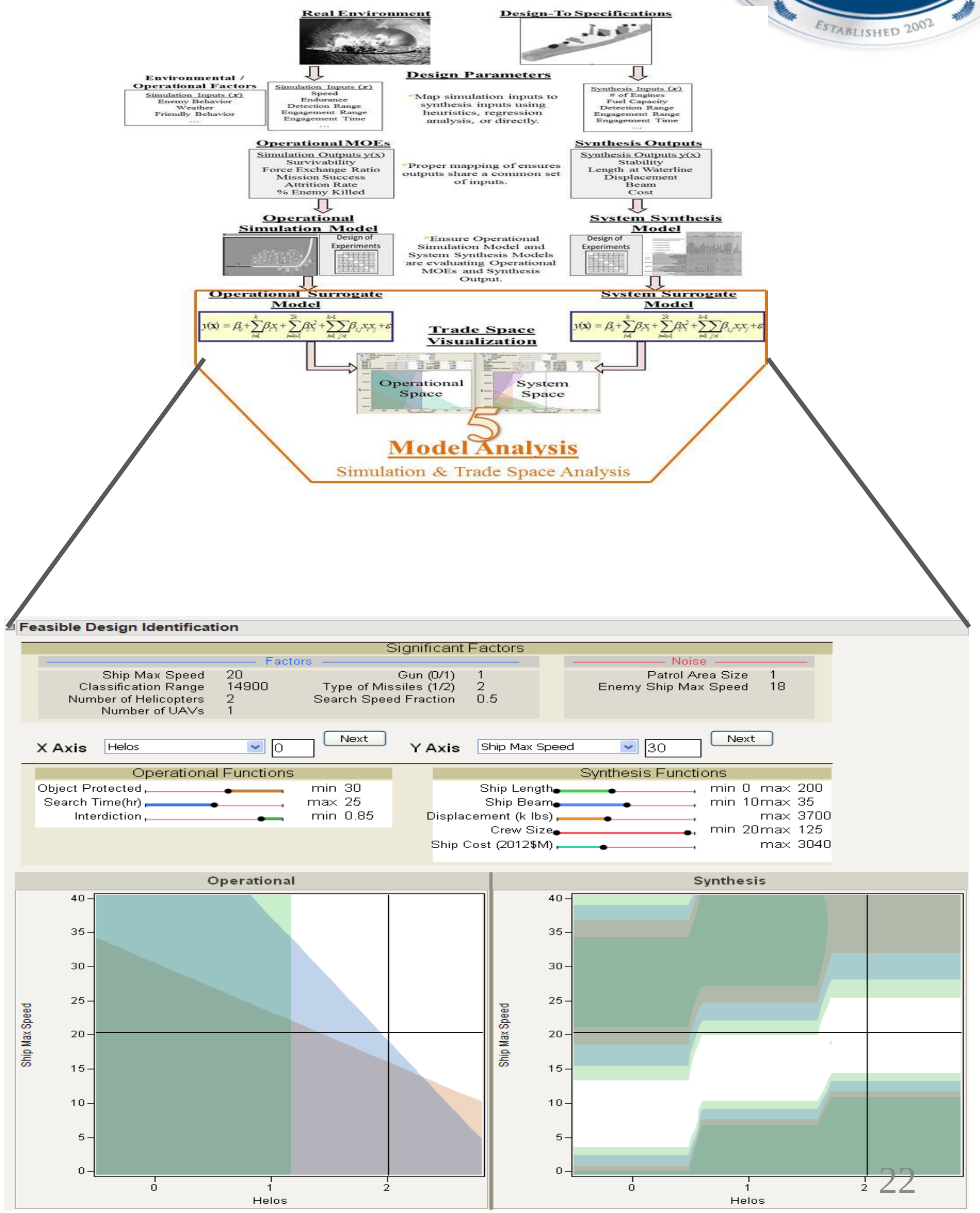
- Block Definition and Internal Block Diagrams describe the set of physical components must be represented in any external models
- Activity, Sequence, Use Case, and State Machine Diagrams specify the behaviors that must be represented in any external models
- Discrete Event Models
  - Process Oriented, Top-Down Model Construction, Limited Entity Autonomy, Pre-scripted Events
- Agent Based Models
  - Behavior Oriented, Bottom-Up Model Construction, Active Entity Decision Making, Non-Fixed Event Structure



MBSE MEASA (Step 5)

Step 5: Model Analysis

- The goal of model analysis is evaluation of how well the Physical Architecture combinations (Step 3) satisfy the Functional Architecture (Step 2) define system performance
- The model analysis process should include a mechanism for simultaneous display of the results of the operational simulation models and the system synthesis models
  - Surrogate models, based on model analysis, can facilitate rapid visualization of these results
  - Operational constraints can be introduced for the operational models
  - System constraints can be introduced for the system synthesis models
- Dynamic Decision Making Displays are capable of illuminating system tradespace decisions



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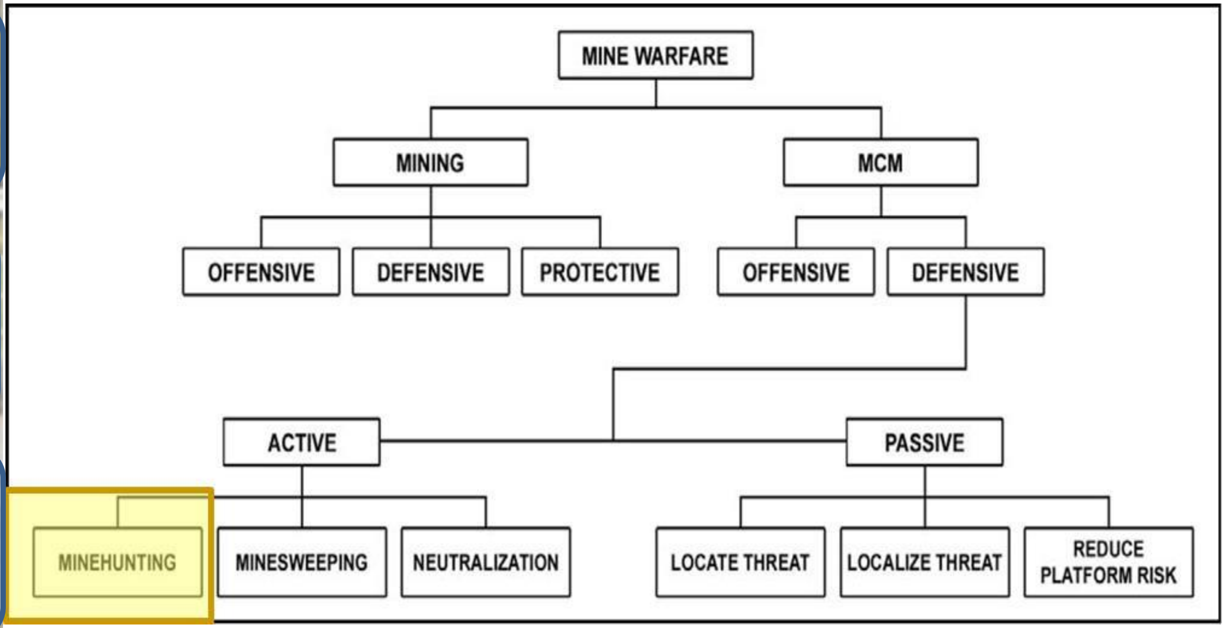
Mine Warfare Overview

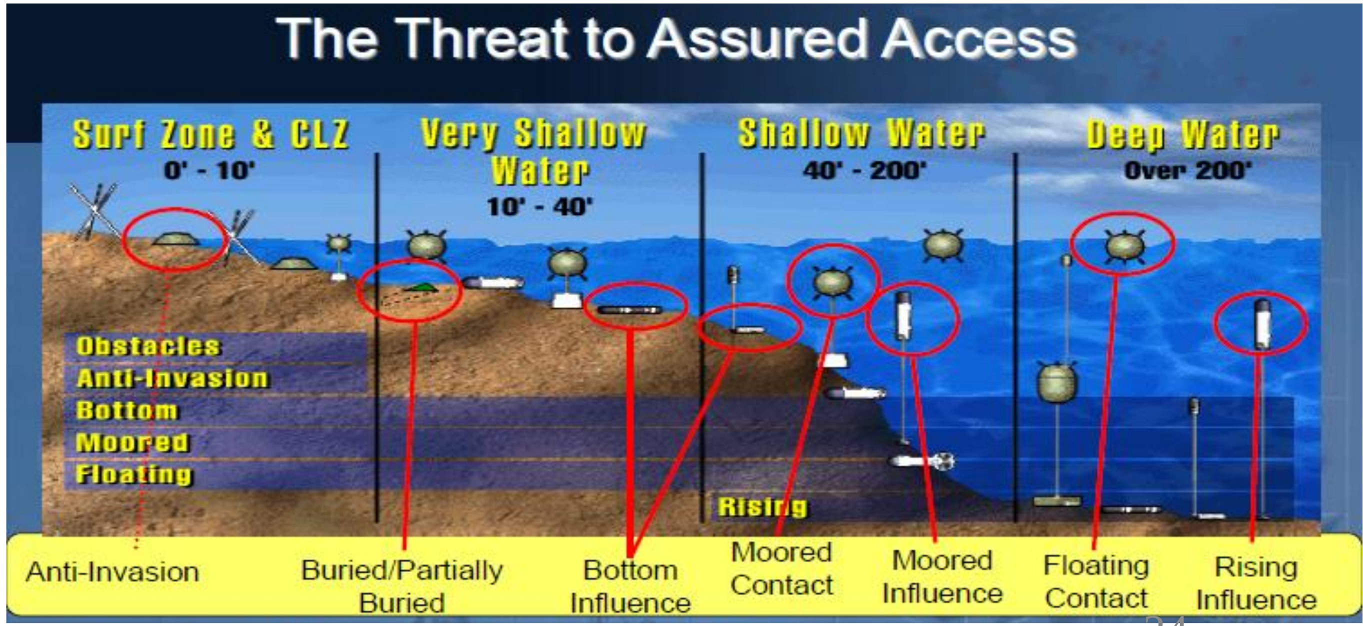
MIW Activities

- MIW encompasses both Mining and Mine countermeasures (MCM)
- MCM can be either offensive or defensive
- Defensive MCM can be either Active or Passive

Types of Mines

- This study focuses solely on influence mines (rather than contact mines)
- This study focuses on mines in Deep Water (Over 200 feet)
- This study assumes all surface mines have been cleared

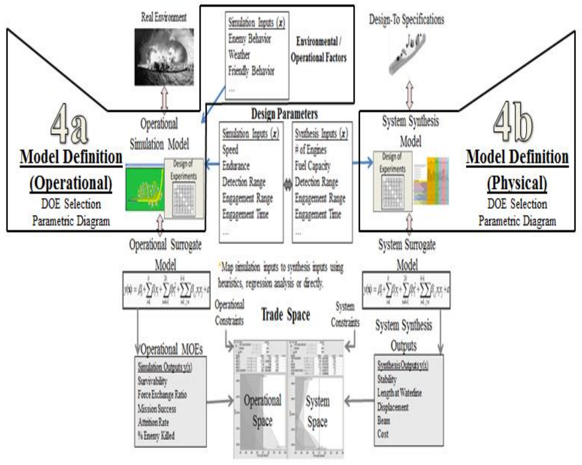


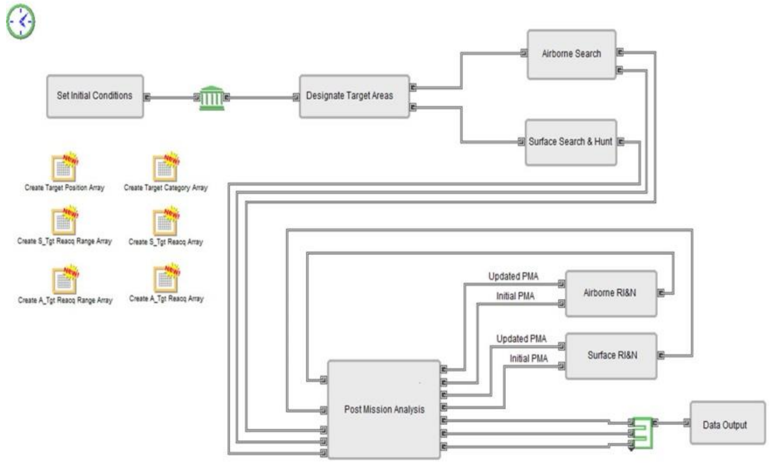


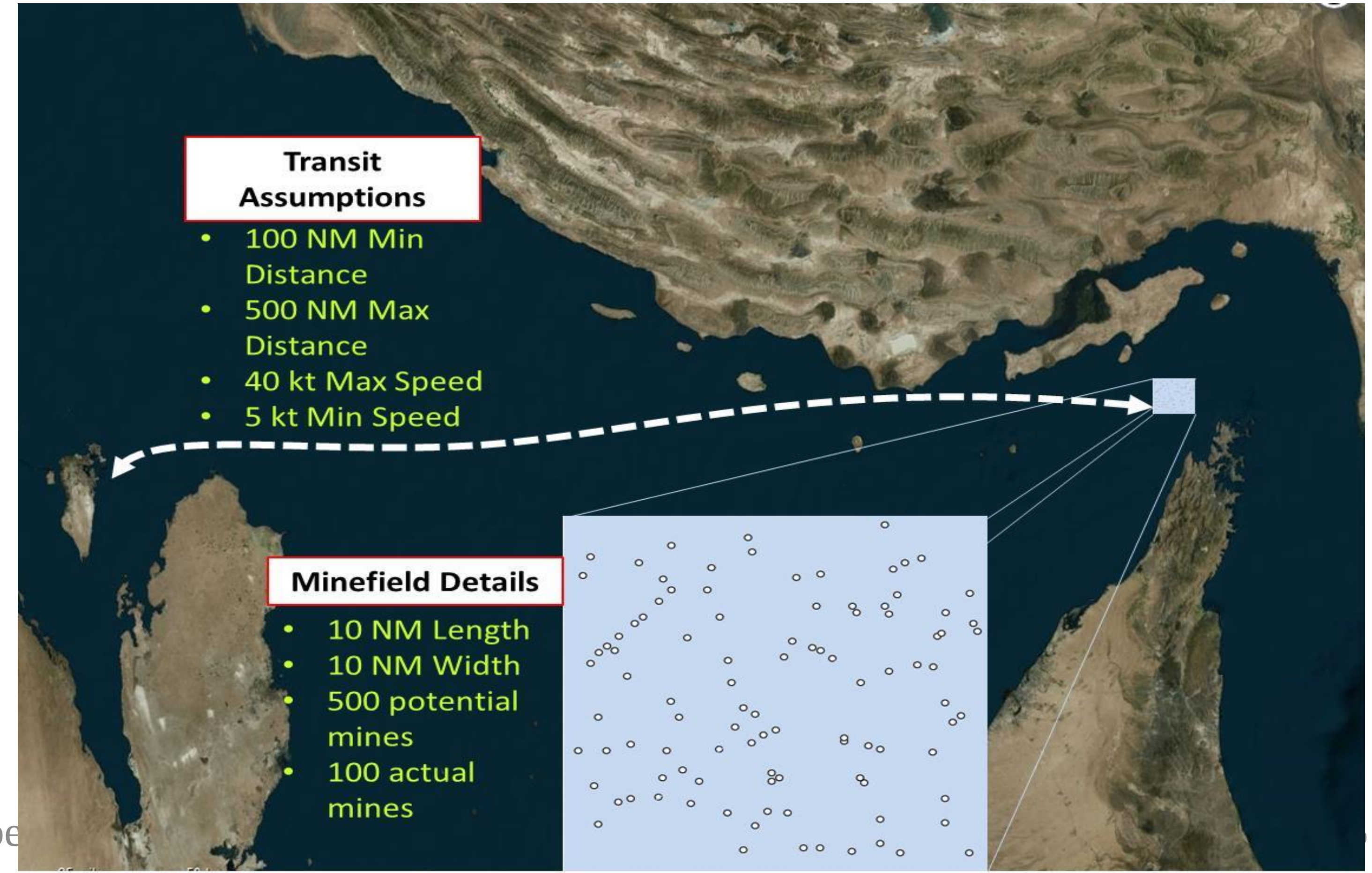
Model Representation

Active, Defensive MCM Operations Model

- The simulation model must represent three distinct stages of operation
  - Transit to the minefield
  - Minehunting
  - Mine Neutralization
- Physical systems must exist in the simulation to conduct:
  - Transit
  - Mine Detection
  - Mine Classification
  - Mine Identification
  - Mine Neutralization
- To ensure that the results are as generalizable as possible:
  - Transit distance is varied
  - Transit speed is varied







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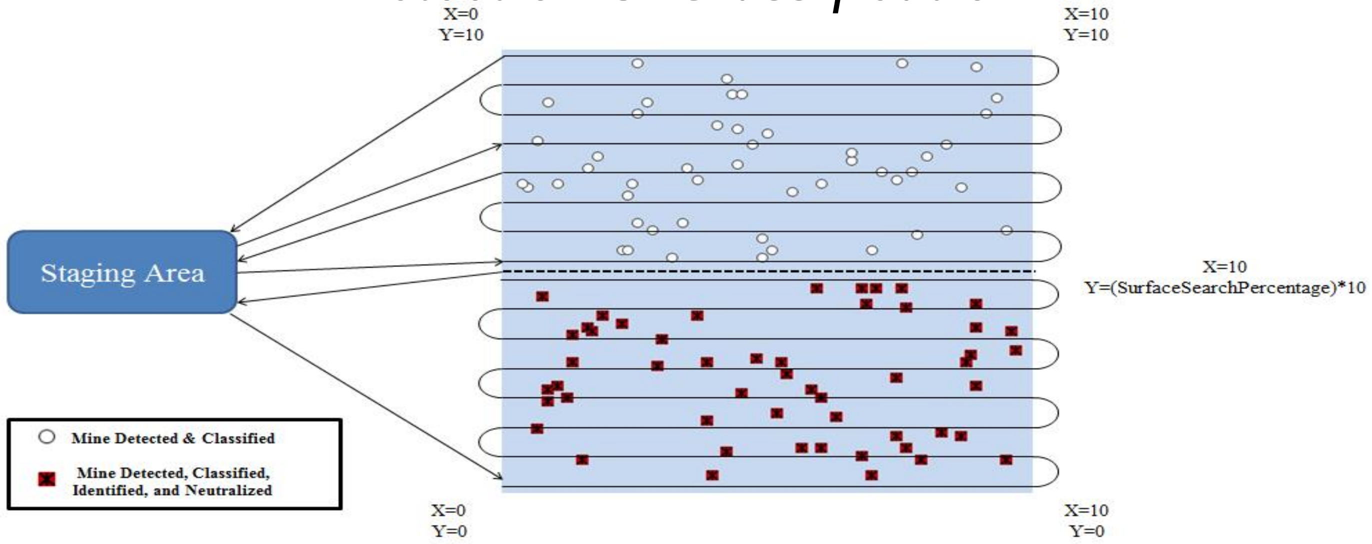
Model Representation: MCM-1 Configurations

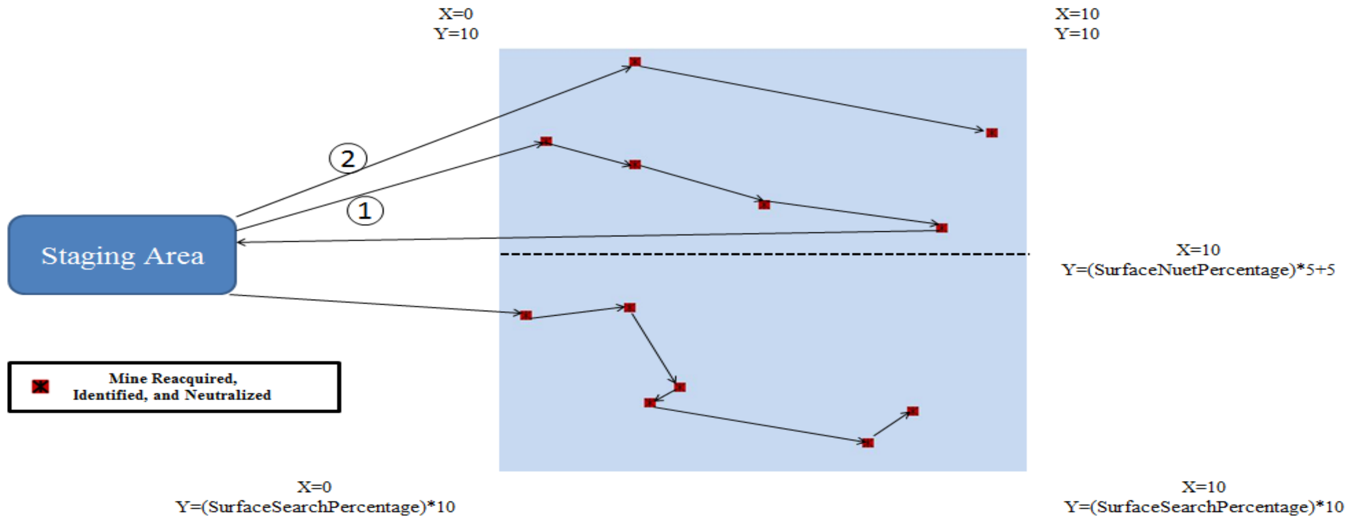
<u>Active, Defensive MCM using MCM-1 Avenger</u>

- The minefield is divided into two portions, one for the MCM-1 and one for the MH-53E
- Mines passed through the simulation in the MCM-1 Avenger area proceed through:
  - Detection (Potential Mines → MILECs)
  - Classification (MILECs → MILCOs)
  - Identification (MILCOs → Identified Mine)
  - Neutralization (Identified Mines → Neutralized Mines)
- After Post Mission Analysis (PMA) a list of MILCOs to be reacquired is populated, again the percentage assigned to each asset is varied
  - The systems no longer proceed from left to right, rather a nearest neighbor algorithm populates a target list
  - Each target undergoes Reacquisition, Identification, and Neutralization

Detection & Classification



Identification & Neutralization

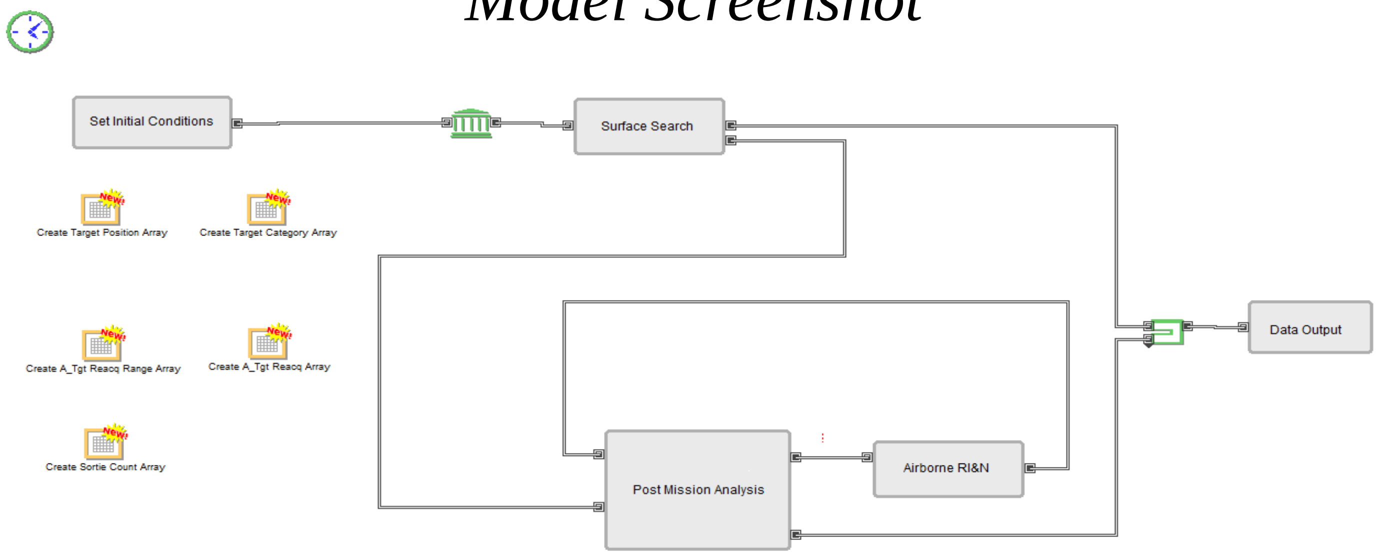


Model Representation: LCS Configurations

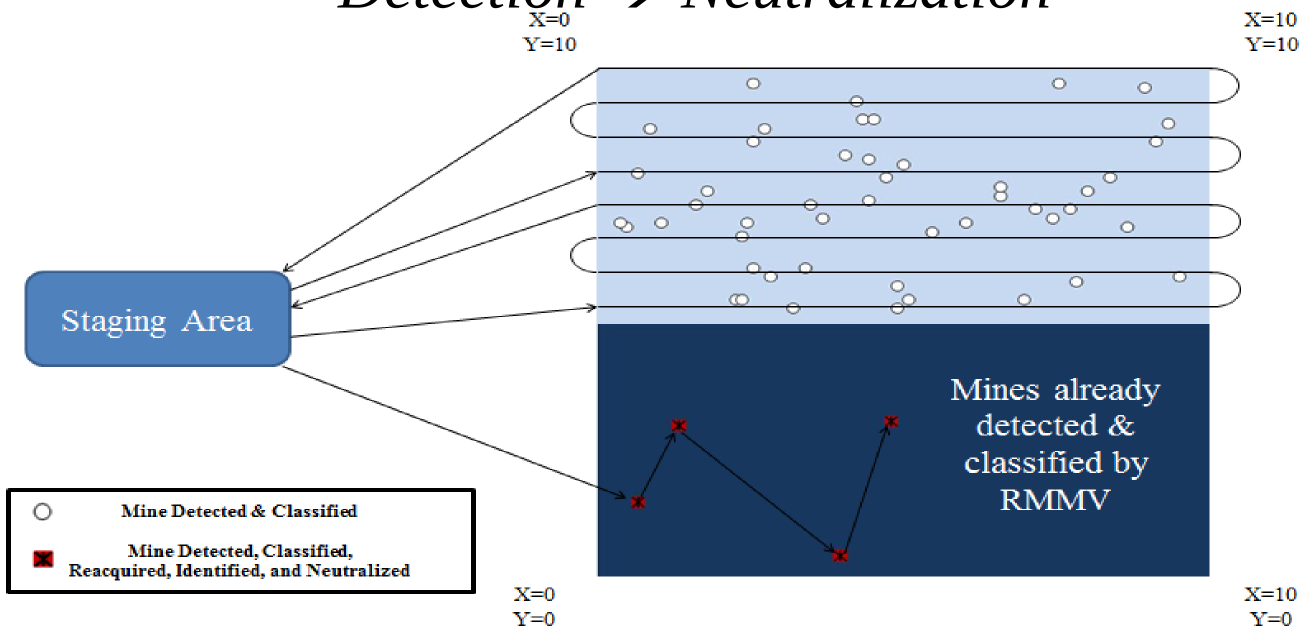
Active, Defensive MCM using Littoral Combat Ship

- The minefield is searched by a Remote Multi-Mission Vehicle (RMMV)
  - Operation of the RMMV is nearly equivalent to the MH-53E from the MCM-1 configurations (MH-53E can end sortie on either side of minefield, RMMV cannot)
- After Post Mission Analysis (PMA) a list of MILCOs to be reacquired is populated, a MH-60S then proceeds through neutralization
  - The MH-60S is capable of searching a portion of the minefield that has already been searched while the RMMV continues to search another portion of the minefield
  - Each target undergoes Reacquisition, Identification, and Neutralization
  - This actually results in a simplified simulation even though it is practically considered more difficult

Model Screenshot



Detection → Neutralization



Variable Identification

MCM-1 Configuration Variables

- 51 Input Variables
- Multiple hunting assets → additional variables

LCS Configuration Variables

- 32 Input Variables
- Dedicated search & hunt assets

MCM-1 Configurations

Surface Asset Variables			Airborne Asset Variables		
Variable	Minimum	Maximum	Variable	Minimum	Maximum
Logistics Variables			**Logistics Variables**		
Transit to Area Speed (kts)	5	10	Transit to Area Speed (kts)	N/A	N/A
Transit to Minefield Speed (kts)	5	15	Transit to Minefield Speed (kts)	90	180
Search Gear Stream Time (hrs)	0.25	2	Search Gear Stream Time (hrs)	0.2	0.5
Search Gear Recovery Time (hrs)	0.25	2	Search Gear Recovery Time (hrs)	0.2	0.5
Turn Time (seconds)	300	600	Turn Time (seconds)	120	240
Maintenance Time (hours)	24	48	Maintenance Time (hours)	1	2
Sortie Time (hours)	350	500	Sortie Time (hours)	3	5
RI&N Deployment Time (hours)	0.1	2	RI&N Deployment Time (hours)	0.25	0.5
RI&N Recovery Time (hours)	0.1	2	RI&N Recovery Time (hours)	0.25	0.5
Hunting & Neutralization Variables			**Hunting & Neutralization Variables**		
Search Speed (kts)	2.5	5	Search Speed (kts)	15	30
Number of Tracks (per NM)	20	25	Number of Tracks (per NM)	20	25
Probability of Detection	0.7	0.9	Probability of Detection	0.7	0.9
Probability of Classification (Mine as MILCO)	0.7	0.9	Probability of Classification (Mine as MILCO)	0.7	0.9
Probability of Classification (Non-Mine as Non-MILCO)	0.7	0.9	Probability of Classification (Non-Mine as Non-MILCO)	0.7	0.9
Probability of Reacquisition (MILCO)	0.7	0.9	Probability of Reacquisition (MILCO)	0.7	0.9
Probability of Reacquisition (Non-MILCO)	0.1	0.2	Probability of Reacquisition (Non-MILCO)	0.1	0.2
Probability of Identification (MILCO)	0.7	1	Probability of Identification (MILCO)	0.7	1
Probability of Identification (Non-MILCO)	0.7	1	Probability of Identification (Non-MILCO)	0.7	1
Probability of Neutralization	0.7	1	Probability of Neutralization	0.7	1
Reaquisition and Identification Mean Time (hours)	0.25	1	Reaquisition and Identification Mean Time (hours)	0.25	0.5
Reaquisition and Identification Standard Deviation (hours)	0.1	0.5	Reaquisition and Identification Standard Deviation (hours)	0.1	0.25
Neutralization Mean Time (hours)	0.25	1	Neutralization Mean Time (hours)	N/A	N/A
Neutralization Standard Deviation (hours)	0.1	0.5	Neutralization Standard Deviation (hours)	N/A	N/A
Neutralizer Speed (kts)	2.5	5	Neutralizer Speed (kts)	2.5	5

Environmental Variables

Variable	Minimum	Maximum
Number of Minefield Passes	1	3
Transit Distance (miles)	100	500
Staging Area Distance (miles)	10	20
Surface Search Percentage	0.3	0.7
Surface Neutralization Percentage	0.3	0.7

LCS Configurations

Surface Asset Variables			Airborne Asset Variables		
Variable	Minimum	Maximum	Variable	Minimum	Maximum
Logistics Variables			**Logistics Variables**		
Transit to Area Speed (kts)	15	40	Transit to Area Speed (kts)	N/A	N/A
Transit to Minefield Speed (kts)	10	40	Transit to Minefield Speed (kts)	90	180
Search Gear Stream Time (hrs)	0.25	2	Search Gear Stream Time (hrs)	N/A	N/A
Search Gear Recovery Time (hrs)	0.25	2	Search Gear Recovery Time (hrs)	N/A	N/A
Turn Time (seconds)	300	600	Turn Time (seconds)	120	240
Maintenance Time (hours)	2	4	Maintenance Time (hours)	1	2
Sortie Time (hours)	10	20	Sortie Time (hours)	3	5
RI&N Deployment Time (hours)	N/A	N/A	RI&N Deployment Time (hours)	0.25	0.5
RI&N Recovery Time (hours)	N/A	N/A	RI&N Recovery Time (hours)	0.25	0.5
Hunting & Neutralization Variables			**Hunting & Neutralization Variables**		
Search Speed (kts)	5	15	Search Speed (kts)	15	30
Number of Tracks (per NM)	20	25	Number of Tracks (per NM)	N/A	N/A
Probability of Detection	0.7	0.9	Probability of Detection	N/A	N/A
Probability of Classification (Mine as MILCO)	0.7	0.9	Probability of Classification (Mine as MILCO)	N/A	N/A
Probability of Classification (Non-Mine as Non-MILCO)	0.7	0.9	Probability of Classification (Non-Mine as Non-MILCO)	N/A	N/A
Probability of Reacquisition (MILCO)	N/A	N/A	Probability of Reacquisition (MILCO)	0.7	0.9
Probability of Reacquisition (Non-MILCO)	N/A	N/A	Probability of Reacquisition (Non-MILCO)	0.1	0.2
Probability of Identification (MILCO)	N/A	N/A	Probability of Identification (MILCO)	0.7	1
Probability of Identification (Non-MILCO)	N/A	N/A	Probability of Identification (Non-MILCO)	0.7	1
Probability of Neutralization	N/A	N/A	Probability of Neutralization	0.7	1
Reaquisition and Identification Mean Time (hours)	N/A	N/A	Reaquisition and Identification Mean Time (hours)	0.25	0.5
Reaquisition and Identification Standard Deviation (hours)	N/A	N/A	Reaquisition and Identification Standard Deviation (hours)	0.1	0.25
Neutralization Mean Time (hours)	N/A	N/A	Neutralization Mean Time (hours)	0.25	1
Neutralization Standard Deviation (hours)	N/A	N/A	Neutralization Standard Deviation (hours)	0.1	0.5
Neutralizer Speed (kts)	N/A	N/A	Neutralizer Speed (kts)	2.5	5

Environmental Variables

Variable	Minimum	Maximum
Number of Minefield Passes	1	3
Transit Distance (miles)	100	500
Staging Area Distance (miles)	10	20
Surface Search Percentage	0.3	0.7
Surface Neutralization Percentage	0.3	0.7

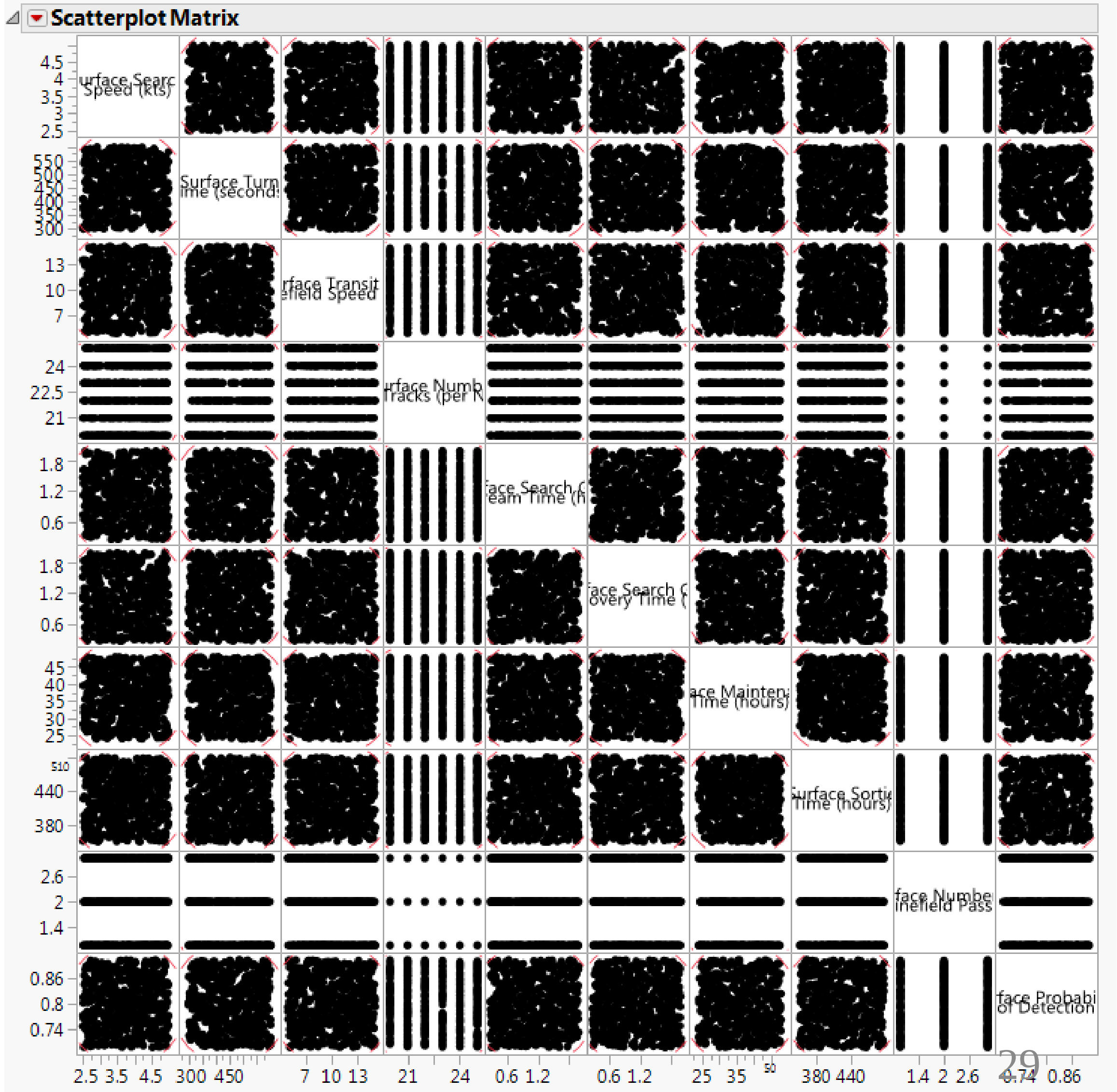
Experimental Design Selection

Nearly Orthogonal Nearly Balanced Designs

- Proper experimental design selection is vital to the analysis of detailed simulation models
- Establishing a baseline and testing individual excursions is inappropriate
- Simulation models allow for the examination of a very large number of variables and allow for many simulation runs to be conducted
- Space Filling Designs allow for this examination of a large number of variables as well as offer tremendous flexibility in terms of model fitting based on the output data
- Nearly Orthogonal Nearly Balanced Designs accommodate up to 300 factors (the factors may be either continuous or discrete)
- This research used such a design (requiring 512 design points) and conducted 30 replications of each design point for both the LCS and MCM-1 configuration models

Specific Implementation

- 512 Design Points Required
- 30 replications using 2 simulations
- 30,720 total model runs



Experimental Design Generation

- It may be necessary to generate a custom design in two cases:
  - More than 300 factors of interest
  - More than 20 levels for a factor with a given level
- This can be expanded utilizing a mixed integer approach specified by Vieira (2011)
  - Requires the use of licensed software
- Evolutionary algorithms offer an alternative
  - First demonstrated by Mitchell (1974)
  - Recently implemented at NPS by MacCalman (2013)

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Genetic Algorithm Basics

- Genetic algorithms are a subset of evolutionary algorithms that follow a standard generic process
  - An initial set of candidate solutions (in the case of experimental designs, potential columns of the design matrix) are generated
    - This is referred to as the first generation
  - Each individual (in the case of experimental designs, each candidate column) in that generation is evaluated based on a predefined fitness function
  - Individuals with higher fitness values are selected and their characteristics are modified (either through mutation or recombination, as in traditional biology) and saved to create a second generation
  - The process is repeated for the second generation
  - The algorithm terminates after identifying a solution that meets a predefined fitness function value or after a predefined time period

Design Criteria for Experimental Designs

- Specification of acceptance criteria is the first step in implementation of a genetic algorithm
- Two criteria were proposed in Vieira (2011) that work well
  - Orthogonality
    - Assessed through the maximum absolute pairwise correlation between any two columns of the design matrix

Correlation Between Two Columns

$$\rho_{xy} = \frac{\sum_{i=0}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left(\sum_{i=0}^{n}(x_i - \bar{x})^2\right)\left(\sum_{i=0}^{n}(y_i - \bar{y})^2\right)}}$$

Maximum Absolute Pairwise Correlation

$$\rho_{map} = \max\left\{\left|\rho_{xy}\right|, \forall(x \neq y)\right\}$$

  - Imbalance
    - Assessed as the maximum imbalance within a given candidate column

Imbalance of a Given Column

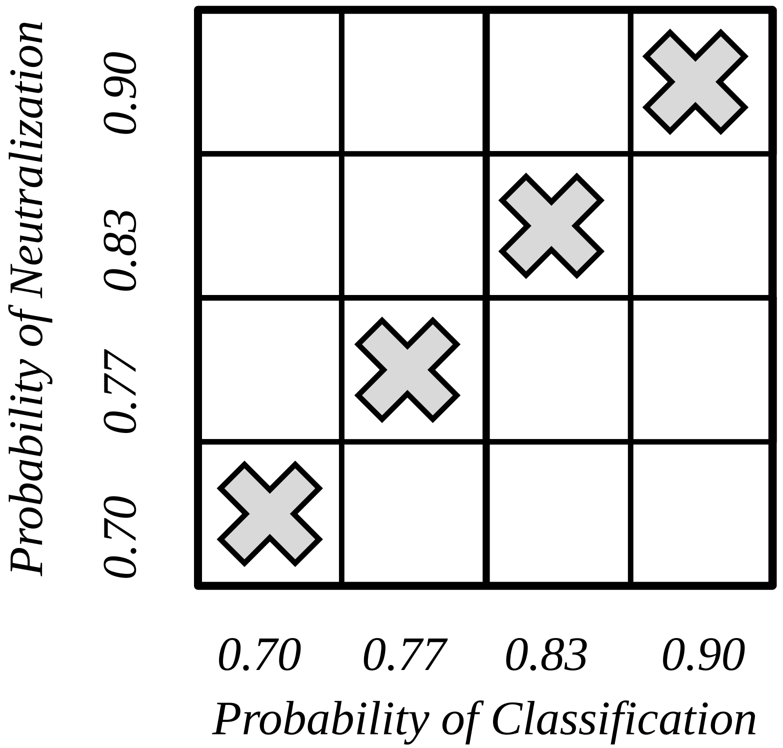
$$\delta_x = \max_{l=1,\ldots,\beta_x}\left|\frac{\omega_{xl} - \left(\frac{n}{\beta_x}\right)}{\left(\frac{n}{\beta_x}\right)}\right|$$

Maximum Imbalance

$$\delta = \max\left\{\delta_x, x = 1,\ldots,k\right\}$$

Design Criteria Simplification

- Consider a minehunting system defined by two systems, a classification system and a neutralization system
  - Assume that each system can take four discrete values (0.70, 0.77, 0.83, 0.90)
  - Assume that only four tests are possible (even though there are sixteen possible combinations)
  - How should we select the tests?
- This is an example of four test points that, when assessed by the correlation criterion, would demonstrate a correlation of 1.0 (perfect correlation…which is a bad thing)
- These four test points actually have zero imbalance (which is a good thing)



Correlation Between Two Columns

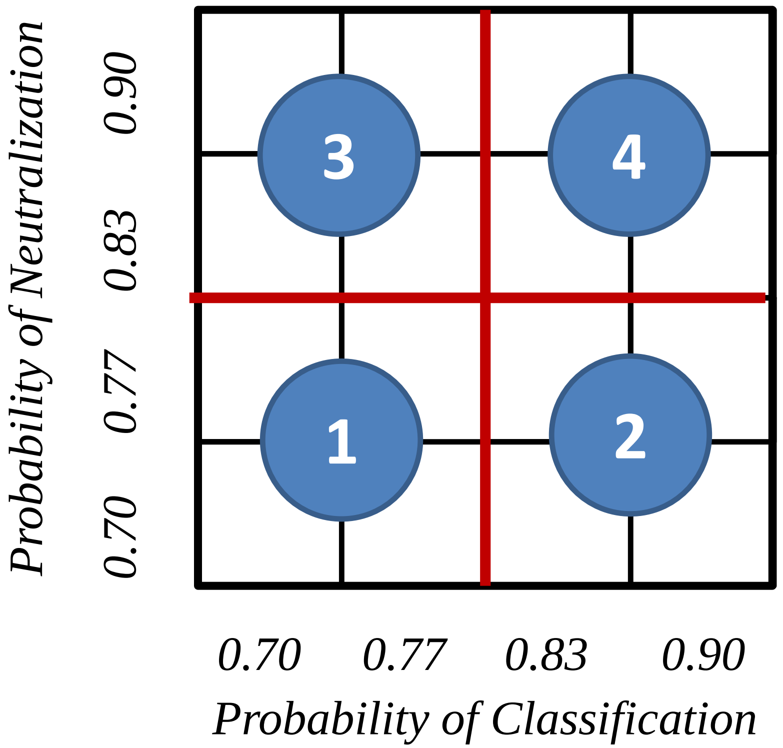
$$\rho_{xy} = \frac{\sum_{i=0}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left(\sum_{i=0}^{n}(x_i - \bar{x})^2\right)\left(\sum_{i=0}^{n}(y_i - \bar{y})^2\right)}}$$

Imbalance of a Given Column

$$\delta_x = \max_{l=1,\ldots,\beta_x} \left| \frac{\omega_{xl} - \left(\frac{n}{\beta_x}\right)}{\left(\frac{n}{\beta_x}\right)} \right|$$

Design Criteria Simplification (2)

- Consider a minehunting system defined by two systems, a classification system and a neutralization system
  - Assume that each system can take four discrete values (0.70, 0.77, 0.83, 0.90)
  - Assume that only four tests are possible (even though there are sixteen possible combinations)
  - How should we select the tests?
- A design that performs well with respect to the imbalance criterion will only test once in each column
- A design that performs well with respect to correlation will only test once in each zone
  - Now we're solving a Su-Do-Ku



Correlation Between Two Columns

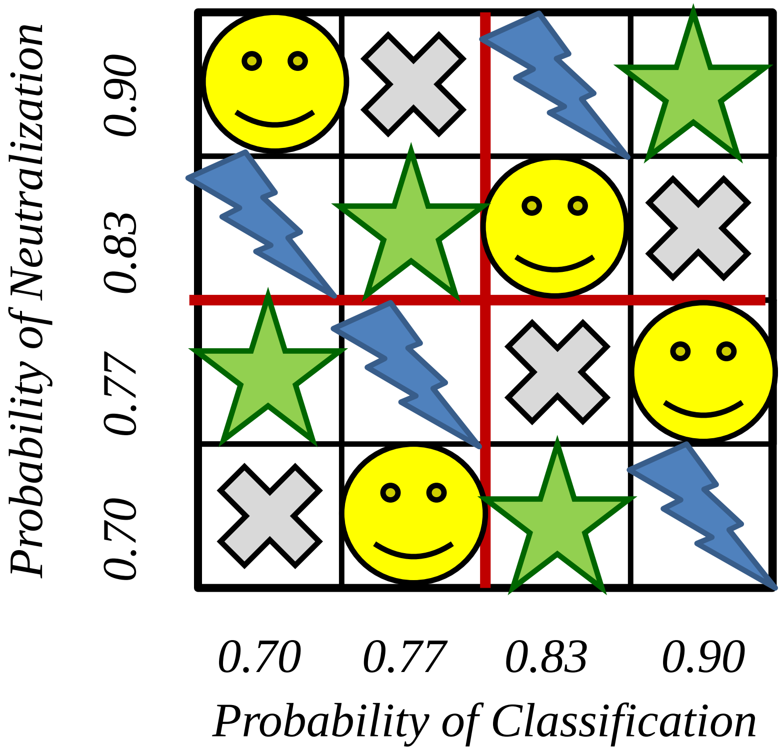
$$\rho_{xy} = \frac{\sum_{i=0}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left(\sum_{i=0}^{n}(x_i - \bar{x})^2\right)\left(\sum_{i=0}^{n}(y_i - \bar{y})^2\right)}}$$

Imbalance of a Given Column

$$\delta_x = \max_{l=1,\dots,\beta_x} \left| \frac{\omega_{xl} - \left(\frac{n}{\beta_x}\right)}{\left(\frac{n}{\beta_x}\right)} \right|$$

Design Criteria Simplification (3)

- Consider a minehunting system defined by two systems, a classification system and a neutralization system
  - Assume that each system can take four discrete values (0.70, 0.77, 0.83, 0.90)
  - Assume that only four tests are possible (even though there are sixteen possible combinations)
  - How should we select the tests?
- A design that performs well with respect to the imbalance criterion will only test once in each column
- A design that performs well with respect to correlation will only test once in each zone
  - Now solutions become readily apparent



Correlation Between Two Columns

$$\rho_{xy} = \frac{\sum_{i=0}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\left(\sum_{i=0}^{n}(x_i-\bar{x})^2\right)\left(\sum_{i=0}^{n}(y_i-\bar{y})^2\right)}}$$

Imbalance of a Given Column

$$\delta_x = \max_{l=1,\dots,\beta_x} \left| \frac{\omega_{xl} - \left(\frac{n}{\beta_x}\right)}{\left(\frac{n}{\beta_x}\right)} \right|$$

Genetic Algorithm Results

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- Results: The genetic algorithm approach provides a mechanism for supplementing existing NO/B designs as well as generating new NO/B experimental designs.
- The algorithm was then used to create designs for 1,000 factors.
  - The total number of runs (n) for a k-factor experimental design should fall in the range $3k \leq n \leq 10k$.
- Accordingly a 4,000 run design for 1,000 factors was generated
- The design had a ρ_{map} value of 0.072 and a maximum imbalance (δ) of 0.089

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Initial Model Analysis

Effectiveness Definition: Measures of Effectiveness (MOEs) are required to assess the ability of each MCM configuration to complete an Active, Defensive MCM Operation

Approach: As with the architecture development, MOEs are taken from mine warfare guidance, in particular NWP 3-15. Traditional mine warfare analysis focuses on the idea of "residual risk," informally defined as the probability that something remains in the minefield. The system architecture definition, which presented logistics functions beyond the traditional scope of MCM analysis (specifically the transit to the minefield) suggested that additional MOEs are required

MOE 1: *Percentage of Mines Cleared*

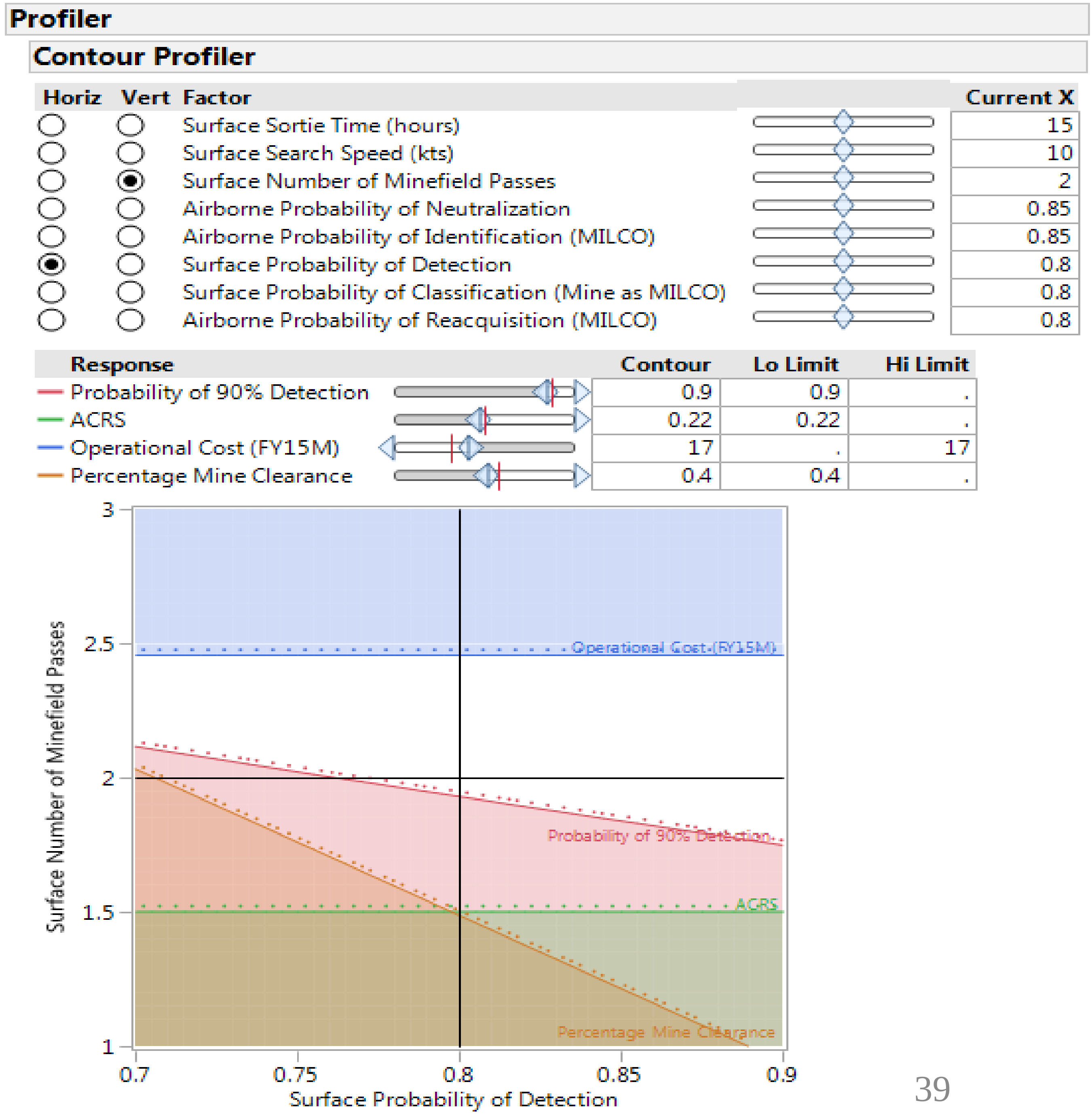
MOE 2: *Probability of 90% Mine Detection*

MOE 3: *Area Coverage Rate Sustained (ACRS)*

Tradespace Analysis: LCS

LCS Configuration Tradespace Visualization

- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.22
  - Operational Cost less than $17M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the right
- Many two dimensional projections are possible, this visualization presents the Probability of Detection (x-axis) and the Number of Minefield Passes (y-axis)
- This “feasible space” exists assuming that each of the other system design parameters are held constant at the values shown in the upper right



Tradespace Analysis: LCS (2)

LCS Configuration Tradespace Visualization

- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.22
  - Operational Cost less than $17M
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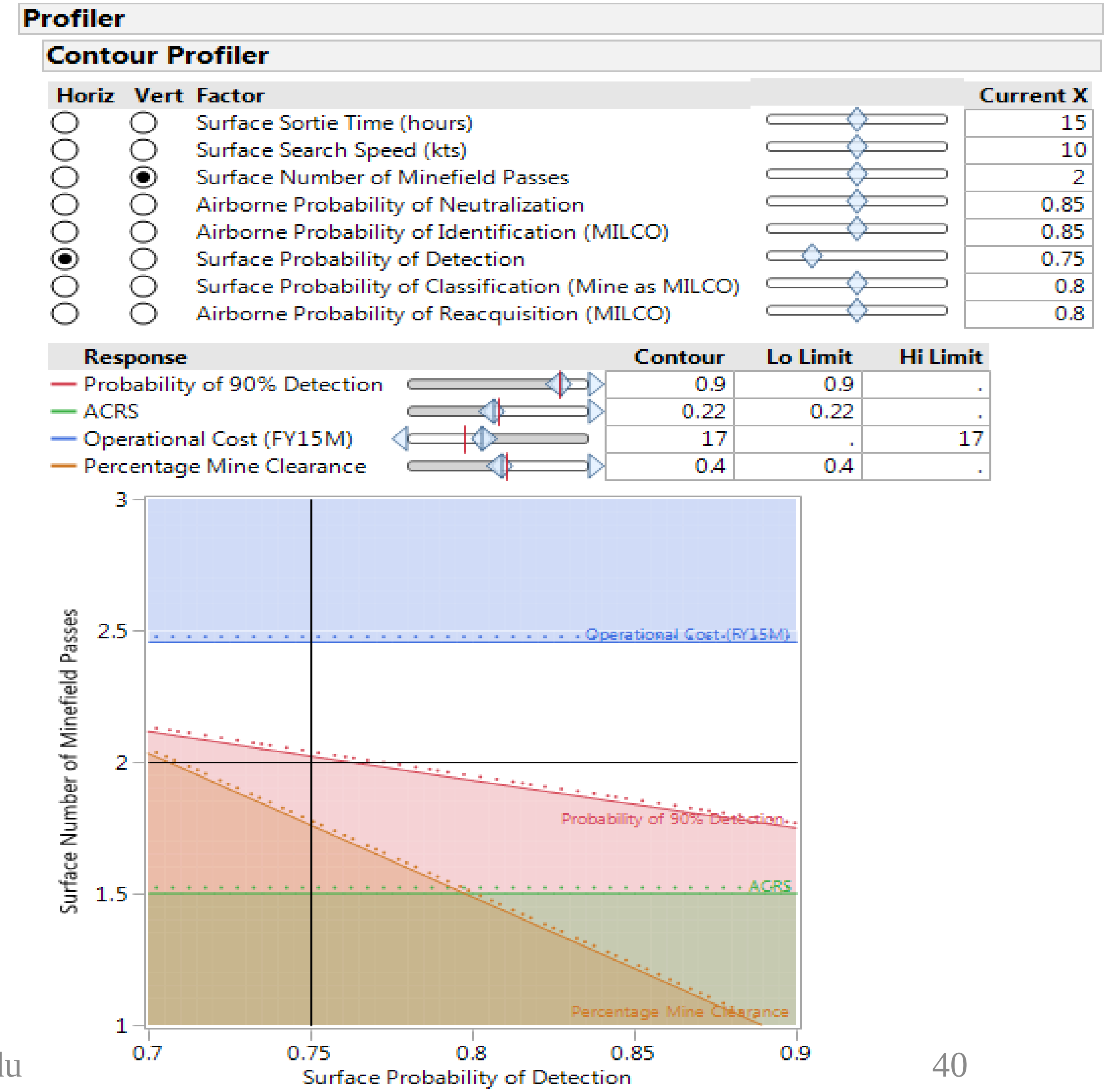

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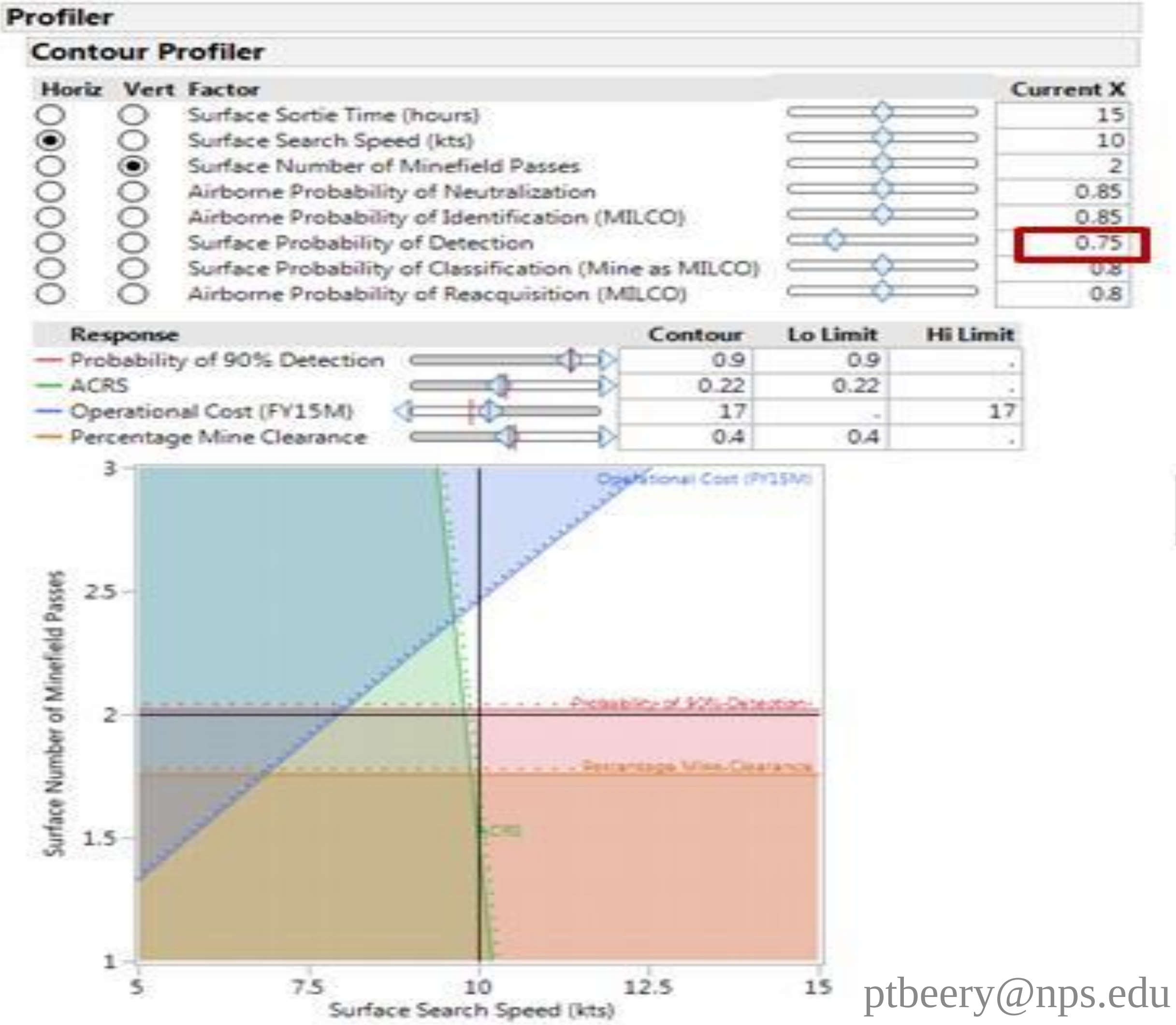
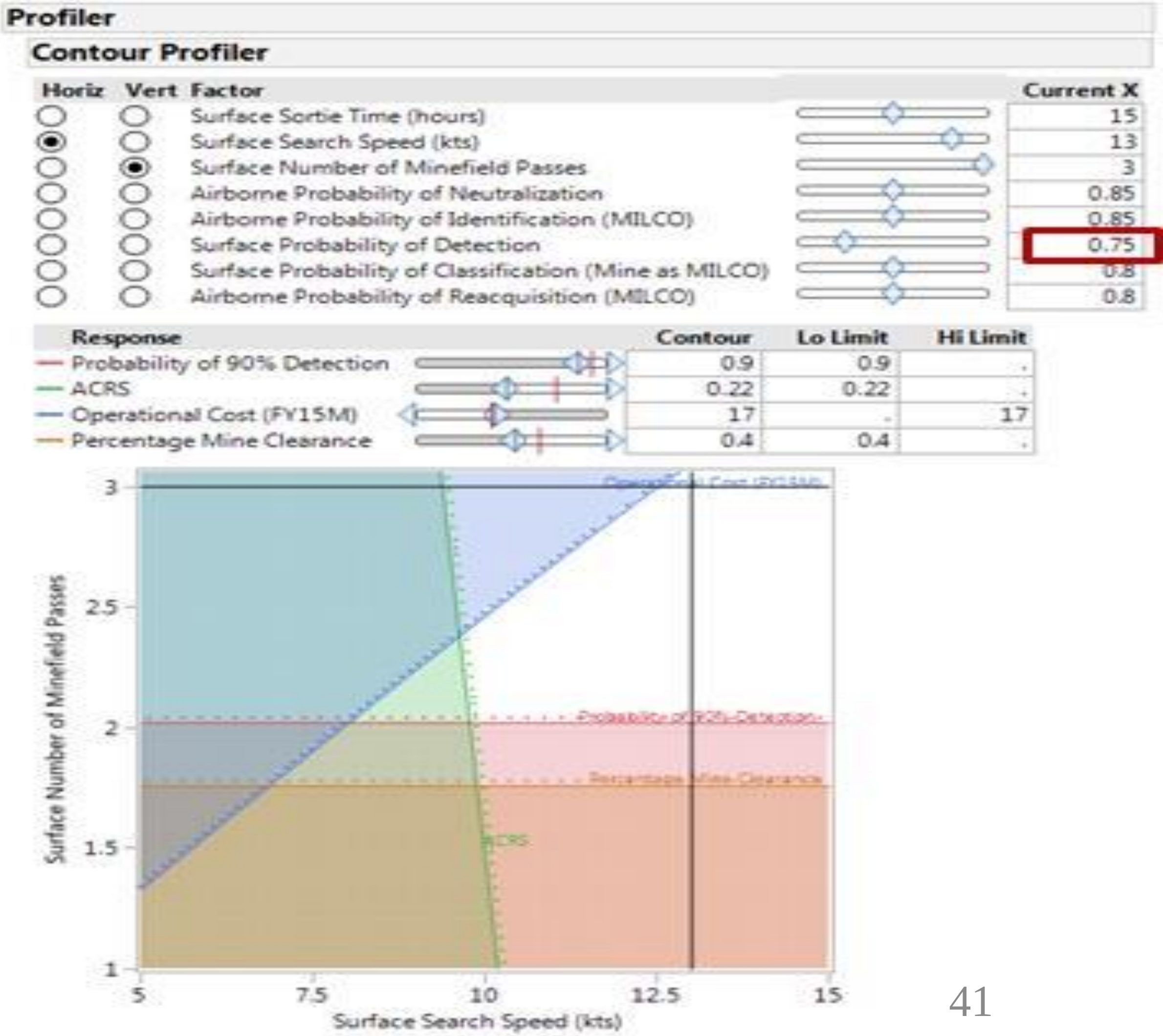
Tradespace Analysis: LCS (3)

- The reduction of the Probability of Detection to 0.75 can be mitigated by altering the value of other potential design parameters
- This type of exploration allows for the identification of trades and alterations that are realistic as well as ones that are not realistic
- Increasing the Surface Search Speed to 13 knots allows for acceptable performance with a third minefield pass





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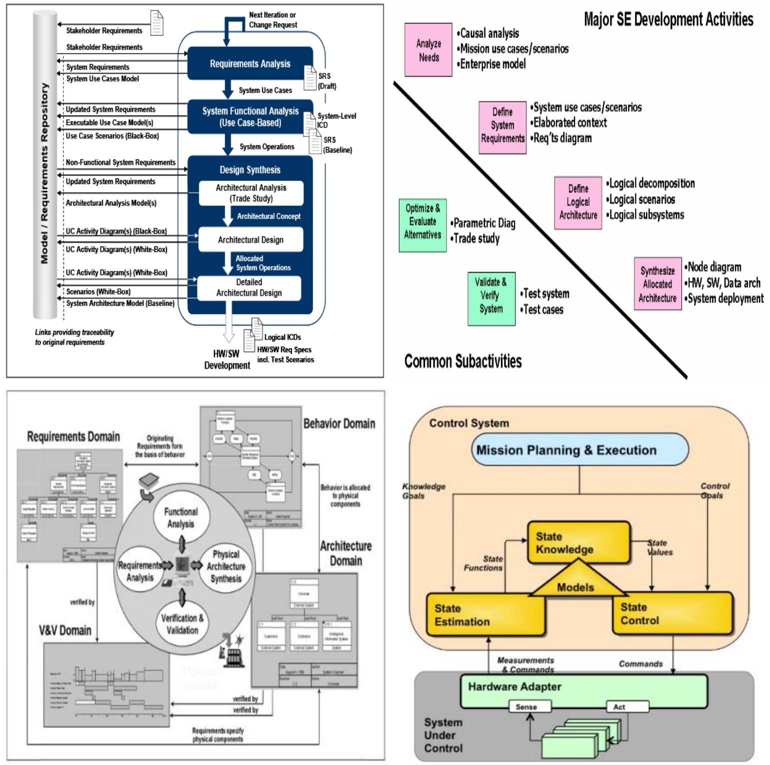
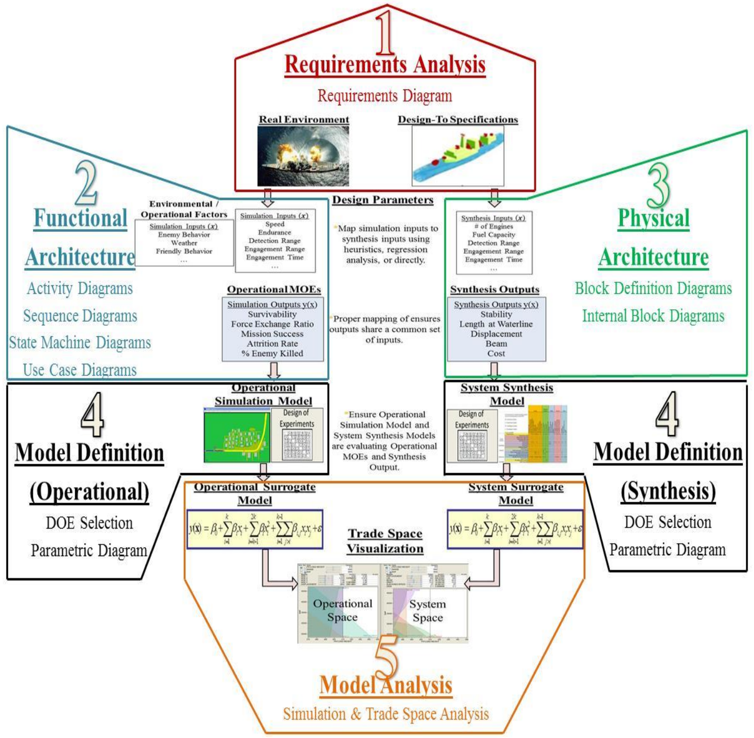
Research Summary

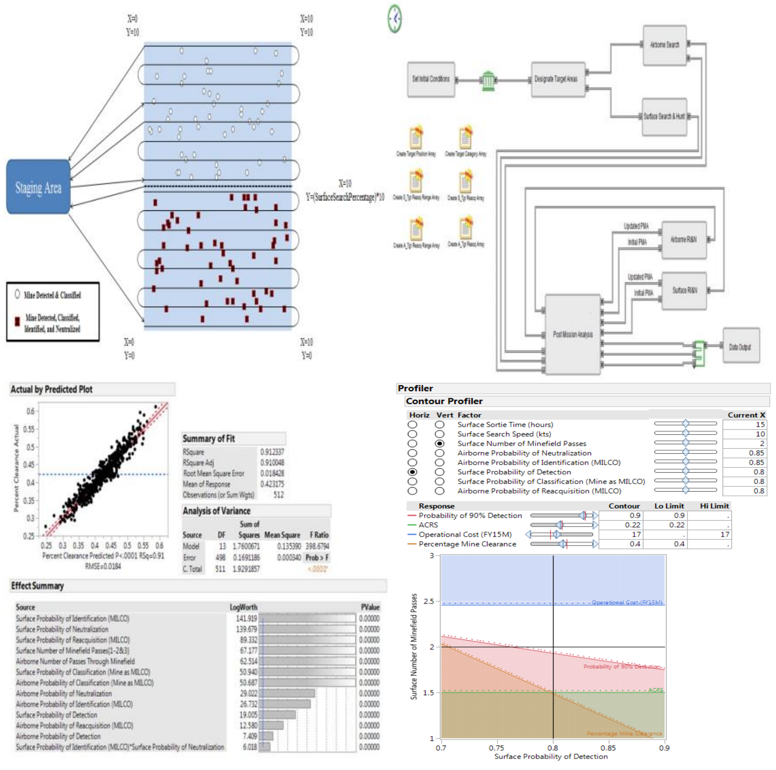
The MBSE MEASA developed in this research expands the utility of existing MBSE methodologies by prescribing how functional and physical architectures can be used to define external performance models which allow for examination of system performance in greater detail (by examining a larger number of system design variables, environmental variables, and operational variables)



The MBSE MEASA Offers Expanded Utility…



Through external simulation models…



To Facilitate Detailed Analysis

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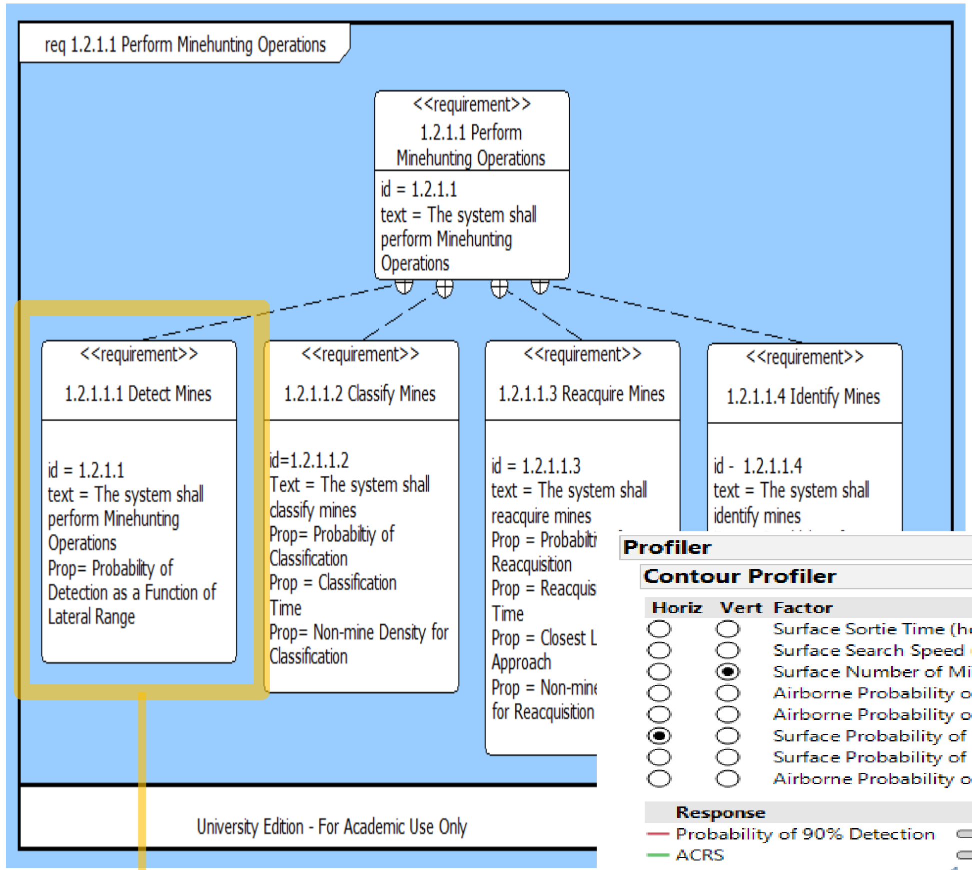
Intended Benefits of MBSE: Evaluate the Research

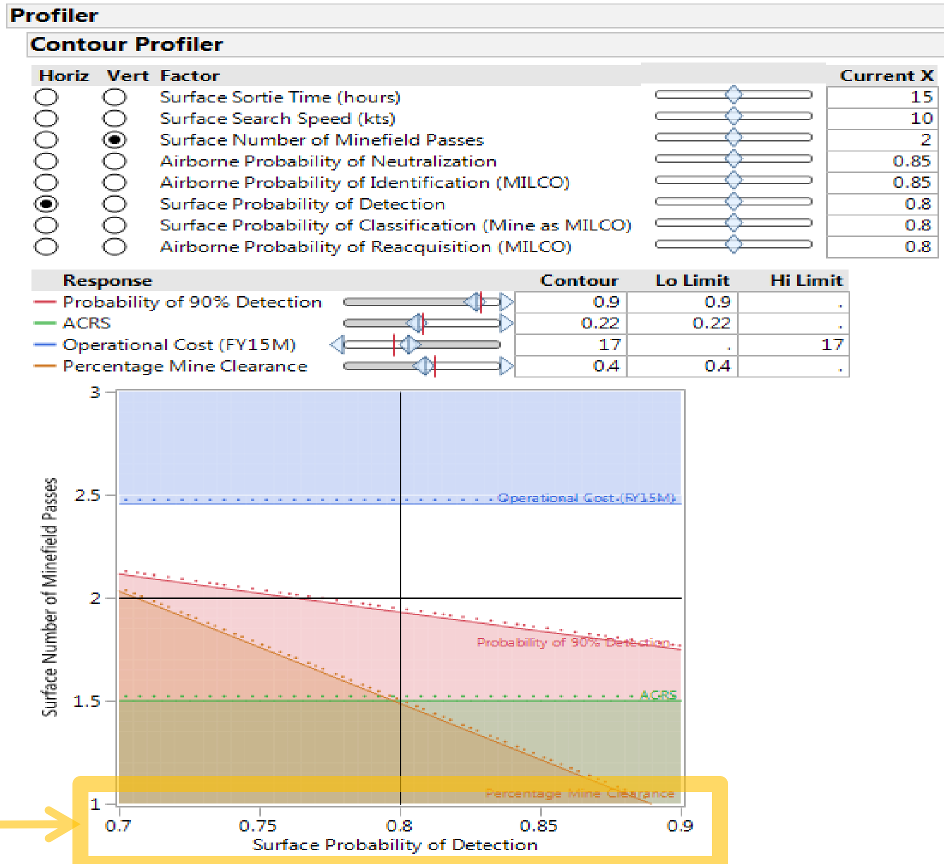
1. **Improved communications** among the development stakeholders

Q: *Does the MBSE MEASA explicitly incorporate stakeholder input?*

A: Yes

1. Requirements Diagram captures stakeholder views in a clear, concise format.
2. Requirements Diagrams are used as the basis for the construction of subsequent system architecture models (and therefore as the guidance for external system models)
3. Standards specified in Requirements Diagrams are evaluated through tradespace exploration





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Intended Benefits of MBSE: Evaluate the Research

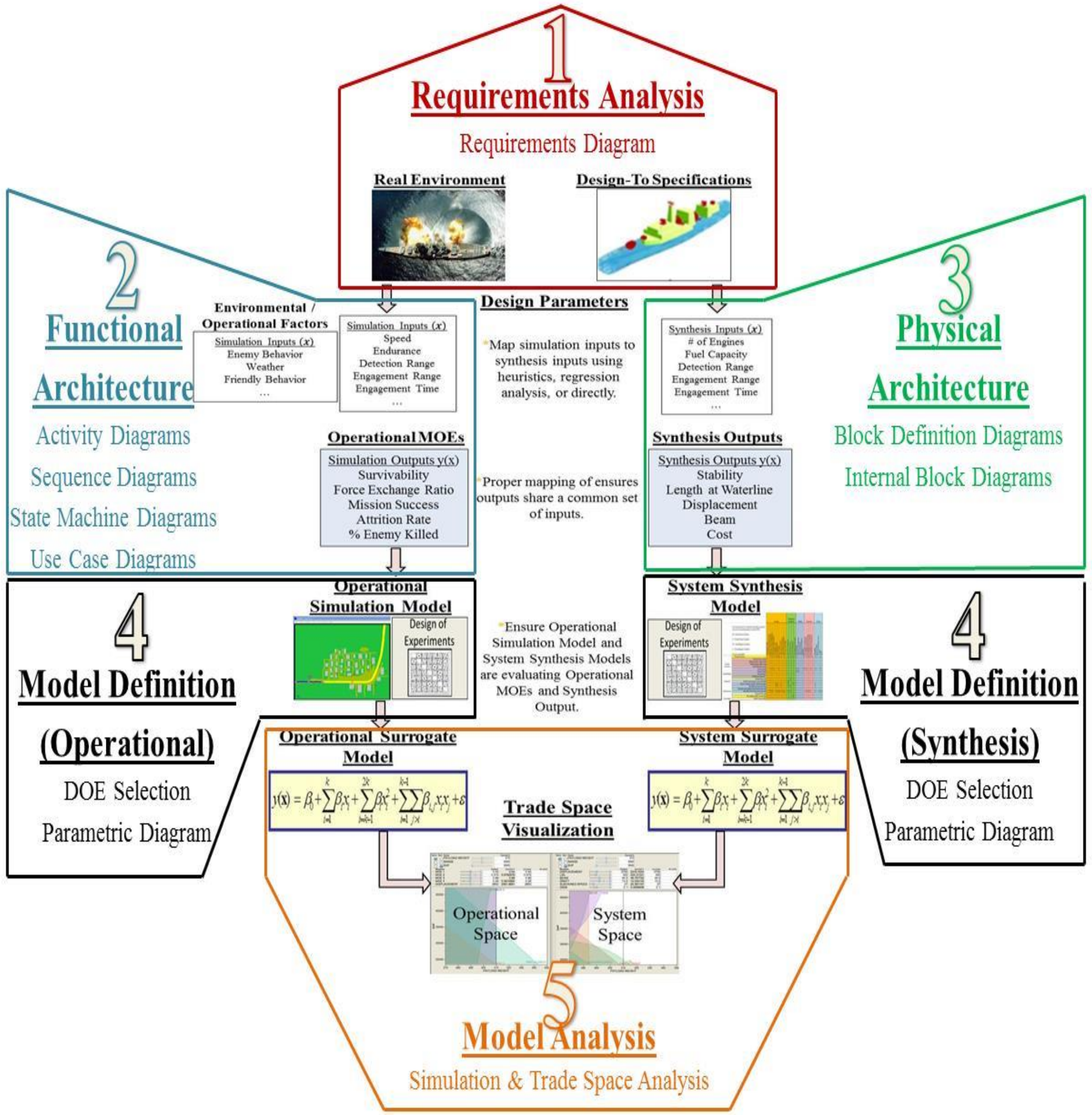
2. **Increased ability to manage system complexity** by enabling a system model to be viewed from multiple perspectives, and to analyze the impact of changes

Q: Does the MBSE MEASA allow the system model to be viewed from multiple perspectives?

Q: Does the MBSE MEASA incorporate a method for analyzing the impact of changes to the system design?

A: Yes

1. SysML Diagrams, the most popular architecture models in MBSE, ensure a comprehensive system model that can be viewed from both a functional and physical perspective
2. External models ensure that the system can be viewed and examined from an operational perspective
3. External simulation models that are traceable to systems architecture products establish a clear linkage between any proposed design changes and the originally established system requirements (and therefore to an original set of stakeholder needs



Intended Benefits of MBSE: Evaluate the Research

3. **<u>Improved product quality</u>** by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness

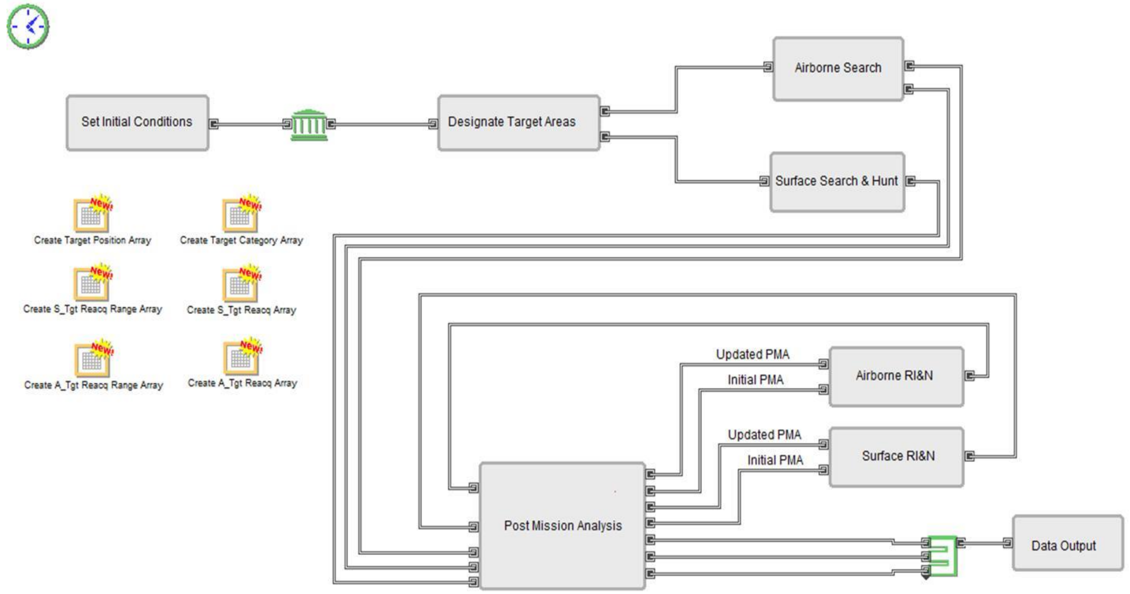
Q: Does the MBSE MEASA provide an unambiguous and precise model of the system?

Q: Can the models developed in the context of the MBSE MEASA be evaluated for consistency, correctness, and completeness?

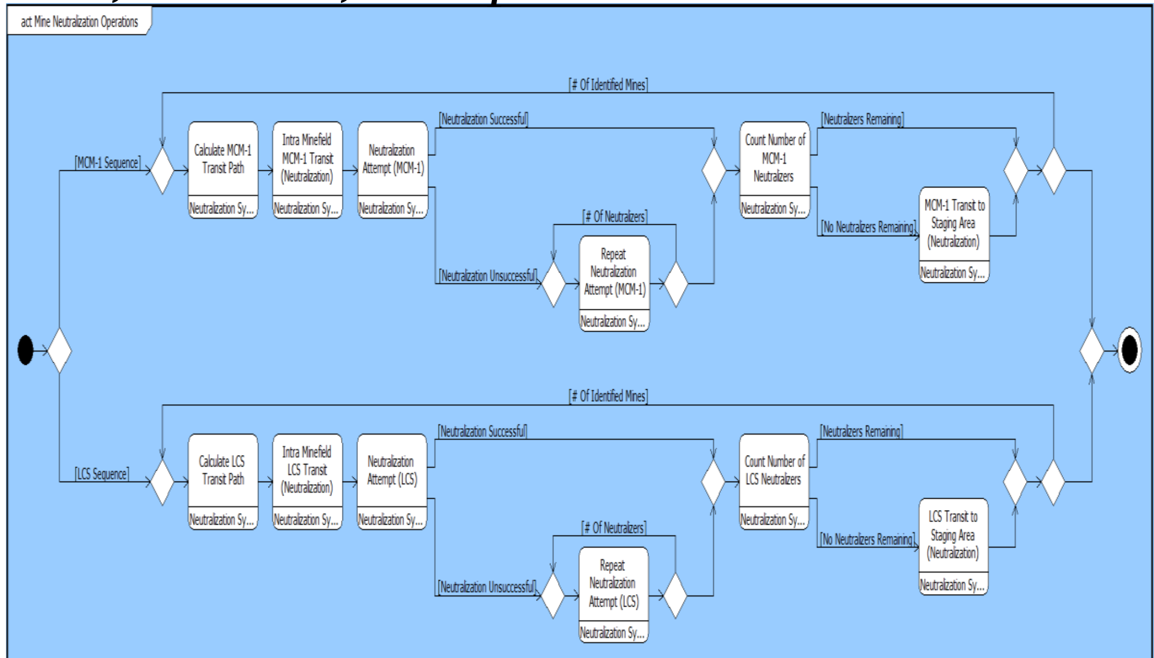
A: Yes

1. SysML utilization as the basis for external model construction ensures that if some expected functionality is not present in an operational simulation model, the accuracy and completeness of the Activity & Sequence Diagrams can be evaluated and updated. If some physical component is not included in a cost of physical model, Block Definition Diagrams can be examined to determine whether or not the component is necessary

Detailed Performance Simulation



Consistent, Correct, Complete Architecture Model



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Intended Benefits of MBSE: Evaluate the Research

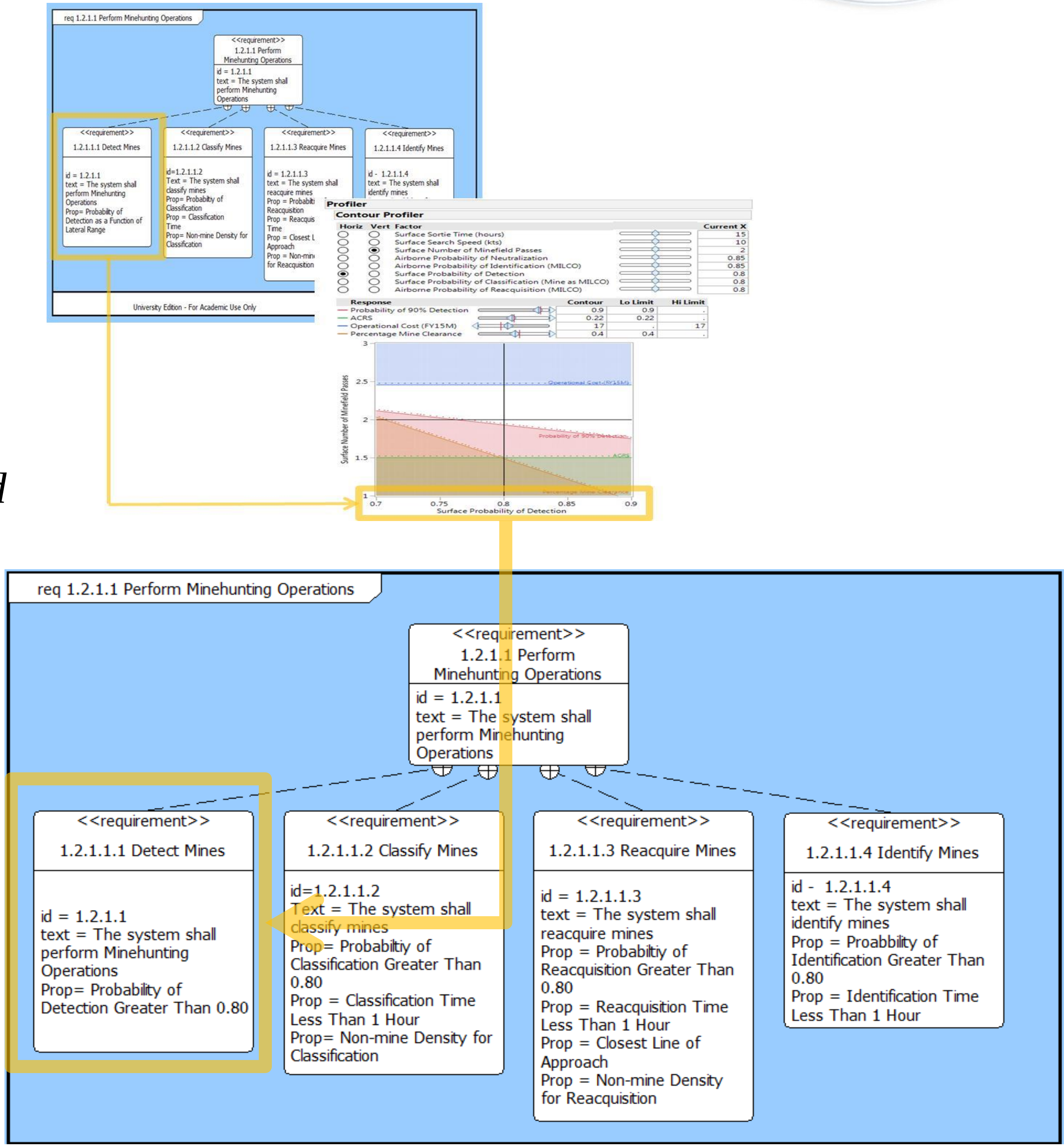
4. **<u>Enhanced knowledge capture and reuse of information</u>** by capturing information in more standardized ways and leveraging built in abstraction mechanisms inherent in model driven approaches. This in-turn can result in reduced cycle time and lower maintenance costs to modify the design

Q: Does the MBSE MEASA capture information in standard ways?

Q: Does the MBSE MEASA enable reduced cycle time and lower maintenance costs to modify system designs?

A: Yes

1. Standard architecture products reduce the time required for system architecture rework
2. Using architecture products as the basis for external model creation reduces the potential for conflict and provides a clear roadmap for the revision of operational, physical, and cost models



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A Model Based Systems Engineering Methodology for Employing Architecture in System Analysis: Developing Simulation Models Using Systems Modeling Language Products to Link Architecture and Analysis

2015 SERC Doctoral Students Forum
2015 SERC Sponsor Research Review
2-3 December 2015

Paul Beery
Ph.D. Candidate
Department of Systems Engineering
Naval Postgraduate School

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Problem Statement

General Problem: Aid decision making in the conceptual design phase of the system lifecycle by producing better requirements, using a more efficient process, and linking systems architecture and system analysis

Approach: This dissertation develops a MBSE Methodology for the Employment of Architecture in System Analysis (MEASA) for analyzing large scale, complex systems through operational simulations and system synthesis models during the conceptual design phase of the system lifecycle

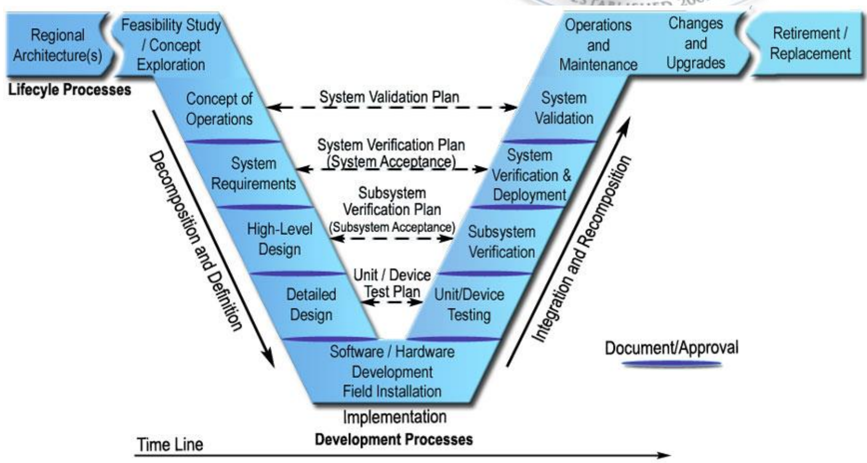
Sub Problem 1: Clearly demonstrates how traditionally developed systems architecture products, formally presented as Systems Modeling Language (SysML) products should be used to support development and analysis of external models and simulations

Sub Problem 2: Demonstrate the utility of the MBSE MEASA through an analysis of the operational performance and feasibility of a future U.S. Navy mine warfare system

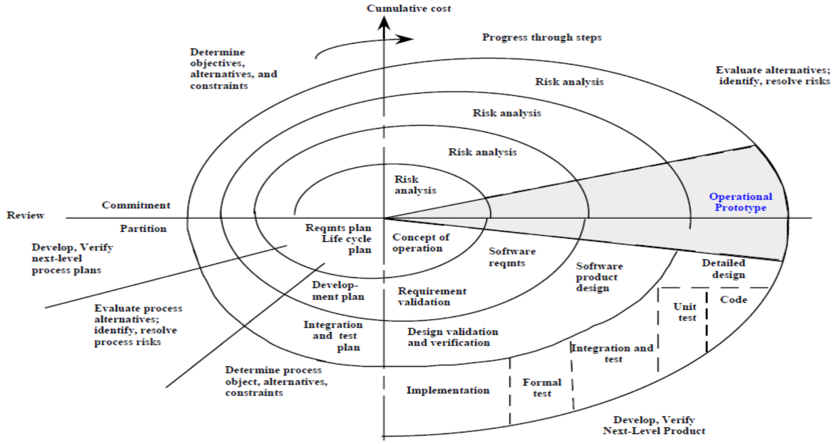
Define a Systems Engineering Process

1. ***Problem Definition***
   1. ***Stakeholder (Customer Analysis)***
   2. ***Requirements Identification***
2. ***System Design***
   1. ***Functional Analysis***
   2. ***Physical Analysis***
   3. ***Design Generation***
   4. ***Modeling & Simulation***
3. ***System Analysis***
   1. ***Performance Analysis***
   2. ***Cost and Risk Analysis***
4. ***System Implementation***
   1. ***Production, Deployment, Operation, Disposal***

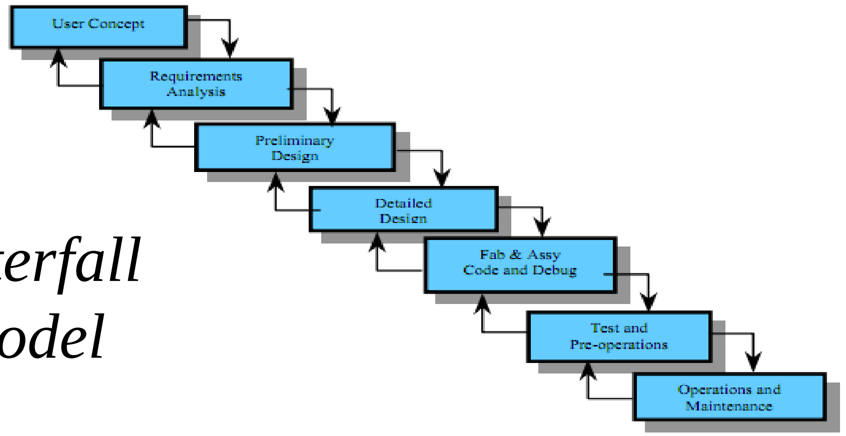
Vee Model



Spiral Model



Waterfall Model



Research Direction

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1. ***Problem Definition***
    1. ***Stakeholder (Customer Analysis)***
    2. ***Requirements Identification***
2. ***System Design***
    1. ***Functional Analysis***
    2. ***Physical Analysis***
    3. ***Design Generation***
    4. ***Modeling & Simulation***
3. ***System Analysis***
    1. ***Performance Analysis***
    2. ***Cost and Risk Analysis***
4. ***System Implementation***
    1. ***Production, Deployment, Operation, Disposal***

Solve A Problem

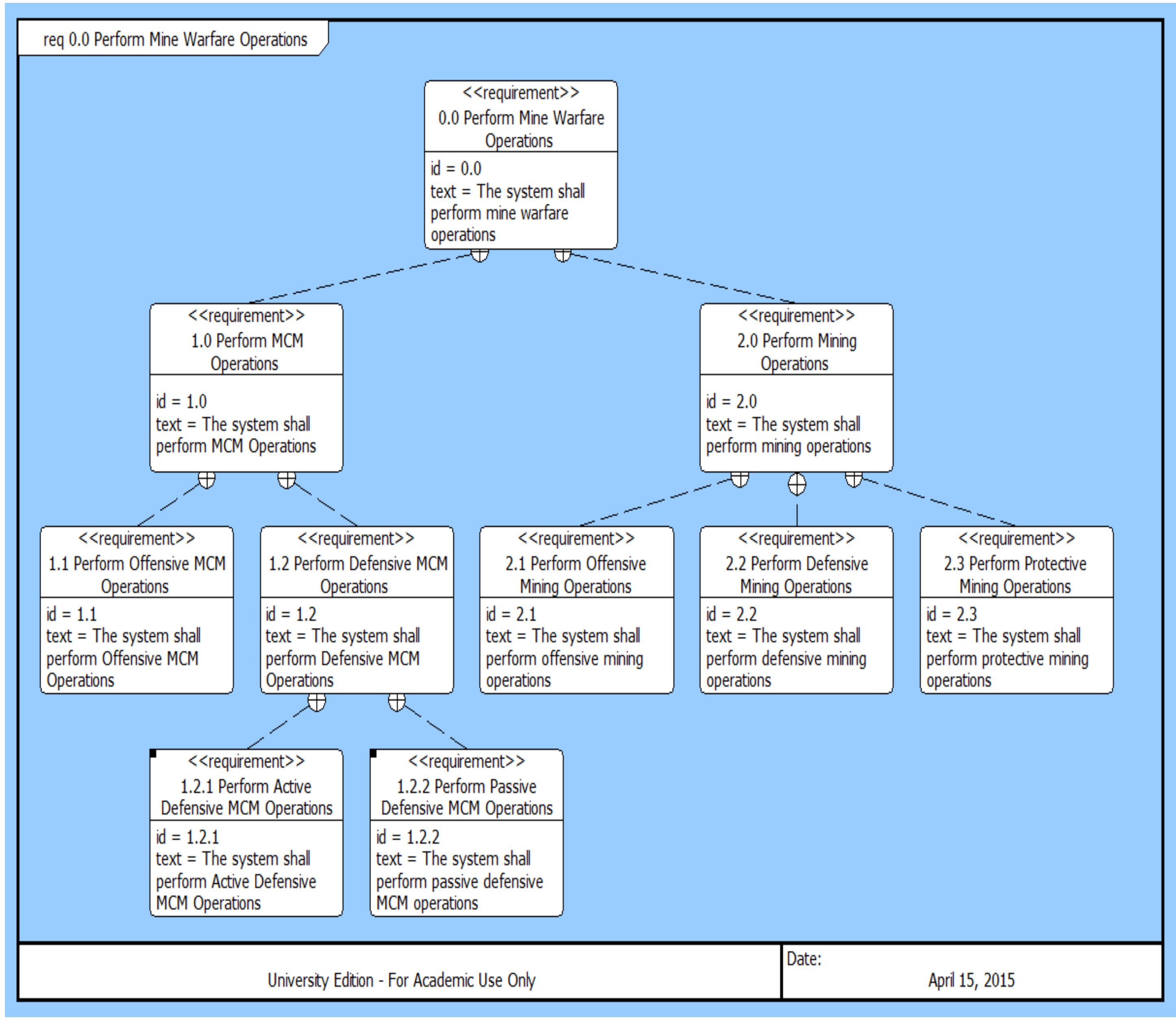
Improve This Process

Limited to Design Process

SysML Diagram Basics

Requirements Diagram

- Most significant departure from UML
- Each requirements specifies either:
  - A capability that must be satisfied
  - A function that must be performed
  - A performance condition that must be achieved
- Goal is to graphically depict hierarchies of requirements
  - Individual requirements can be related to other requirements by *containment, derive, or copy* relationships
  - Requirements can be related to other model elements using *satisfy, verify, refine*, or *trace relationships*
- Each requirement can be uniquely identified in terms of:
  - ID, Name, Text Description, Rationale

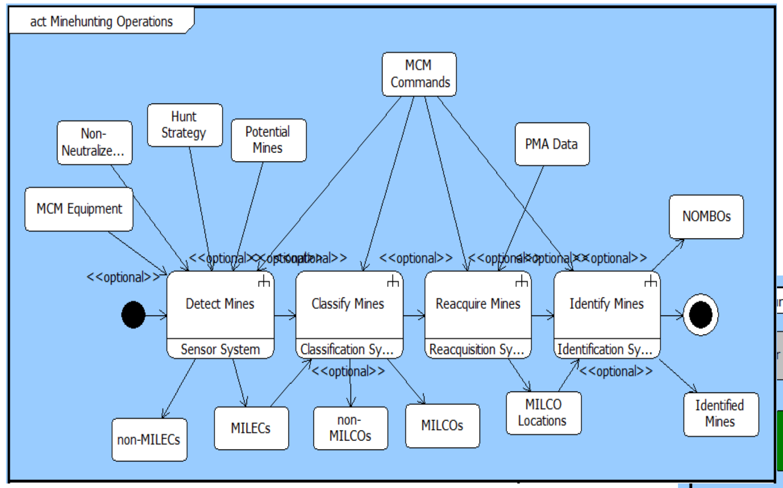


SysML Diagram Basics (2)

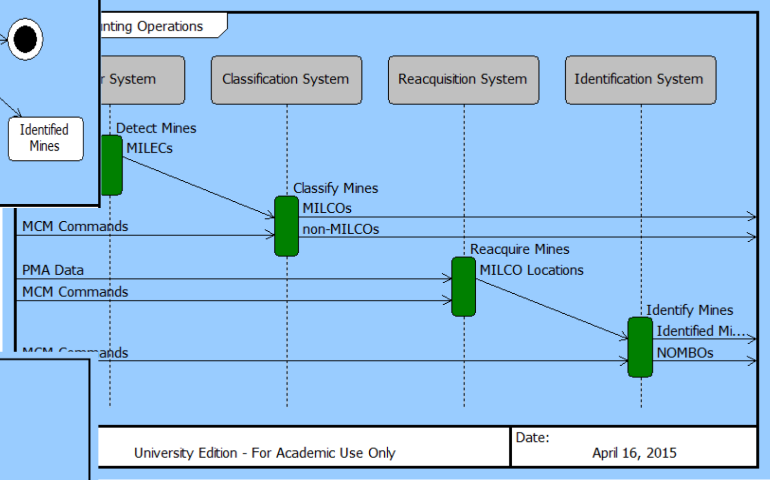
Functional Diagrams

- Functional Diagrams include:
  - Activity Diagram
  - Sequence Diagram
  - Use Case Diagram
  - State Machine Diagram
- ***Activity Diagrams*** model system behavior & operation in terms of inputs and outputs
- ***Sequence Diagrams*** show interactions between physical elements (both message exchanges and trigger actions)
- ***Use Case Diagrams*** describe system behavior dependencies on external actors
- ***State Machine Diagrams*** describe state dependent behaviors of each system element

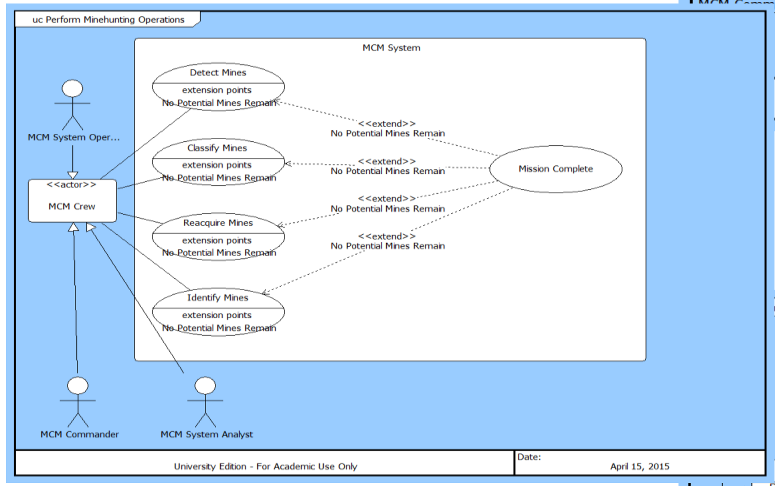
Activity Diagram



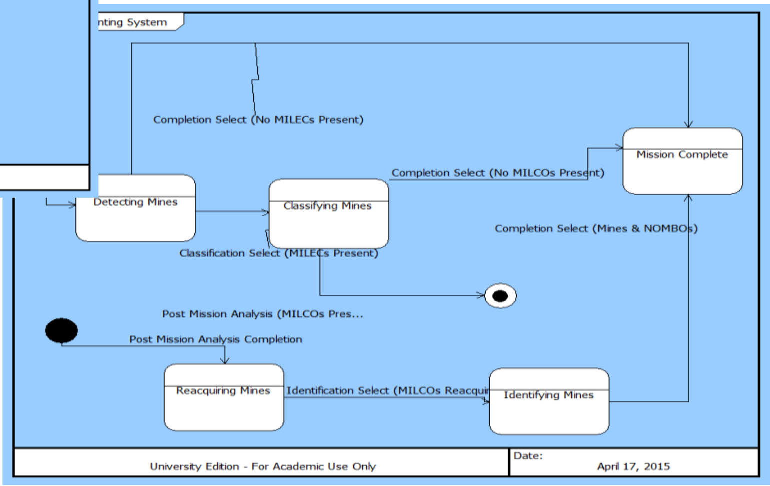
Sequence Diagram



Use Case Diagram



State Machine Diagram



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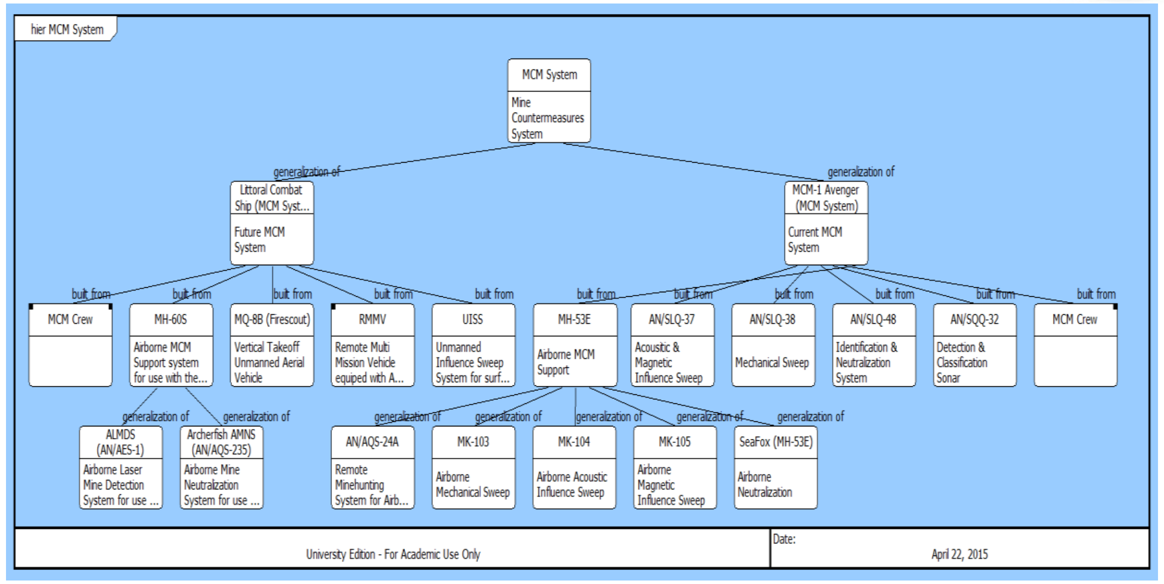
SysML Diagram Basics (3)

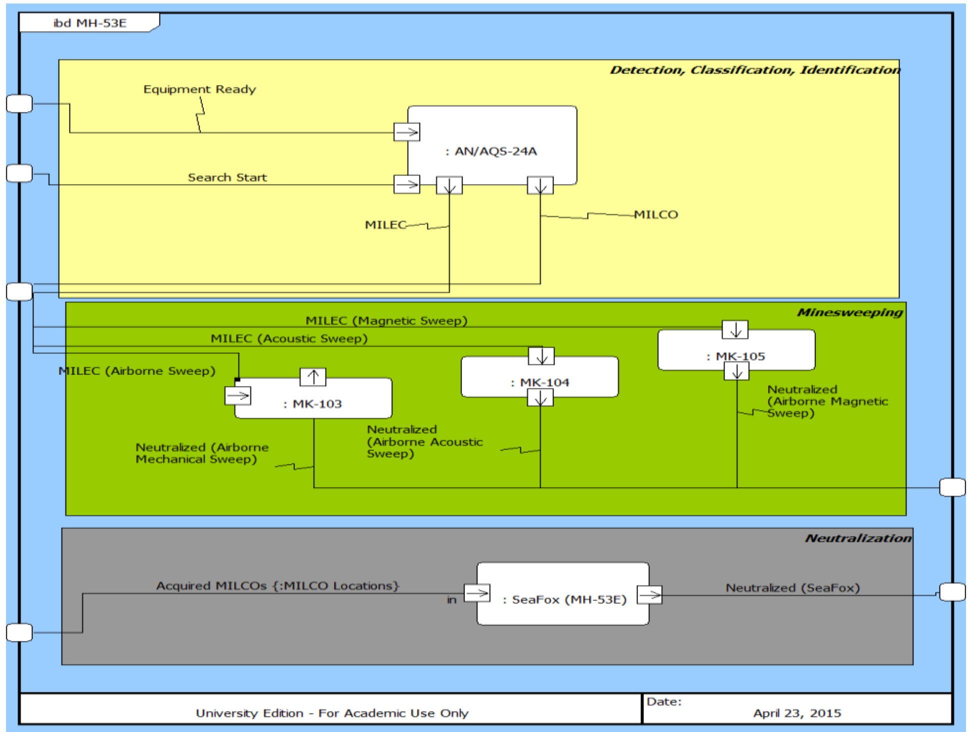
Physical Element Diagrams

- Physical Element Diagrams include:
  - Block Definition Diagrams
  - Internal Block Diagrams
- Block Definition Diagrams define the physical elements of the system model as well as the hierarchical relationships between those elements
  - Particular emphasis is given to the difference between "built from" relationships and "generalization of" relationships
- Internal Block Diagrams define the internal structure of each physical element within the system model with an emphasis on the connections between parts of that element
  - Particular emphasis is given to the difference between "connections" and "links"

Block Definition Diagram



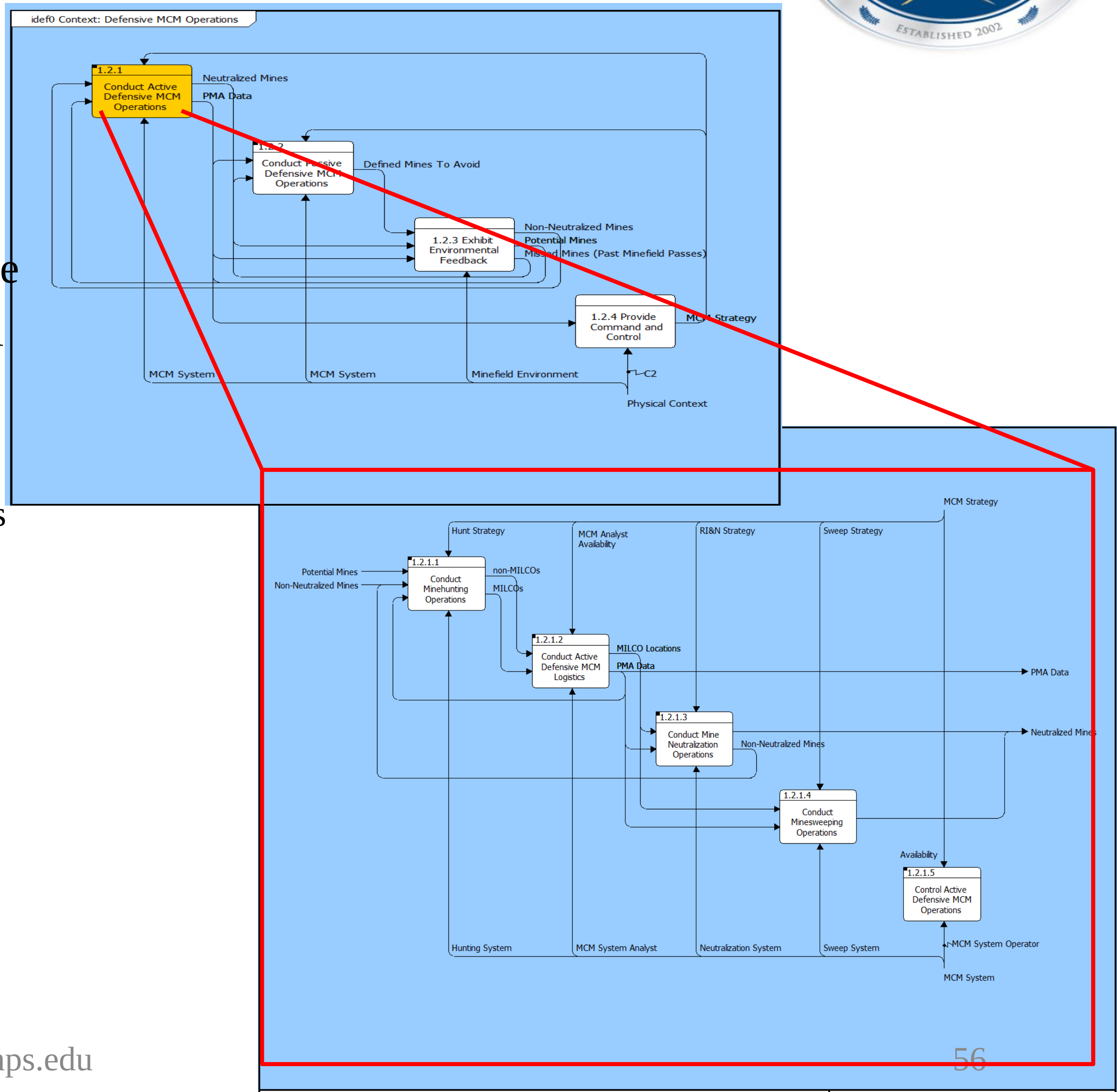
Internal Block Diagram



Mine Warfare Description

Utilize Functional Models (IDEF0 Models)

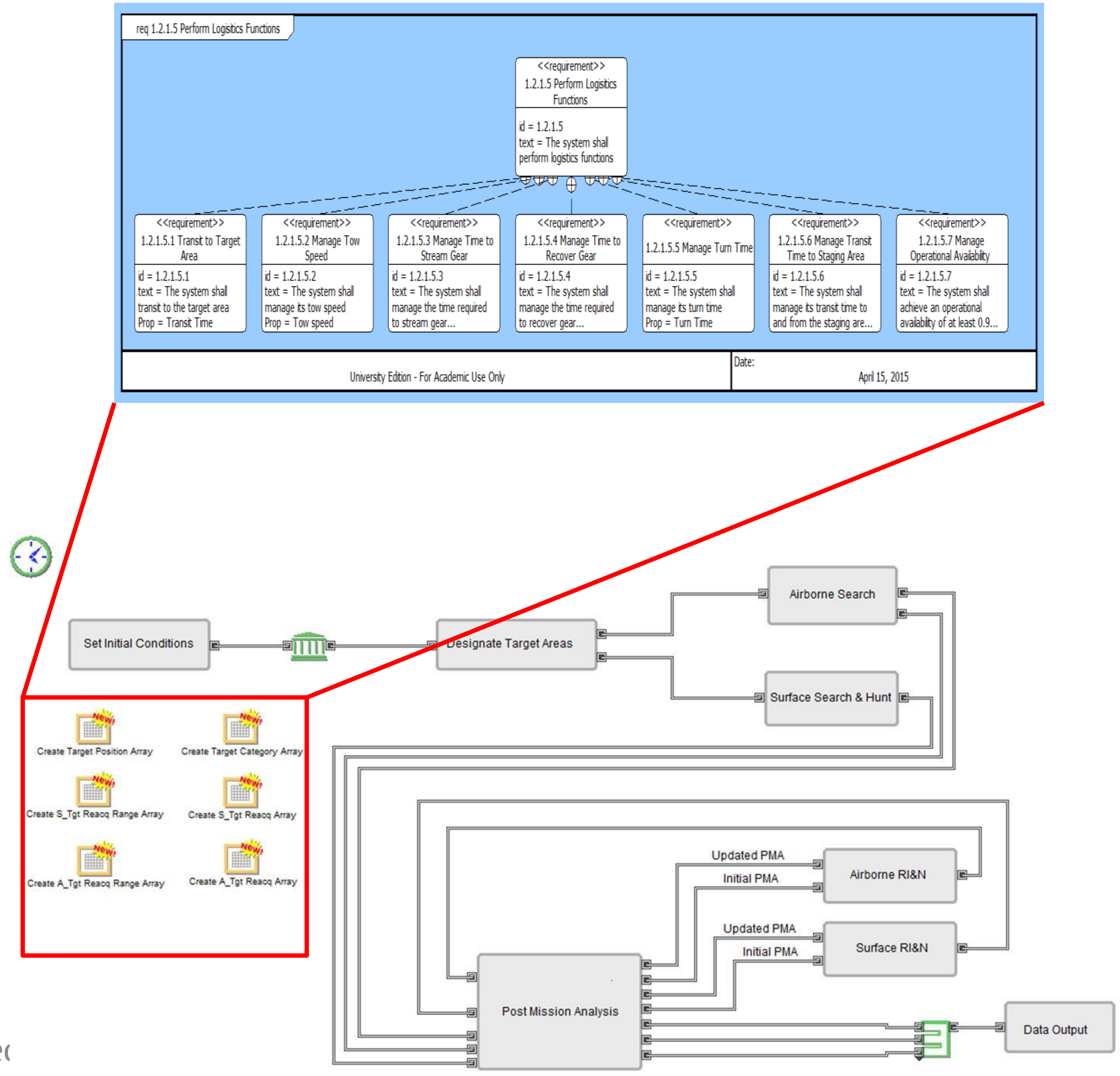
- Specify a system generally in terms of inputs, outputs, controls, and mechanisms
- Developed through interaction with stakeholders and review of formal guidance
- Traceability can be tremendously powerful
- In this particular implementation:
- Active Defensive MCM Operations:
  - Inputs: Potential Mines, Non-Neutralized Mines
  - Controls: MCM Strategy
  - Outputs: Neutralized Mines, PMA Data
  - Mechanisms: MCM System
- Decomposed into:
  - Minehunting
  - Mine Neutralization
  - MCM Logistics
  - Minesweeping
  - MCM Operation Controls



Detailed Requirements Analysis

Visualization of Requirements Diagram Implementation

- Non-refined requirements are each characterized by a quantifiable property
- These properties should be used to identify the variables that are represented in external simulation models
- In this particular implementation:
  - Environmental properties
    - Staging Area Distance
    - Transit Distance
  - Operational implementation
    - Number of minefield passes
    - Distance between search tracks
    - Percentage of neutralization effort assigned to airborne and surface assets
  - System design attributes
    - Probability of Detection
    - Probability of Classification
    - Probability of Identification
    - Probability of Neutralization



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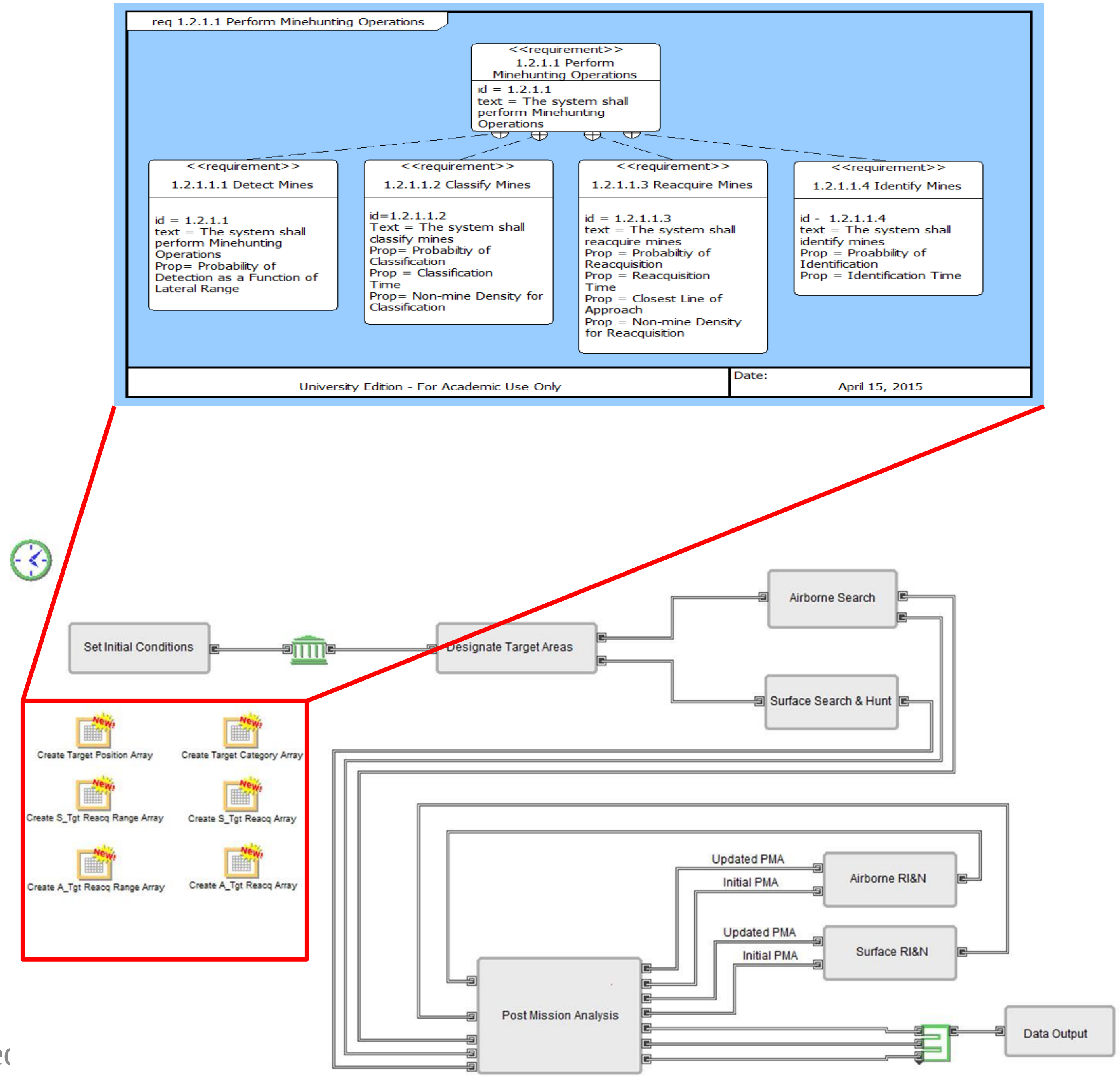
Detailed Requirements Analysis (Ex. #2)

<u>Visualization of Requirements Diagram Implementation</u>

- Non-refined requirements are each characterized by a quantifiable property
- These properties should be used to identify the variables that are represented in external simulation models
- In this particular implementation:
  - Environmental properties
    - Staging Area Distance
    - Transit Distance
  - Operational implementation
    - Number of minefield passes
    - Distance between search tracks
    - Percentage of neutralization effort assigned to airborne and surface assets
  - System design attributes
    - Probability of Detection
    - Probability of Classification
    - Probability of Identification
    - Probability of Neutralization



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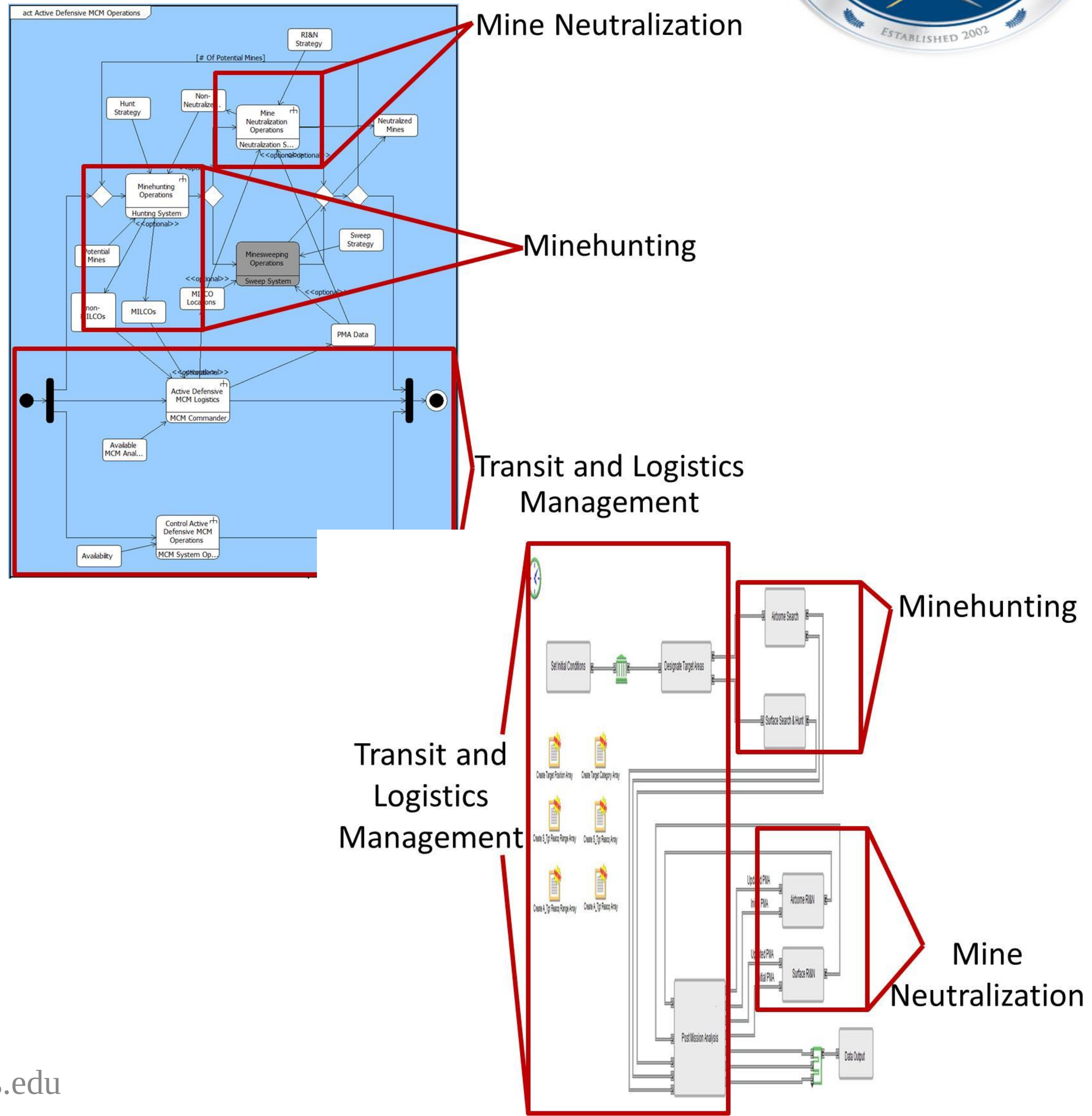
Activity Diagram Utilization

Visualization of Activity Diagram Utilization

- SysML Diagrams are extremely powerful and offer two major advantages over other methods of architectural description
  - Consistency Between Architecture Views
  - Traceability from Architecture Views to Simulation Model characteristics
- Activity Diagrams are often the most comfortable diagrams for presentation to a systems engineering audience
  - Note that Sequence Diagrams are often more comfortable for a software engineering audience
  - Activity Diagrams are evaluated for consistency (see advantage #1 above) with Sequence, Use Case, and State Machine Diagrams
- Activity Diagrams provide comfortable mapping and traceability when the system is examined in detail using a discrete event simulation



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Activity Diagram Utilization (Ex: #2)

Visualization of Activity Diagram Utilization

- SysML Diagrams are extremely powerful and offer two major advantages over other methods of architectural description
  - Consistency Between Architecture Views
  - Traceability from Architecture Views to Simulation Model characteristics
- Activity Diagrams are often the most comfortable diagrams for presentation to a systems engineering audience
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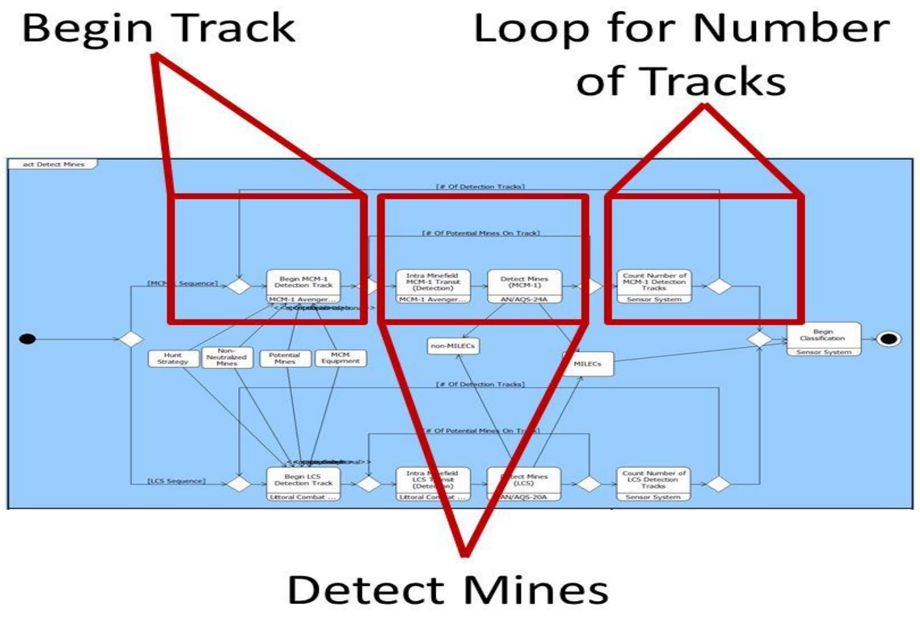
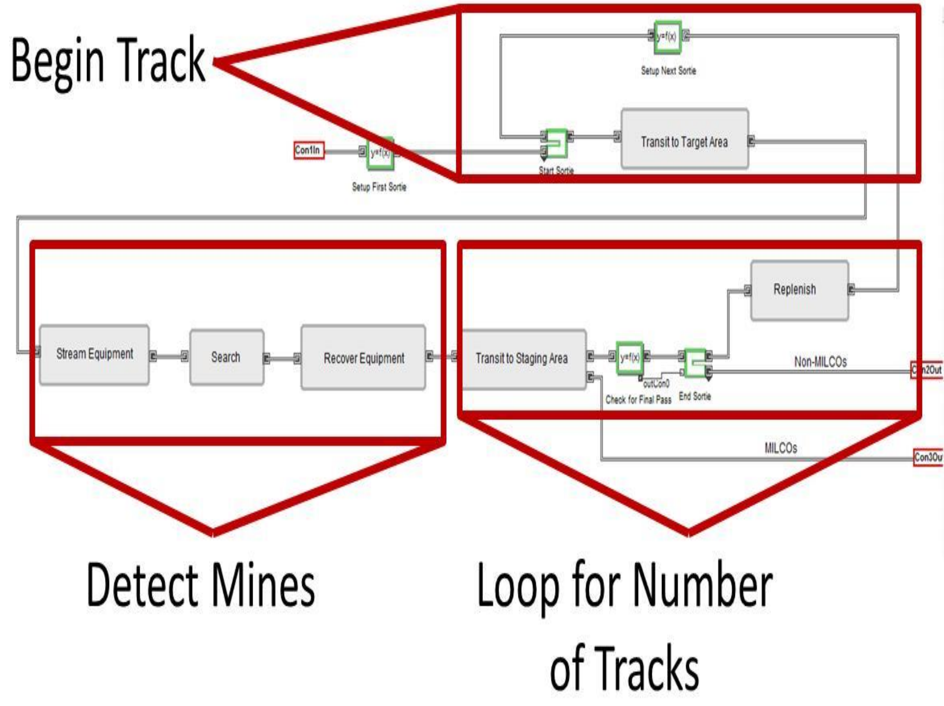
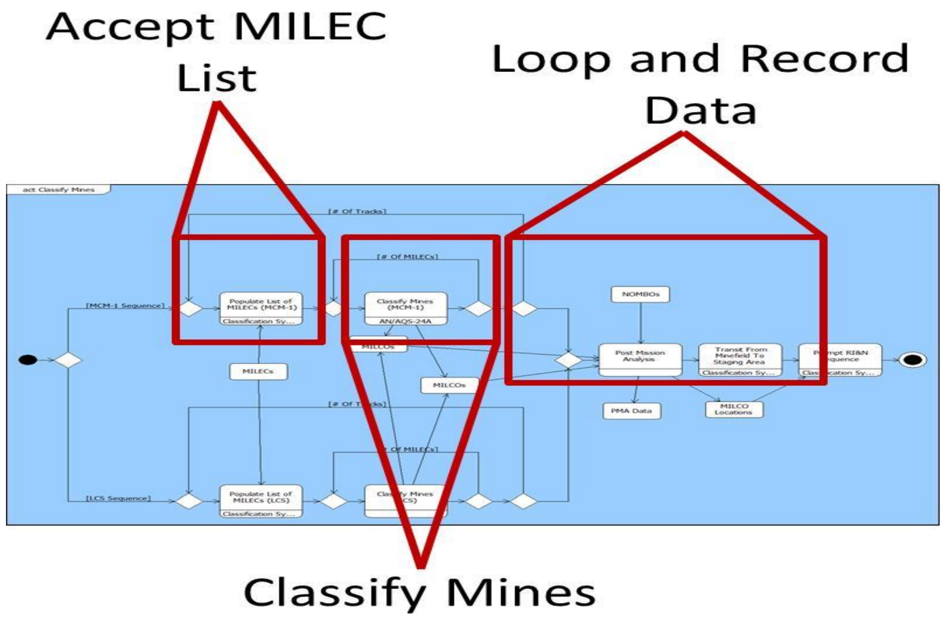


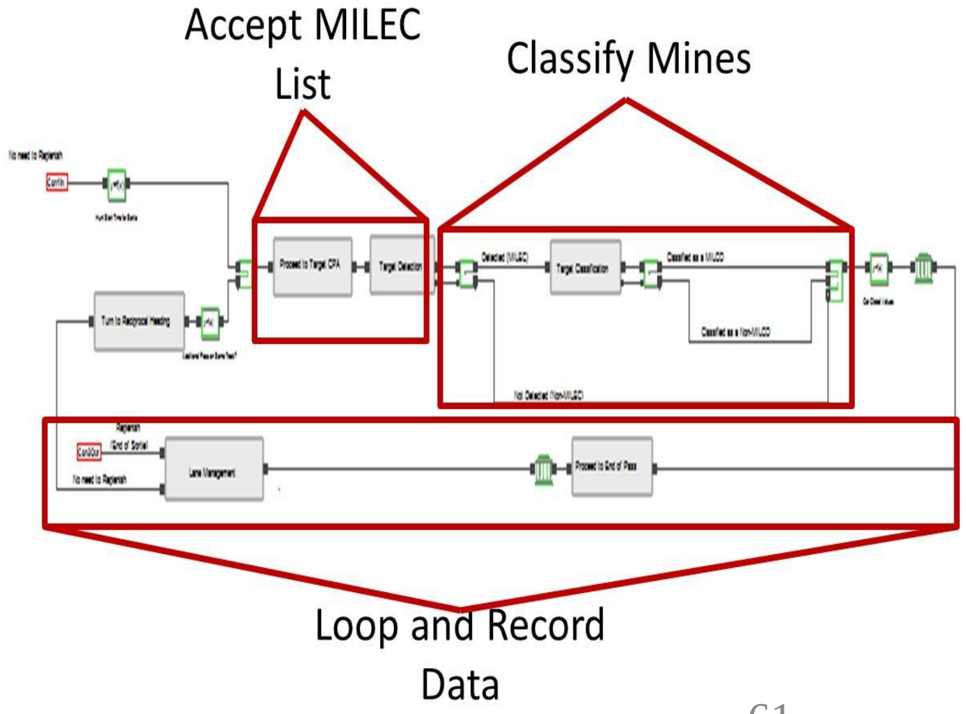


Activity Diagram Utilization (Ex: #3)

Visualization of Activity Diagram Utilization

- SysML Diagrams are extremely powerful and offer two major advantages over other methods of architectural description
  - Consistency Between Architecture Views
  - Traceability from Architecture Views to Simulation Model characteristics
- Activity Diagrams are often the most comfortable diagrams for presentation to a systems engineering audience
  - Note that Sequence Diagrams are often more comfortable for a software engineering audience
  - Activity Diagrams are evaluated for consistency (see advantage #1 above) with Sequence, Use Case, and State Machine Diagrams
- Activity Diagrams provide comfortable mapping and traceability when the system is examined in detail using a discrete event simulation

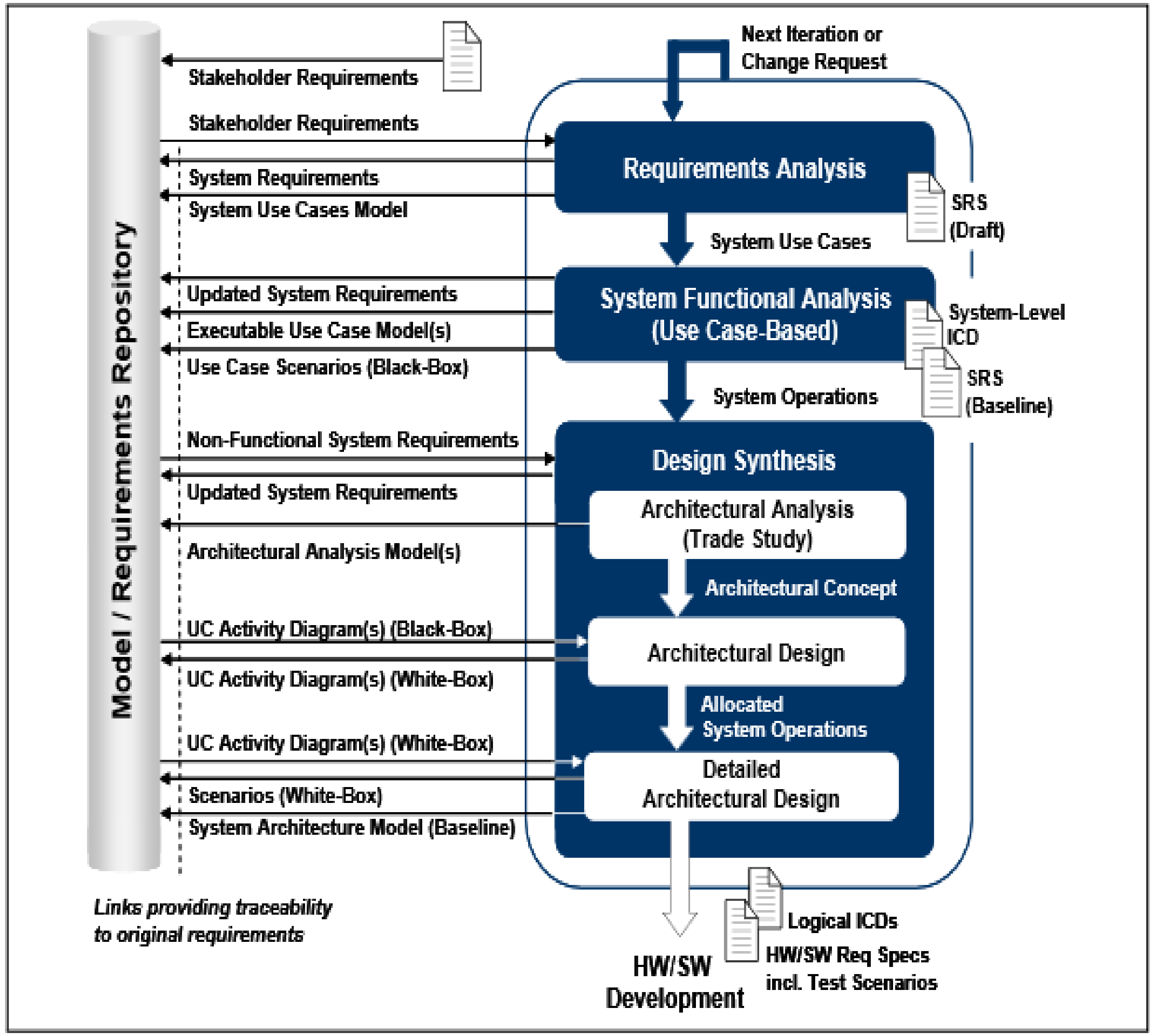




IBM Harmony for Systems Engineering

Fundamentals of IBM Harmony for Systems Engineering

- Intended to be utilized as a central design hub to enable stakeholder collaboration and document generation
- Intended to coordinate and correct system architecture and design
- Process relies heavily on creation of SysML products
- Analysis of system performance is addressed through examination of scenarios during detailed architectural design
- Performance analysis relies on generation of utility curves for each performance criterion
- The use of external modeling and simulation is not specified

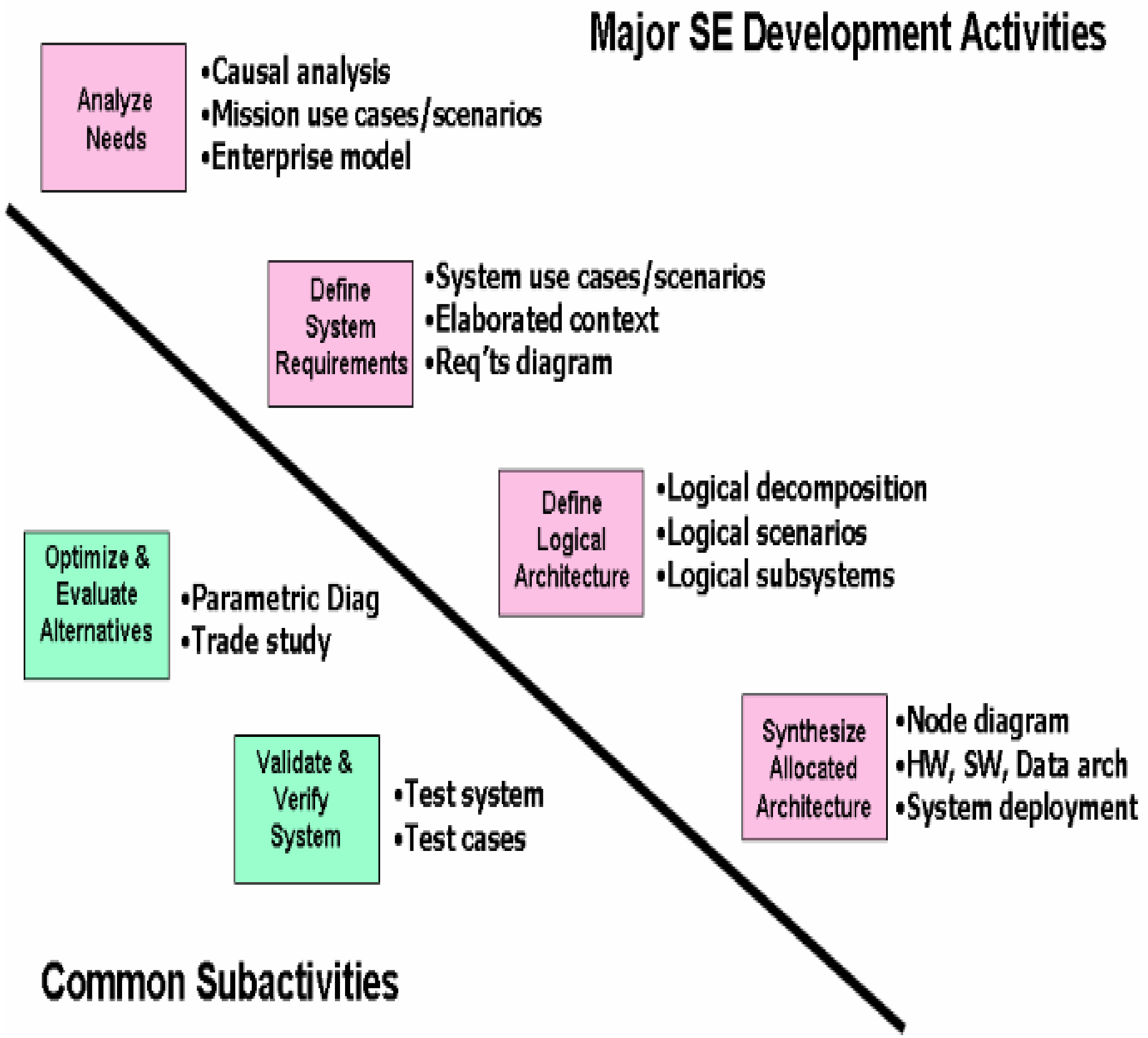


Hoffman, Hans-Peter. 2011. Model Based Systems Engineering with Rational Rhapsody and Rational Harmony for Systems Engineering, Release 3.1.2 Somers, NY" IBM Corporation

INCOSE Object Oriented Systems Engineering Method (OOSEM)

Fundamentals of INCOSE OOSEM

- Intended to coordinate and correct system architecture and design and define the relationships between system development activities
- Process relies heavily on creation of SysML products (although not explicitly specified)
- Analysis of system performance relies on parametric diagrams, which use weighting factors and value measures to optimize system configurations
- The use of external modeling and simulation is not specified
- Regards system testing and analysis as processes that are distinct from major development activities



Estefan, Jeff A. 2008. Survey of Model-Based Systems Engineering Methodologies, Rev. B. Padadena, CA: California Institute of Technology

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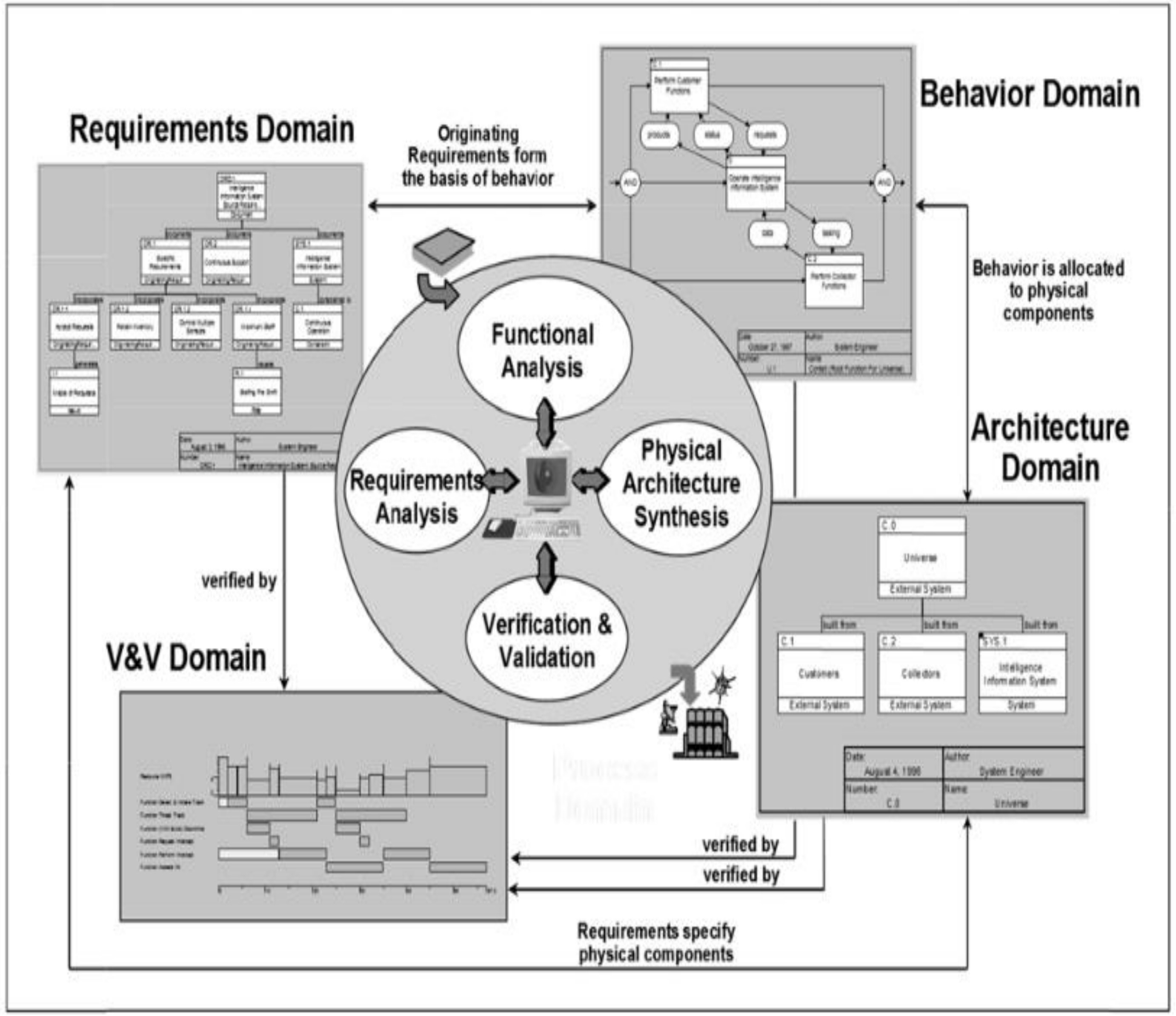
Vitech Model Based Systems Engineering Methodology

Fundamentals of Vitech MBSE

- Expected to be executed clockwise, beginning in the Requirements Domain
- Intended to coordinate system development incrementally at increasing layers of granularity, progressing towards realization of a complete system
- Process relies heavily on creation of systems architecture products (SysML can be supported but is not specified)
- Analysis of system performance relies on execution of Vitech's proprietary discrete event simulator (CORESim)
- The use of external modeling and simulation is not specified

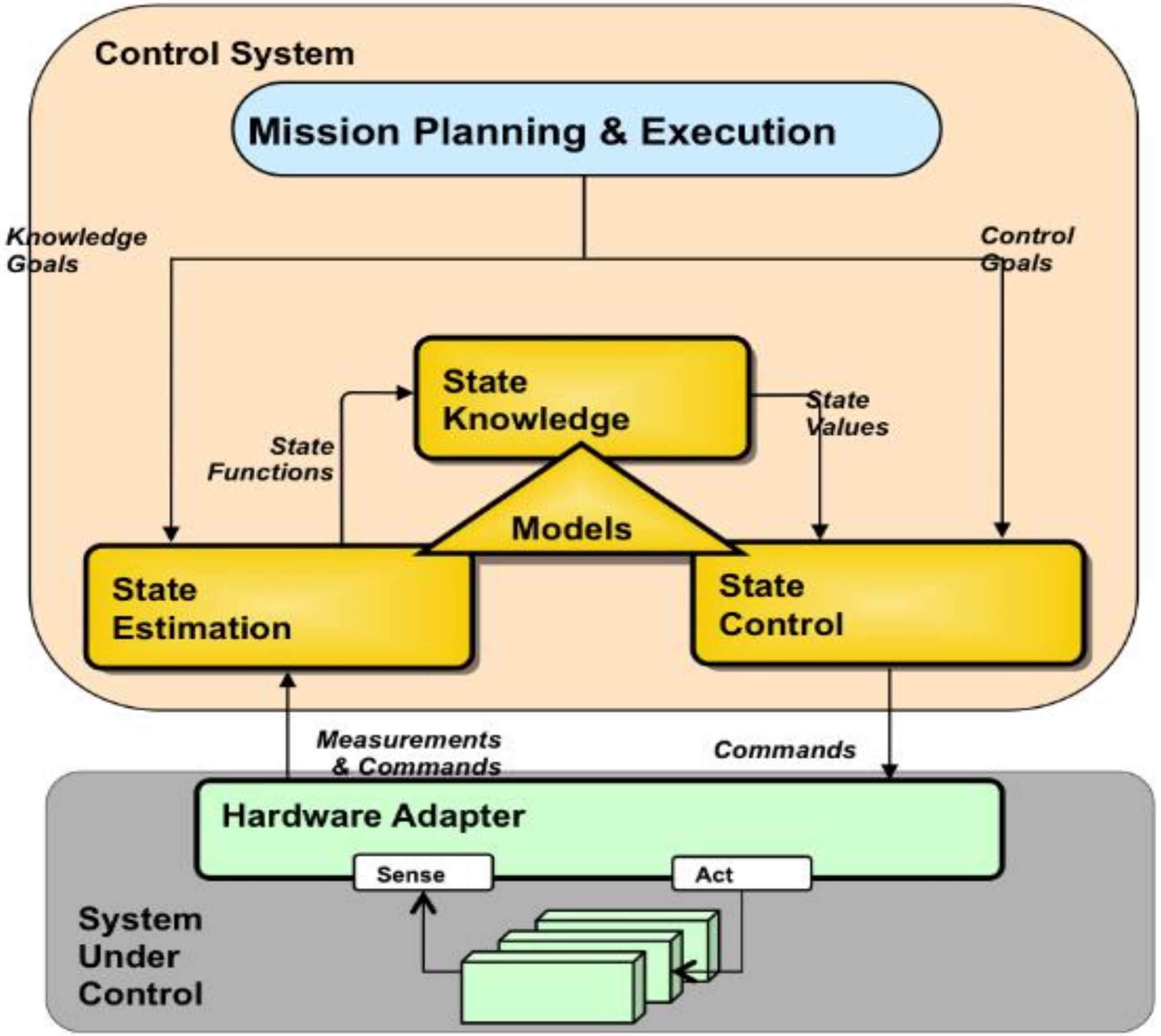


Vitech Corporation. 2010. Core 7 Definition Guide. Blacksburg, VA: Vitech Corporation.

NASA Jet Propulsion Lab State Analysis

Fundamentals of NASA JPL State Analysis

- Intent is to improve communication between physical engineers and software engineers
- Attempt to integrate both model based architectures and state based architectures
- Resembles a control systems approach to MBSE
- Process is based on definition of a physical system and modeling the potential states (momentary system conditions) of that system and relationships between states
- Approach utilizes UML products
- Clearly delineates between the physical system and the control software system



Wagner, David A., Matthew B. Bennett, Robert Karban, Nicolas Rouquette, Steven Jenkins, Michel Ingham. "An Ontology for State Analysis: Formalizing the Mapping to SysML." *Aerospace Conference, 2012 IEEE*, 1-16, IEEE: 2012.

Dori Object-Process Methodology

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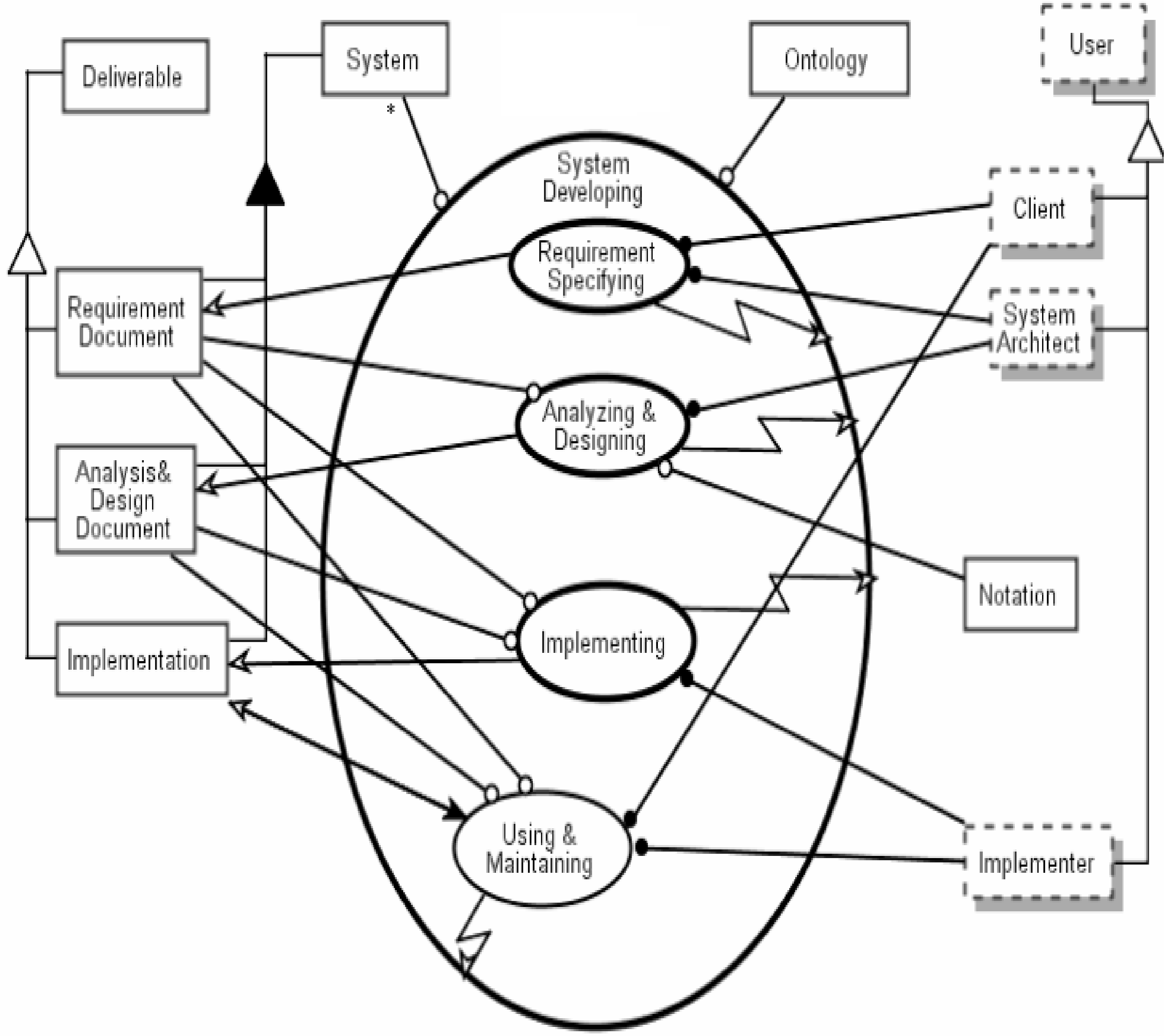
Fundamentals of Object-Process Methodology

- Intended to be domain independent architecture development focused on information exchange between systems
- Clearly delineates between physical systems (objects) and processes (which initiate changes in object states)
- Expected to be implemented from the top-down
- Utilizes propriety diagrams and language
- Production of an artifact after each step allows for iteration of the entire process as well as each step of the process
- Extends JPL State Analysis by specifying objects and processes that are internal or external to the system

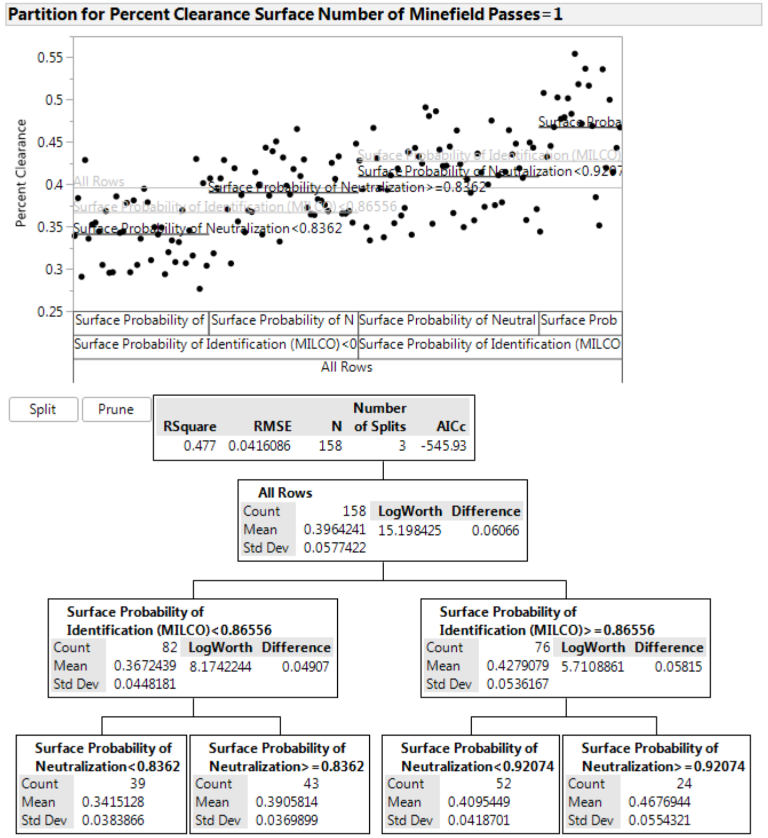


Dori, Dov. 2002. Object Process Methodology: A Holistic Systems Paradigm. New York, NY: Springer.

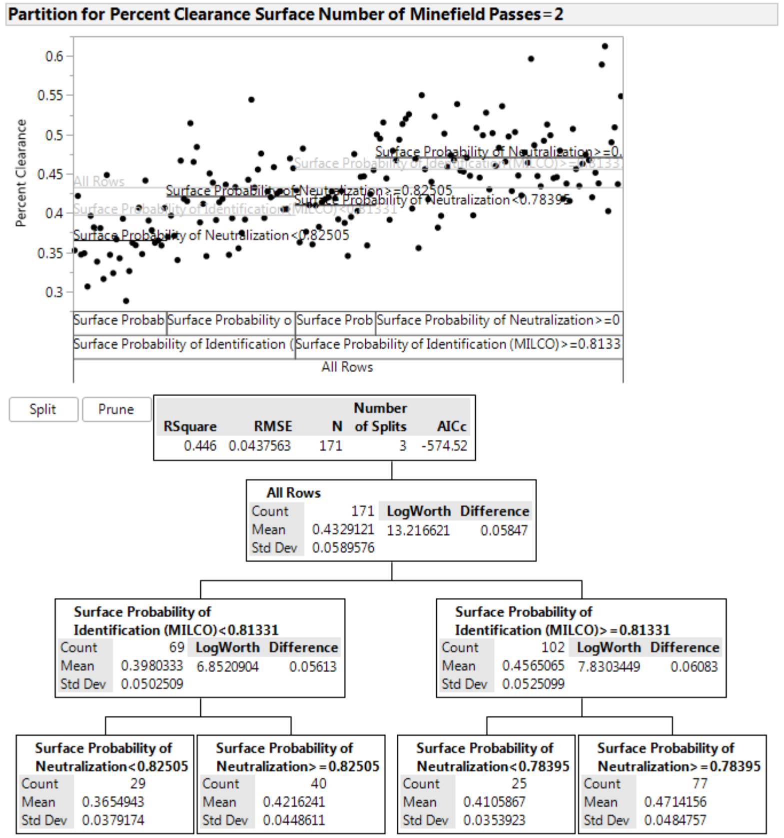
Initial Model Analysis: MCM-1

- Initial analysis suggested that the Percent Clearance MOE is most substantially impacted by the probabilities of Identification and Neutralization (Detection and Classification were also statistically significant)
- The number of minefield passes conducted was the only environmental/operational variable that had a statistically significant impact on performance
- Regardless of the number of minefield passes, the Probability of Identification was the #1 performance driver and the Probability of Neutralization was the #2 performance driver

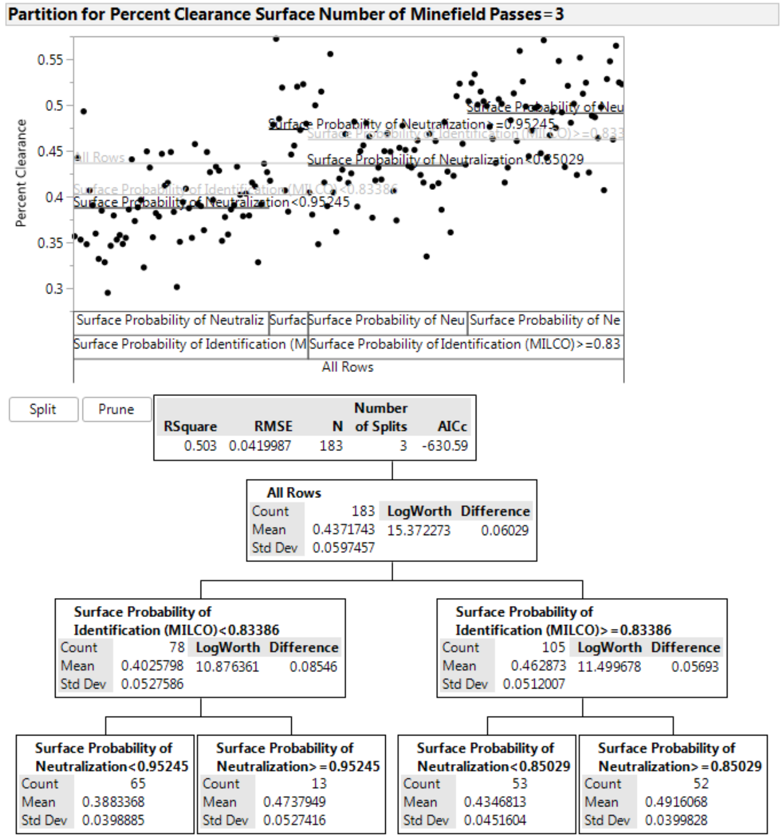
One Minefield Pass



Two Minefield Passes



Three Minefield Passes



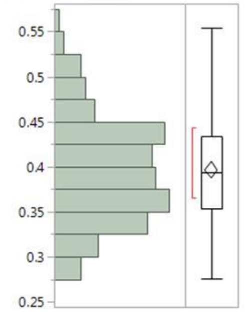
Initial Model Analysis: MCM-1(cont.)

MCM-1 Percent Clearance Analysis

- One Minefield Pass: Average 39% Clearance
- Two Minefield Passes: Average 43% Clearance
- Three Minefield Passes: Average 43% Clearance
- *Takeaway:*
  - *There may be diminishing returns associated with a third minefield pass*
- *Questions:*
  - *Is the second/third minefield pass practically important? Is the cost worth it?*

Distributions Multiple Passes=0

Percent Clearance



Quantiles

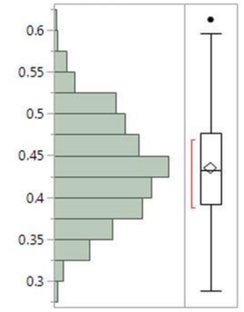
100.0%	maximum	0.5543333333
99.5%		0.5543333333
97.5%		0.518775
90.0%		0.4755333333
75.0%	quartile	0.4335833333
50.0%	median	0.394
25.0%	quartile	0.3530833333
10.0%		0.3195333333
2.5%		0.2952916667
0.5%		0.2763333333
0.0%	minimum	0.2763333333

Summary Statistics

Mean	0.3964241
Std Dev	0.0577422
Std Err Mean	0.0045937
Upper 95% Mean	0.4054975
Lower 95% Mean	0.3873506
N	158

Distributions Multiple Passes=1

Percent Clearance



Quantiles

100.0%	maximum	0.6123333333
99.5%		0.5999333333
97.5%		0.5521666667
90.0%		0.5145
75.0%	quartile	0.4765
50.0%	median	0.4325
25.0%	quartile	0.39125
10.0%		0.3554444444
2.5%		0.3280416667
0.5%		0.293425
0.0%	minimum	0.288

Summary Statistics

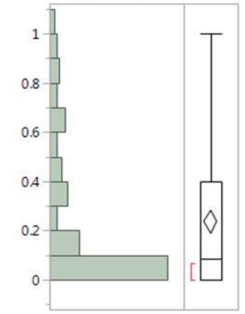
Mean	0.4351154
Std Dev	0.0593206
Std Err Mean	0.0031529
Upper 95% Mean	0.4413161
Lower 95% Mean	0.4289147
N	354

MCM-1 Probability of 90% Detection Analysis

- One Minefield Pass: Average 23% Probability of 90% Detection
- Multiple Minefield Passes: Average 78% Probability of 90% Detection
- One Minefield Pass: Median 8% Probability of 90% Detection
- Multiple Minefield Passes: Median 100% Probability of 90% Detection
- *Takeaway: Multiple passes are certainly valuable with respect to the Probability of 90% Detection*

Distributions Multiple Passes=0

Prob 90% Detection



Quantiles

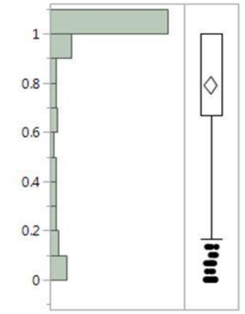
100.0%	maximum	1
99.5%		1
97.5%		0.9675000003
90.0%		0.766666667
75.0%	quartile	0.4
50.0%	median	0.0833333335
25.0%	quartile	0
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	0.235443
Std Dev	0.3015807
Std Err Mean	0.0239925
Upper 95% Mean	0.2828327
Lower 95% Mean	0.1880534
N	158

Distributions Multiple Passes=1

Prob 90% Detection



Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	1
50.0%	median	1
25.0%	quartile	0.666666667
10.0%		0.133333333
2.5%		0
0.5%		0
0.0%	minimum	0

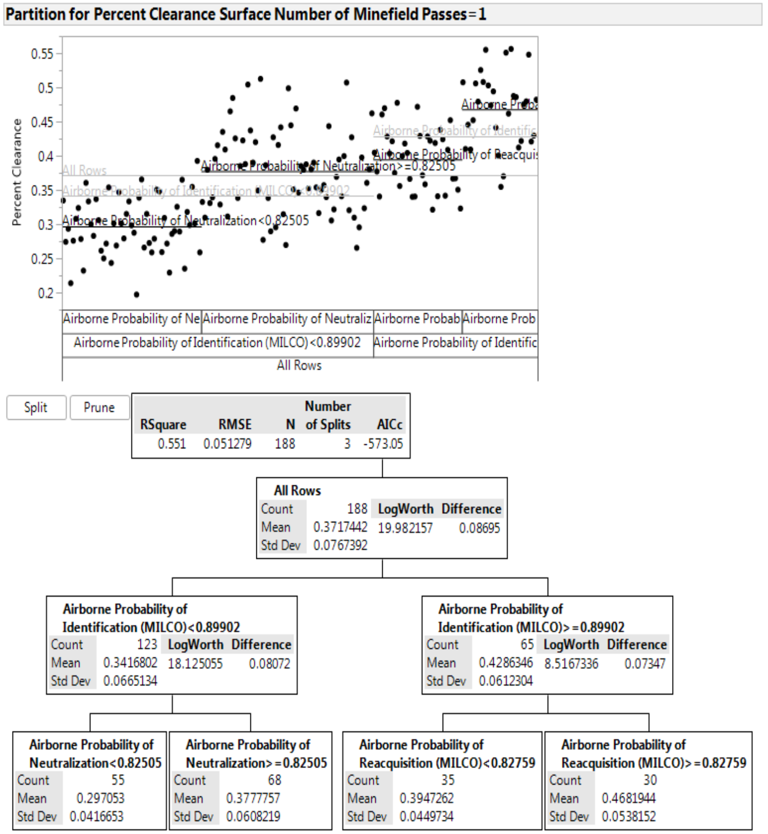
Summary Statistics

Mean	0.7898305
Std Dev	0.3376633
Std Err Mean	0.0179466
Upper 95% Mean	0.8251262
Lower 95% Mean	0.7545348
N	354

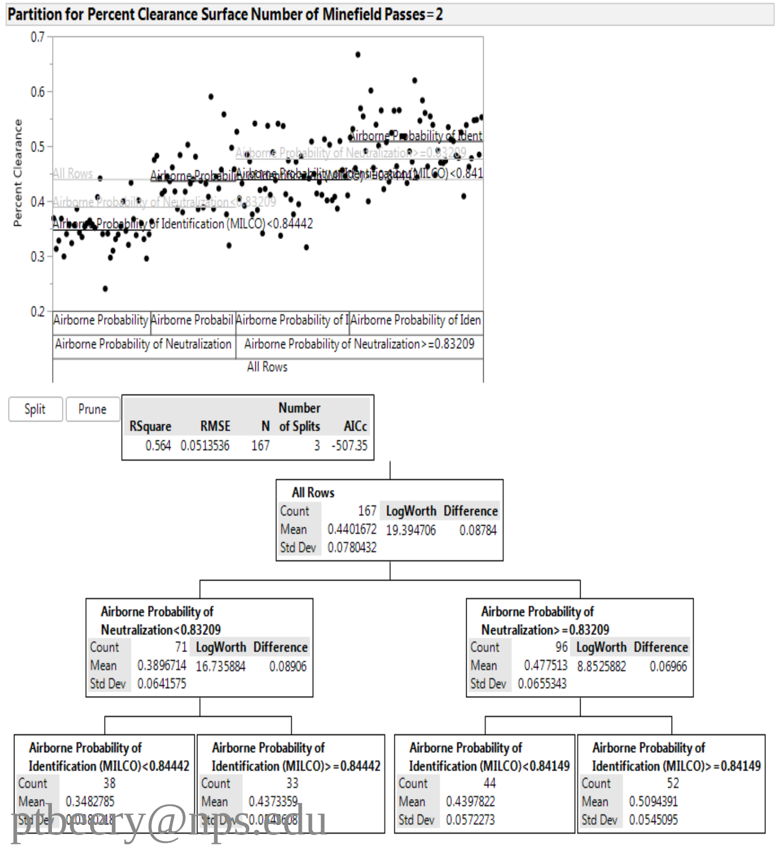
Initial Model Analysis: LCS

- Initial analysis suggested that the Percent Clearance MOE is most substantially impacted by the probabilities of Identification and Neutralization (Detection and Classification were also statistically significant)
- The number of minefield passes conducted was the only environmental/operational variable that had a statistically significant impact on performance
- Regardless of the number of minefield passes, the Probability of Identification and the Probability of Neutralization were the top two performance drivers (unlike with the MCM-1, there was reordering)

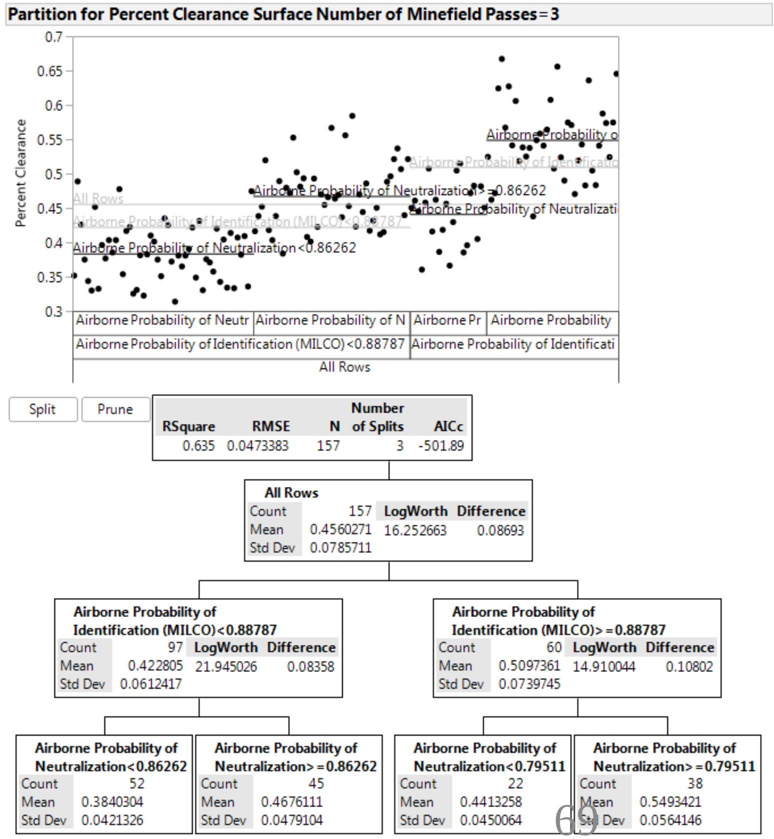
One Minefield Pass



Two Minefield Passes



Three Minefield Passes



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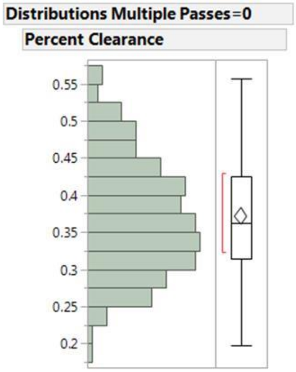
Initial Model Analysis: LCS(cont.)

LCS Percent Clearance Analysis

- One Minefield Pass: Average 37% Clearance
- Two Minefield Passes: Average 44% Clearance
- Three Minefield Passes: Average 45% Clearance
- *Takeaway:*
  - *There may be diminishing returns associated with a third minefield pass*
- *Questions:*
  - *Is the second/third minefield pass practically important? Is the cost worth it?*

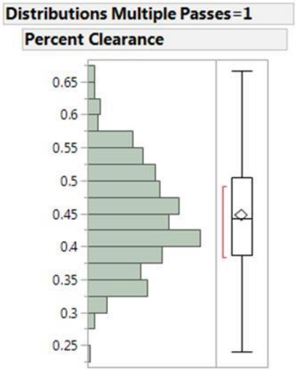


Quantiles

100.0%	maximum	0.55625
99.5%		0.55625
97.5%		0.5316041667
90.0%		0.4798333333
75.0%	quartile	0.4251041667
50.0%	median	0.3627083333
25.0%	quartile	0.3146875
10.0%		0.274
2.5%		0.2341979167
0.5%		0.1970833333
0.0%	minimum	0.1970833333

Summary Statistics

Mean	0.3717442
Std Dev	0.0767392
Std Err Mean	0.0055968
Upper 95% Mean	0.3827852
Lower 95% Mean	0.3607033
N	188



Quantiles

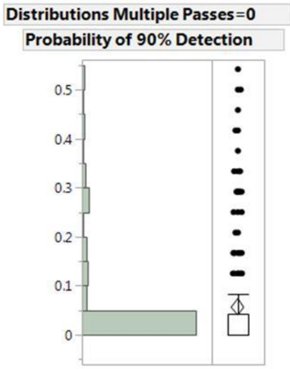
100.0%	maximum	0.6670833333
99.5%		0.6668229167
97.5%		0.6180729167
90.0%		0.5533333333
75.0%	quartile	0.5040625
50.0%	median	0.4420833333
25.0%	quartile	0.38625
10.0%		0.341875
2.5%		0.31625
0.5%		0.2747916667
0.0%	minimum	0.2404166667

Summary Statistics

Mean	0.4478524
Std Dev	0.0785801
Std Err Mean	0.0043656
Upper 95% Mean	0.4564409
Lower 95% Mean	0.4392638
N	324

LCS Probability of 90% Detection Analysis

- One Minefield Pass: Average 5% Probability of 90% Detection
- Multiple Minefield Passes: Average 96% Probability of 90% Detection
- One Minefield Pass: Median 0% Probability of 90% Detection
- Multiple Minefield Passes: Median 100% Probability of 90% Detection
- *Takeaway: Multiple passes are certainly valuable with respect to the Probability of 90% Detection*

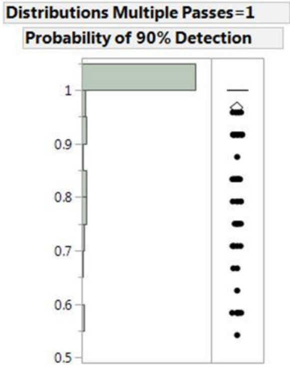


Quantiles

100.0%	maximum	0.5416666667
99.5%		0.5416666667
97.5%		0.428125
90.0%		0.25
75.0%	quartile	0.0416666667
50.0%	median	0
25.0%	quartile	0
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	0.056516
Std Dev	0.1180527
Std Err Mean	0.0086099
Upper 95% Mean	0.0735009
Lower 95% Mean	0.039531
N	188



Quantiles

100.0%	maximum	1
99.5%		1
97.5%		1
90.0%		1
75.0%	quartile	1
50.0%	median	1
25.0%	quartile	1
10.0%		0.8333333333
2.5%		0.6666666667
0.5%		0.5677083333
0.0%	minimum	0.5416666667

Summary Statistics

Mean	0.9675926
Std Dev	0.0871791
Std Err Mean	0.0048433
Upper 95% Mean	0.977121
Lower 95% Mean	0.9580642
N	324

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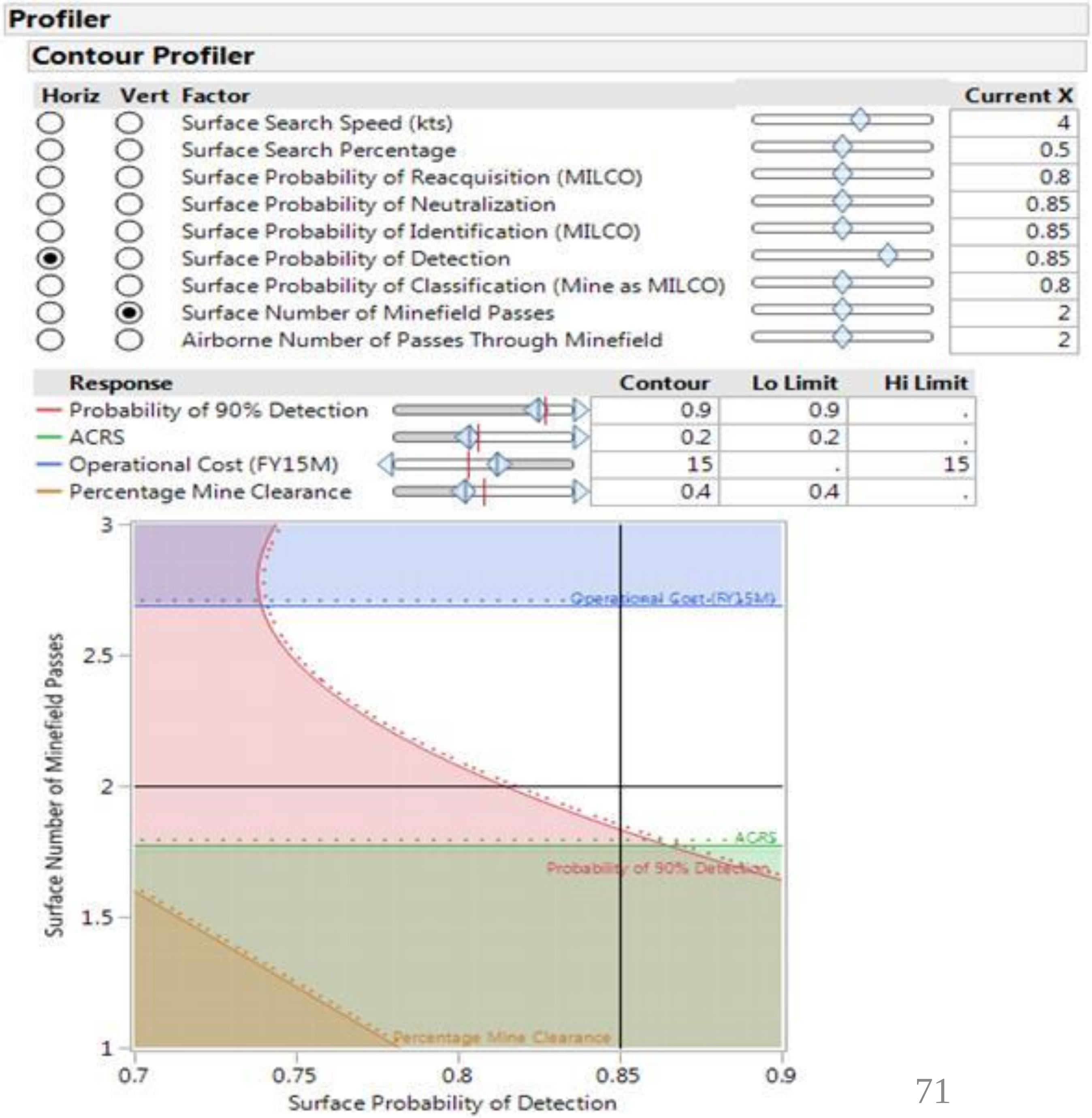
Tradespace Analysis: MCM-1

MCM-1 Configuration Tradespace Visualization

- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.20
  - Operational Cost less than $15M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the right
- Many two dimensional projections are possible, this visualization presents the Probability of Detection (x-axis) and the Number of Minefield Passes (y-axis)
- This “feasible space” exists assuming that each of the other system design parameters are held constant at the values shown in the upper right



Tradespace Analysis: MCM-1 (2)

MCM-1 Configuration Tradespace Visualization

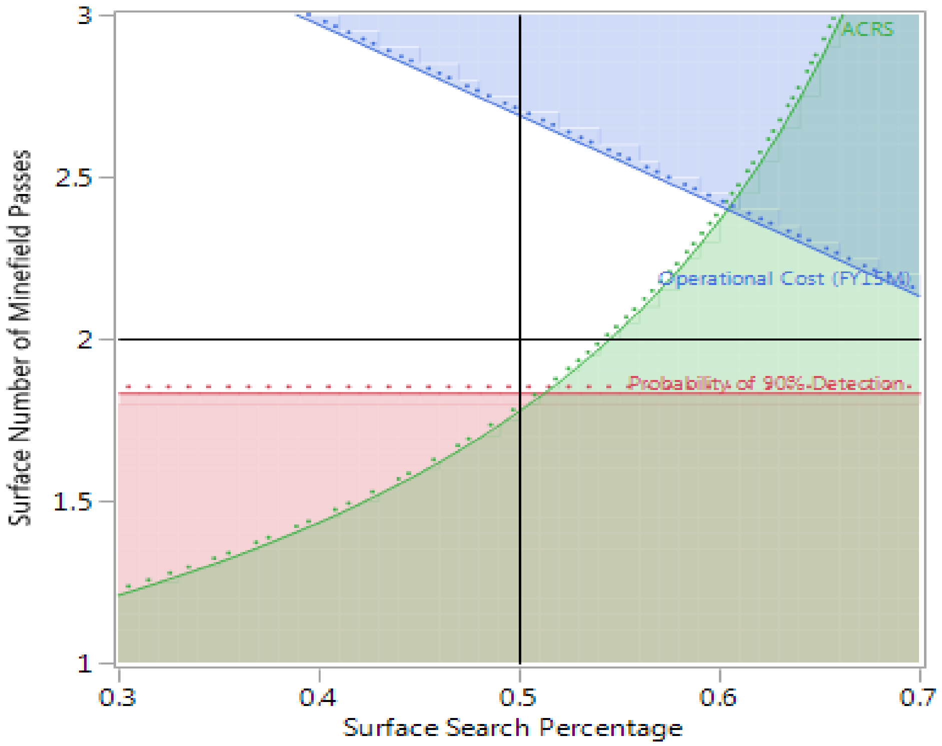
- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.20
  - Operational Cost less than $15M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the left
- Many two dimensional projections are possible, this visualization presents the **Surface Search Percentage** (x-axis) and the Number of Minefield Passes (y-axis)
- This "feasible space" exists assuming that each of the other system design parameters are held constant at the values shown in the upper right

Profiler

Contour Profiler

Horiz	Vert	Factor	Current X
○	○	Surface Search Speed (kts)	4
●	○	Surface Search Percentage	0.5
○	○	Surface Probability of Reacquisition (MILCO)	0.8
○	○	Surface Probability of Neutralization	0.85
○	○	Surface Probability of Identification (MILCO)	0.85
○	○	Surface Probability of Detection	0.85
○	○	Surface Probability of Classification (Mine as MILCO)	0.8
○	●	Surface Number of Minefield Passes	2
○	○	Airborne Number of Passes Through Minefield	2

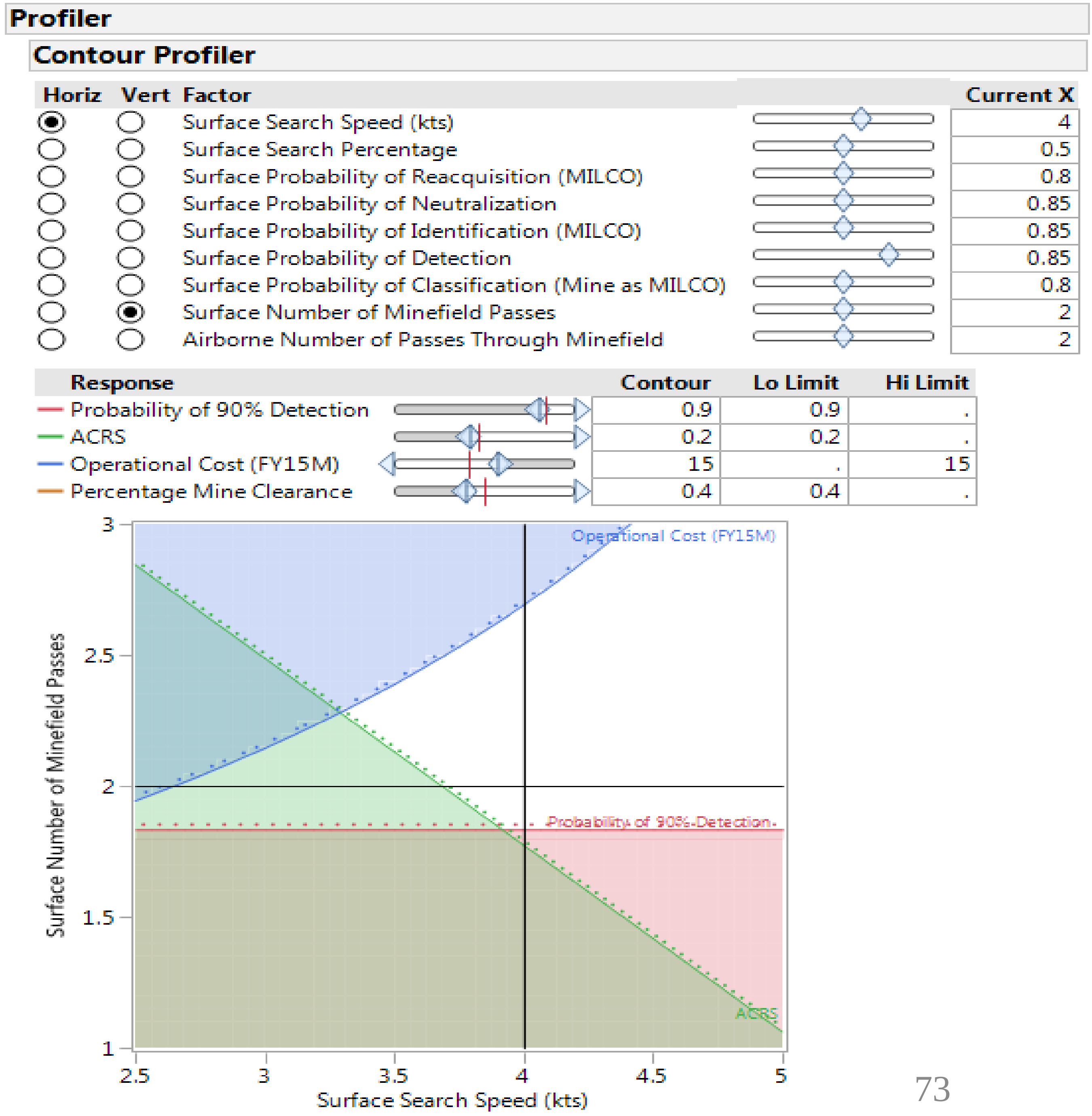
Response	Contour	Lo Limit	Hi Limit
Probability of 90% Detection	0.9	0.9	.
ACRS	0.2	0.2	.
Operational Cost (FY15M)	15	.	15
Percentage Mine Clearance	0.4	0.4	.



Tradespace Analysis: MCM-1 (3)

MCM-1 Configuration Tradespace Visualization

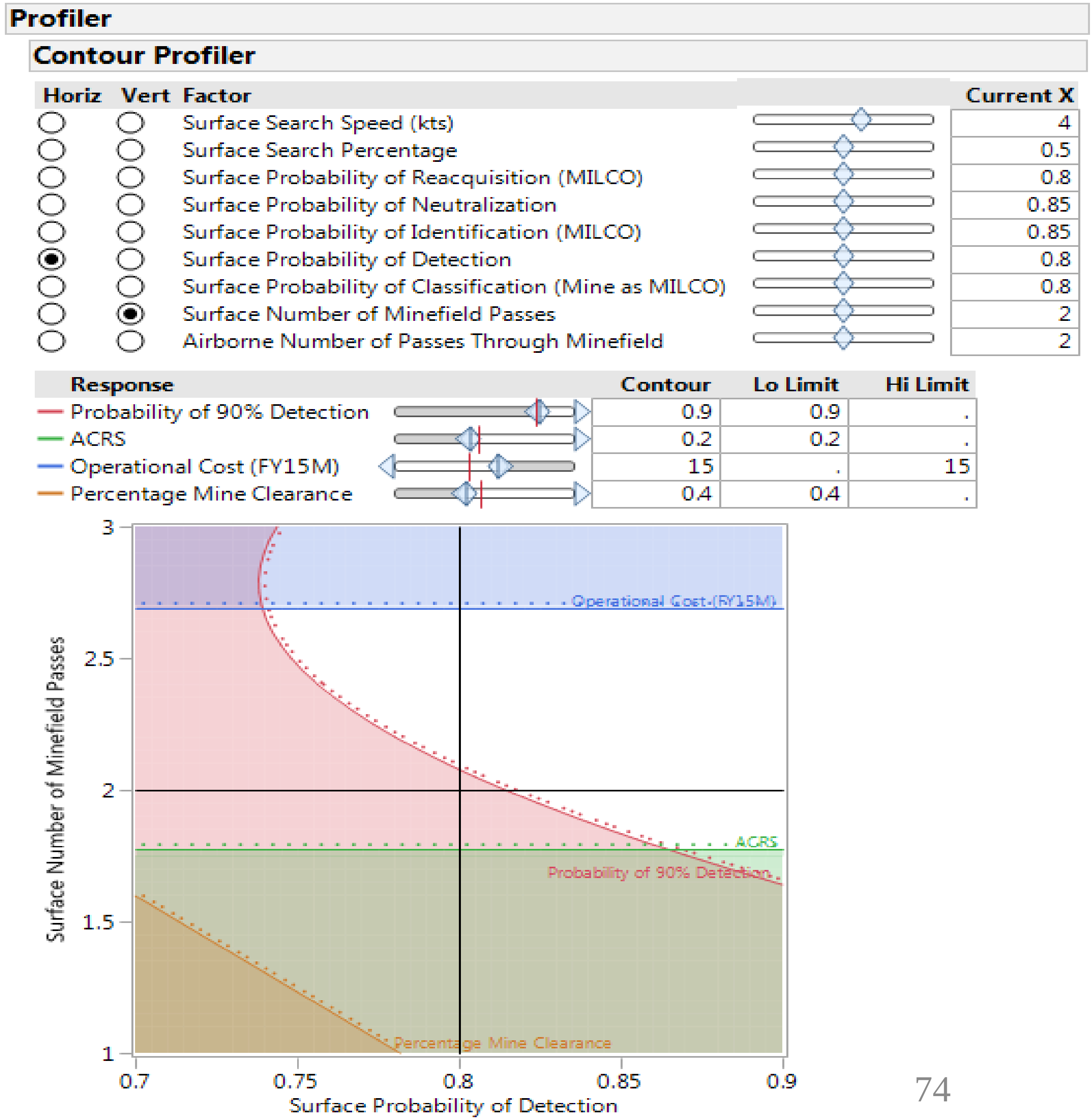
- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.20
  - Operational Cost less than $15M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the right
- Many two dimensional projections are possible, this visualization presents the **Surface Search Speed** (x-axis) and the Number of Minefield Passes (y-axis)
- This "feasible space" exists assuming that each of the other system design parameters are held constant at the values shown in the upper right



Tradespace Analysis: MCM-1 (4)

MCM-1 Configuration Tradespace Visualization

- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.20
  - Operational Cost less than $15M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the right
- Many two dimensional projections are possible, this visualization presents the **Probability of Detection** (x-axis) and the Number of Minefield Passes (y-axis)
- This “feasible space” exists assuming that each of the other system design parameters are held constant at the values shown in the upper right



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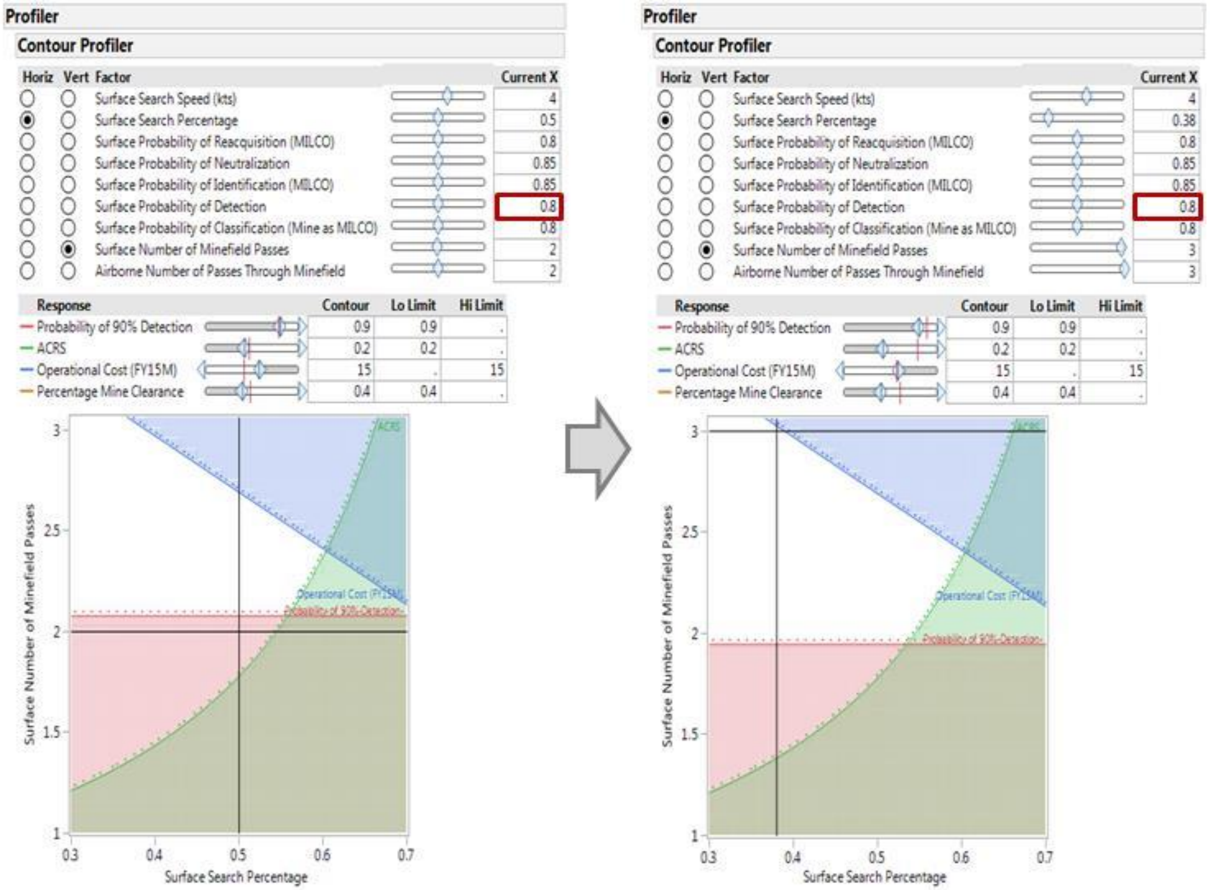
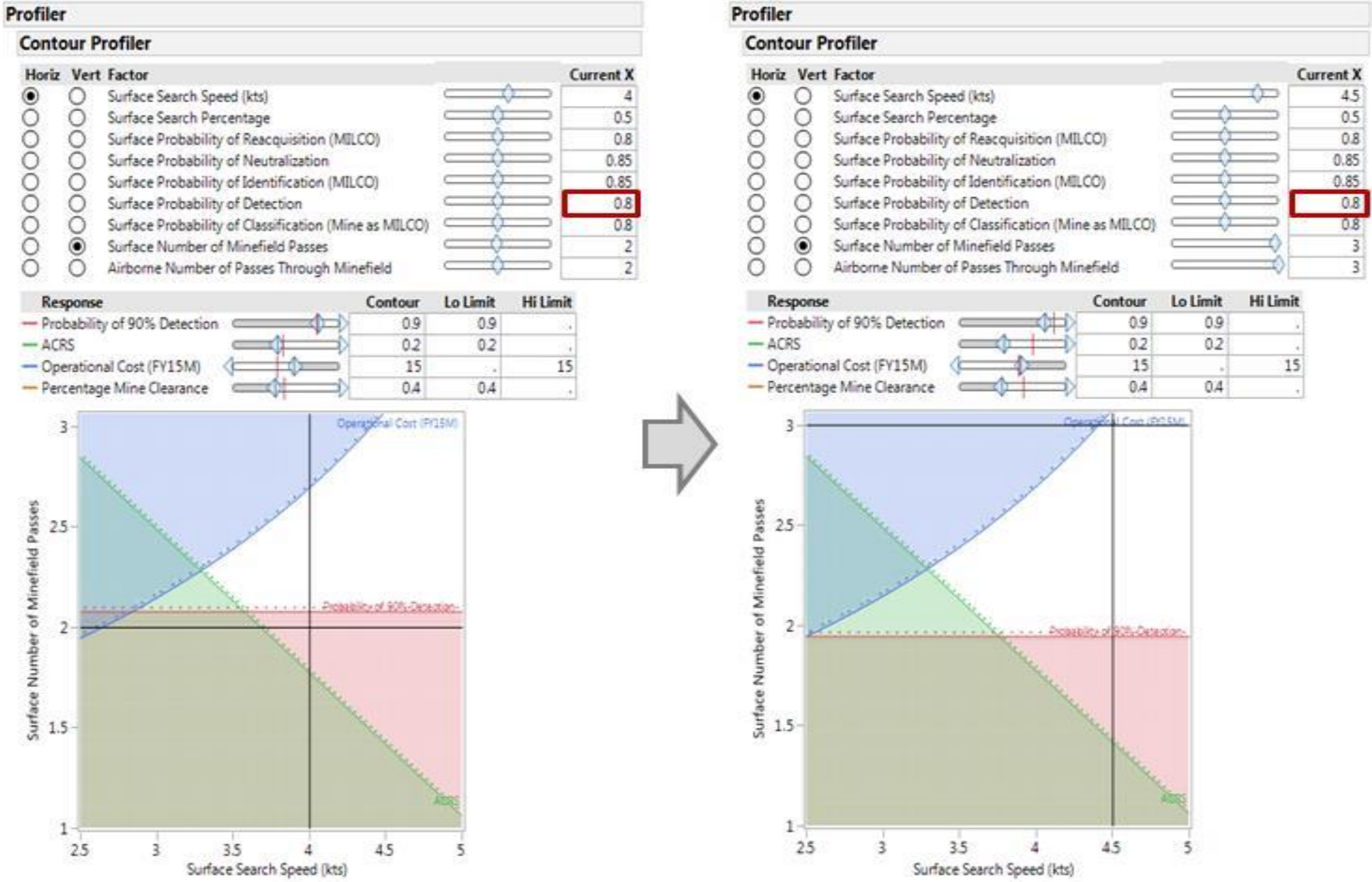
Tradespace Analysis: MCM-1 (5)

- The reduction of the Probability of Detection to 0.80 knots can be mitigated by altering the value of other potential design parameters
- This type of exploration allows for the identification of trades and alterations that are realistic as well as ones that are not realistic
- Decreasing the Surface Search Percentage to 0.38 allows for acceptable performance with a third minefield pass
- Increasing the Surface Search Speed to 4.5 knots allows for acceptable performance with a third minefield pass

Option 1: Surface Search Percentage



Option 2: Surface Search Speed



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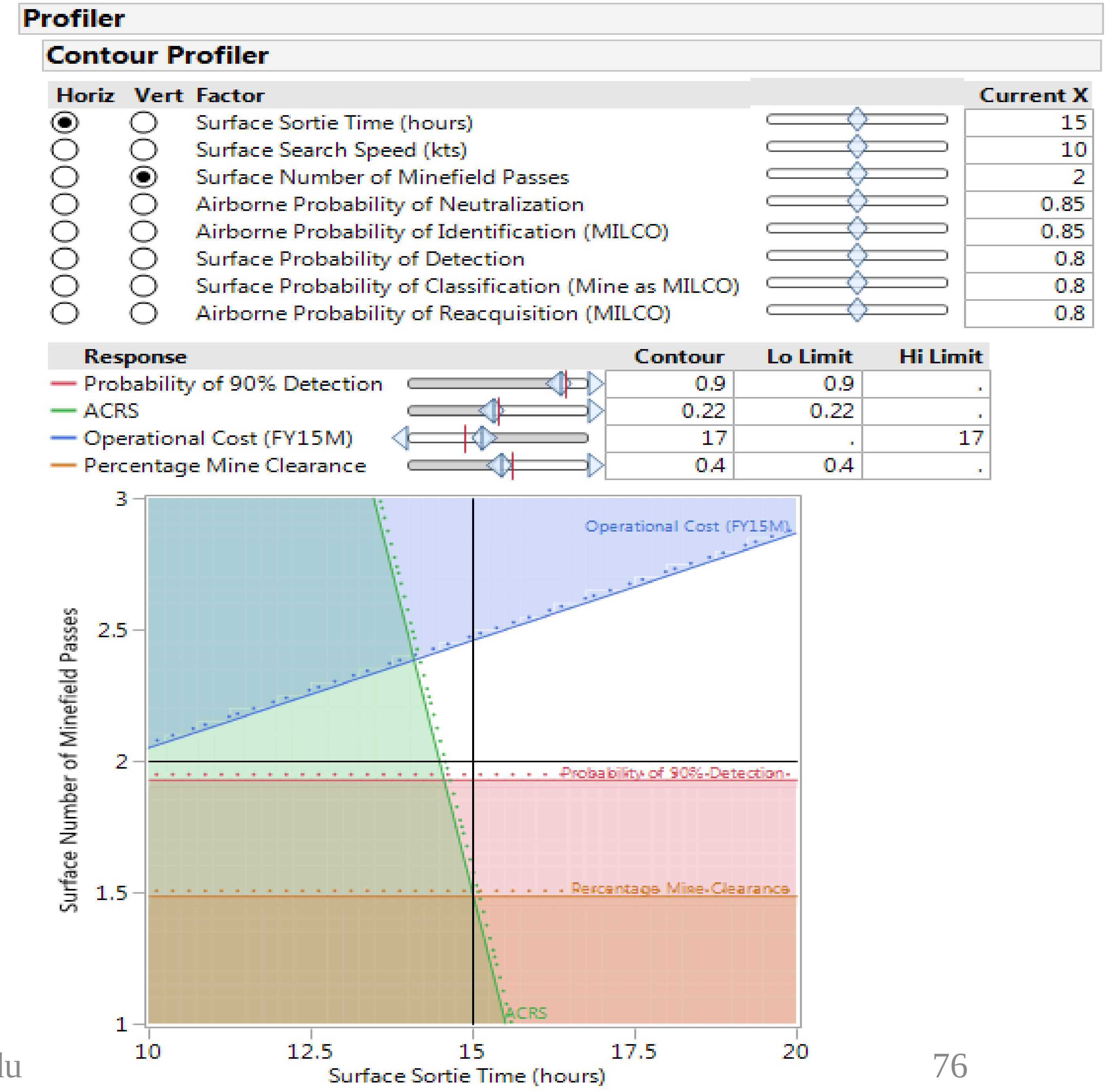
Tradespace Analysis: LCS (2)

<u>LCS Configuration Tradespace Visualization</u>

- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.22
  - Operational Cost less than $17M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the right
- Many two dimensional projections are possible, this visualization presents the **Surface Sortie Time** (x-axis) and the Number of Minefield Passes (y-axis)
- This “feasible space” exists assuming that each of the other system design parameters are held constant at the values shown in the upper right



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Tradespace Analysis: LCS (3)

LCS Configuration Tradespace Visualization

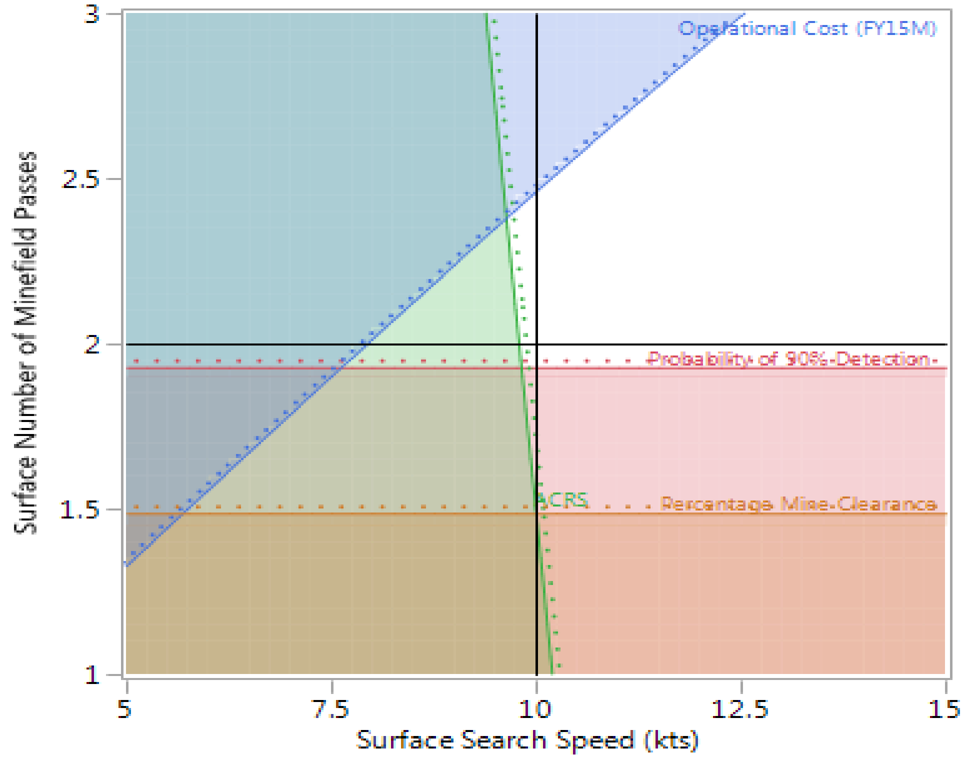
- Constraints have been imposed for each of the MOEs
  - Probability of 90% Detection greater than 0.90
  - ACRS greater than 0.22
  - Operational Cost less than $17M
  - Percent Mine Clearance greater than 0.40
- Feasible configurations identified by the white region on the right
- Many two dimensional projections are possible, this visualization presents the **Surface Search Speed** (x-axis) and the Number of Minefield Passes (y-axis)
- This "feasible space" exists assuming that each of the other system design parameters are held constant at the values shown in the upper right

Profiler

Contour Profiler

Horiz	Vert	Factor	Current X
○	○	Surface Sortie Time (hours)	15
◉	○	Surface Search Speed (kts)	10
○	◉	Surface Number of Minefield Passes	2
○	○	Airborne Probability of Neutralization	0.85
○	○	Airborne Probability of Identification (MILCO)	0.85
○	○	Surface Probability of Detection	0.8
○	○	Surface Probability of Classification (Mine as MILCO)	0.8
○	○	Airborne Probability of Reacquisition (MILCO)	0.8

Response	Contour	Lo Limit	Hi Limit
Probability of 90% Detection	0.9	0.9	.
ACRS	0.22	0.22	.
Operational Cost (FY15M)	17	.	17
Percentage Mine Clearance	0.4	0.4	.



Experimental Design Purpose

- "Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful."[1]
- Proper usage of experimental design helps ensure that any inaccuracies are not a result of improper model/simulation setup
- Experimental design adds rigor to the process of modeling and simulation by planning the model/simulation and defining the nature of the data to be collected
  - This ensures that the assumptions behind statistical analysis techniques are not violated
  - Experimental design specifies the system configurations which must be modeled in order to properly analyze the impact of changes in system configuration on system performance

Box, George E.P, and Norman R. Draper (1987). Empirical Model-Building and Response Surfaces: Wiley

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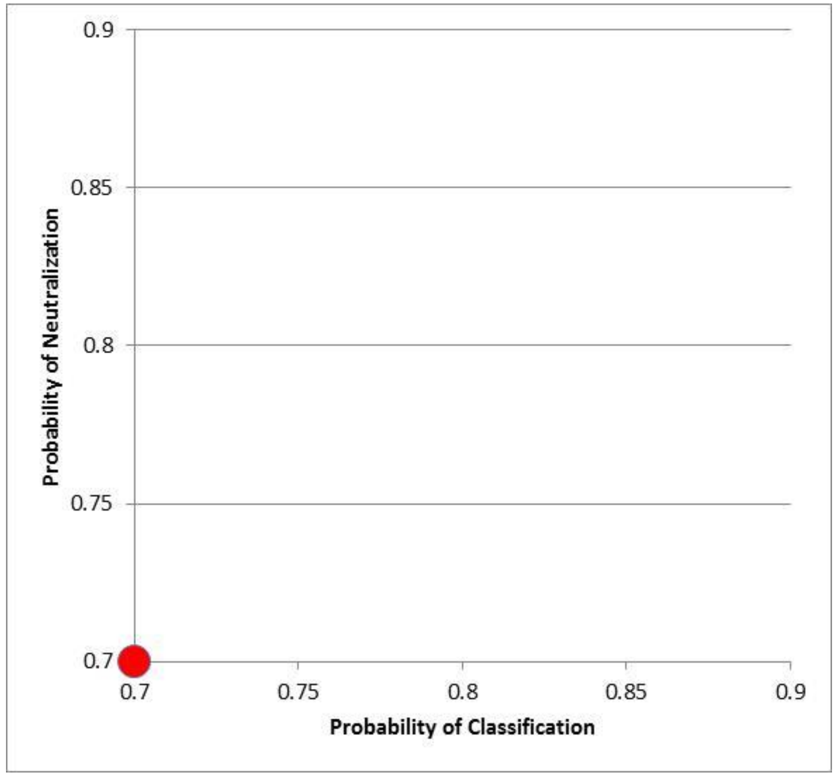
Experimental Design for Simulation Models (1)

- Ex: Simulation of mine warfare system
- Variables of interest:
  - Probability of neutralization
    - Min Value: 0.7
    - Max Value: 0.9
  - Probability of classification
    - Min Value: 0.7
    - Max Value: 0.9
- Response:
  - Percent Mine Clearance
    - Red: Mission Failed
    - Green: Mission Complete

Basline		
Run	Prob Classification	Prob Neutralization
1	0.7	0.7



Experimental Design for Simulation Models (2)

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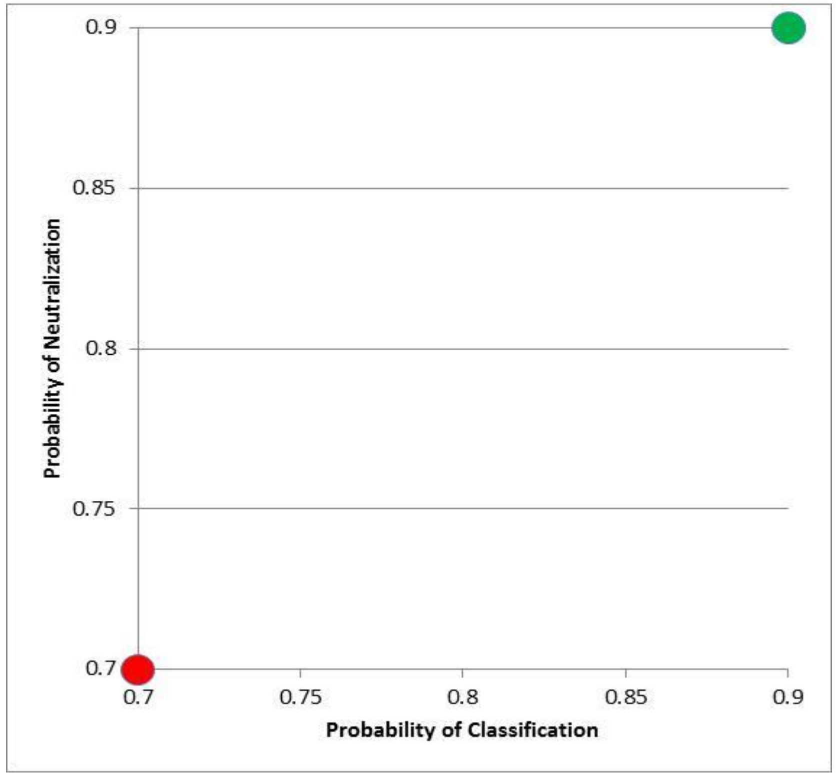
- Ex: Simulation of mine warfare system
- Variables of interest:
  - Probability of neutralization
    - Min Value: 0.7
    - Max Value: 0.9
  - Probability of classification
    - Min Value: 0.7
    - Max Value: 0.9
- Response:
  - Percent Mine Clearance
    - Red: Mission Failed
    - Green: Mission Complete

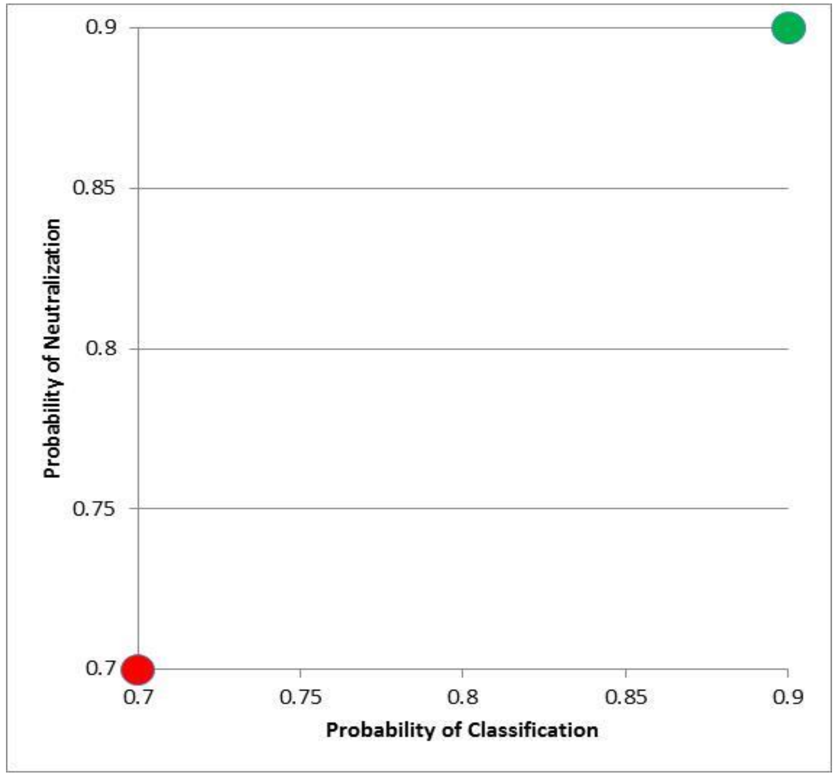
Basline + Single Excursion		
Run	Prob Classification	Prob Neutralization
1	0.7	0.7
2	0.9	0.9



Experimental Design for Simulation Models (3)

- Ex: Simulation of mine warfare system
- Variables of interest:
  - Probability of neutralization
    - Min Value: 0.7
    - Max Value: 0.9
  - Probability of classification
    - Min Value: 0.7
    - Max Value: 0.9
- Response:
  - Percent Mine Clearance
    - Red: Mission Failed
    - Green: Mission Complete

2 Variable 2 Level Factorial		
Run	Prob Classification	Prob Neutralization
1	0.7	0.7
2	0.7	0.9
3	0.9	0.7
4	0.9	0.9



Genetic Algorithm Procedure (Steps 1-3)

- Define an initial set of candidate columns. The number of columns is based on the number of variables in the design matrix (k). Set the number of observations in each column (n). Generate k columns by defining each column as a random permutation of the n integers. This results in definition of an n × k matrix.
- Define the upper and lower bounds for the columns. The upper bound is defined as the maximum of each column. The lower bound is defined as the minimum of each column.
- Define the fitness function. The maximum absolute pairwise correlation (ρ_{map}) and maximum imbalance (δ) are used to calculate the fitness function.

Genetic Algorithm Procedure (Step 4)

- Create a function to calculate ρ_{map}
  - Define a 1×1 vector of zeros
  - Define a design matrix
  - Define an upper triangular matrix that calculates the correlation between each column of the design matrix
  - Convert the upper triangular matrix to a single column and select the largest value (ρ_{map}) from the column
  - Save ρ_{map} in the 1×1 vector of zeros

Genetic Algorithm Procedure (Step 5)

- Create a function to calculate δ_x for each column of the design matrix (where each column has l levels), as well as the δ value resulting from the addition of a potential column
  - Define a $1 \times l$ matrix of zeros
  - Define the ideal number of observations for a given column, calculated as (n/β_x)
  - Count the number of observations that occur at each level within the column, presented in Equation 10 as ω_{xl}
  - Calculate the imbalance associated with each level within the column
  - Save each of the imbalance values in the $1 \times l$ matrix of zeros
  - Save the maximum value in the $1 \times l$ matrix of zeros as δ_x
  - Calculate the maximum δ_x value and save it as δ

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Genetic Algorithm Procedure (Step 6a)

- Define the properties of the genetic algorithm. In general, four properties for genetic algorithms must be defined that govern the behavior of the algorithm. Within Matlab, those parameters are defined as: **Selection Options**, Reproduction Options, Mutation Options, and Crossover Options.
- Selection Options:
  - The genetic algorithm will select a set of the current generation to be used as parents to generate the subsequent generations.
  - This research uses a stochastic uniform selection.
  - After an initial population of n candidate columns has been generated, stochastic uniform selection assigns a rank, in terms of raw fitness value, to each of the members of the generation.
  - Each of the members of the generation is then sorted in ascending order according to their rank from 1 to n.
  - Each individual is then assigned a scaling value proportional to $1/\sqrt{n}$.
  - The scaled values are then used to generate a list of individuals that will be used to create the next generation. By the stochastic uniform convention, a portion of the individuals are identified as elite and are included directly in the next generation. Another portion of the individuals are identified as “parents” that will be modified to create “children.” These children are combined with the elite individuals to define the next generation. Children are generated through either crossover (also called recombination) of parents or mutation of parents. The distribution of those children in the next generation (in terms of elite individuals from the previous generation, crossover children, and mutation children) is specified in the genetic algorithm Reproduction Options.

Genetic Algorithm Procedure (Step 6b)

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- Define the properties of the genetic algorithm. In general, four properties for genetic algorithms must be defined that govern the behavior of the algorithm. Within Matlab, those parameters are defined as: Selection Options, **Reproduction Options**, Mutation Options, and Crossover Options.
- Reproduction Options:
  - The reproduction options in the genetic algorithm specify how children are generated for each generation.
  - The number of elite parents that are automatically included in the next generation is specified directly.
  - In this research an elite count of 5 provided excellent results.
  - The ratio of crossover children to mutation children is also specified (in Matlab it is defined as the percentage of children, other than elite children, developed through crossover).
  - In this research crossover fractions between 0.88 and 0.92 provided the best results.

Genetic Algorithm Procedure (Step 6c)

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- Define the properties of the genetic algorithm. In general, four properties for genetic algorithms must be defined that govern the behavior of the algorithm. Within Matlab, those parameters are defined as: Selection Options, Reproduction Options, **Mutation Options**, and Crossover Options.
- Mutation Options:
  - The mutation options specify how mutation is conducted by the genetic algorithm.
  - Mutation is the process of making small changes to elements of parent individuals to create children. This encourages diversity while also preserving the majority of the characteristics of high performing parents.
  - This research uses adaptive feasible mutation.
  - After the crossover fraction specifies the portion of the parents to be modified via mutation (typically between 0.08 and 0.12 in this research) each of the entries for those parents may be mutated.
  - A mutation probability is specified (the default probability of 0.01 was not changed) and all selected entries are replaced by a random number within the upper and lower bounds specified previously. Utilization of mutation in this fashion allows for increased ability to explore the design space.

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Genetic Algorithm Procedure (Step 6d)

- Define the properties of the genetic algorithm. In general, four properties for genetic algorithms must be defined that govern the behavior of the algorithm. Within Matlab, those parameters are defined as: Selection Options, Reproduction Options, **Mutation Options**, and Crossover Options.
- Crossover Options:
  - The crossover options specify how crossover (also known as recombination in traditional biology) is conducted by the genetic algorithm. Crossover is the process of combining characteristics from two parent individuals to form children.
  - This research uses scattered crossover.
  - Scattered crossover is conducted by creating a random binary vector that is the same size as the columns of the design matrix. Where the binary vector is a 1, the entry from the first parent is used, where the binary vector is a 0, the entry from the second parent is used. The resulting vector defines the new child.
  - As with the mutation operator, implementation of crossover in this fashion increases the freedom of the genetic algorithm to explore the entire solution space.

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