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The Scenario-Based Experimental-Design (SBED) Test Approach

Forecasting System-Level Mission Capabilities with Subsystem Functionality Test Results

The 33rd ITEA T&E Symposium

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Bottom Line Up Front

Goal

Introduce to the T&E community an ability to characterize system-level performance and mission capabilities during early verification phases (component- and subsystem-level verifications).

Complex Systems (CxS) & System of Systems (SoS)

The Scenario-Based Experimental-Design (SBED) Test Approach

Supplement the execution methodology of the traditional component- and subsystem-level test activities with two tools:

1. Mission-Relative Scenario-Based Analysis
2. Experimental Design (DoE)

Outline

I. The Problem

- Why T&E cannot breakaway from its traditional bottom-up approach & manufacture early system-level assessments.
- The need the bridge the gap between SysEng and T&E

II. The Potential Solution

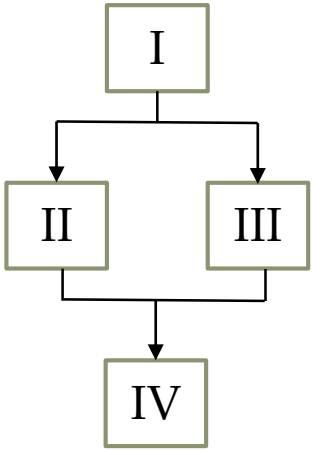
- The Scenario-Based Experimental-Design (SBED) Test Approach

III. Case Study

- Navy Experimental Dive Unit (NEDU) Saturation Fly-Away Diving System (SAT FADS)
- CxS verifcation Process with and without the SBED Approach

IV. Q&A

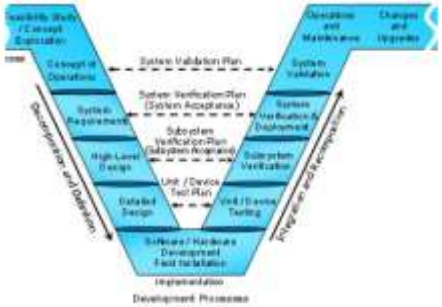
Presentation's mission representative scenario



I. The Fundamental Gap Between Systems Engineering (SE) and T&E

(The Problem)

The Systems Engineering (SE) V



T&E Roles in CxS & SoS Development Cycle

Traditional T&E Roles

- Verification – to confirm system-of-interest performs its intended functions and meet the performance requirements. [4]
- Validation – to establish system-of-interest's applicability to stakeholders' requirements [5]

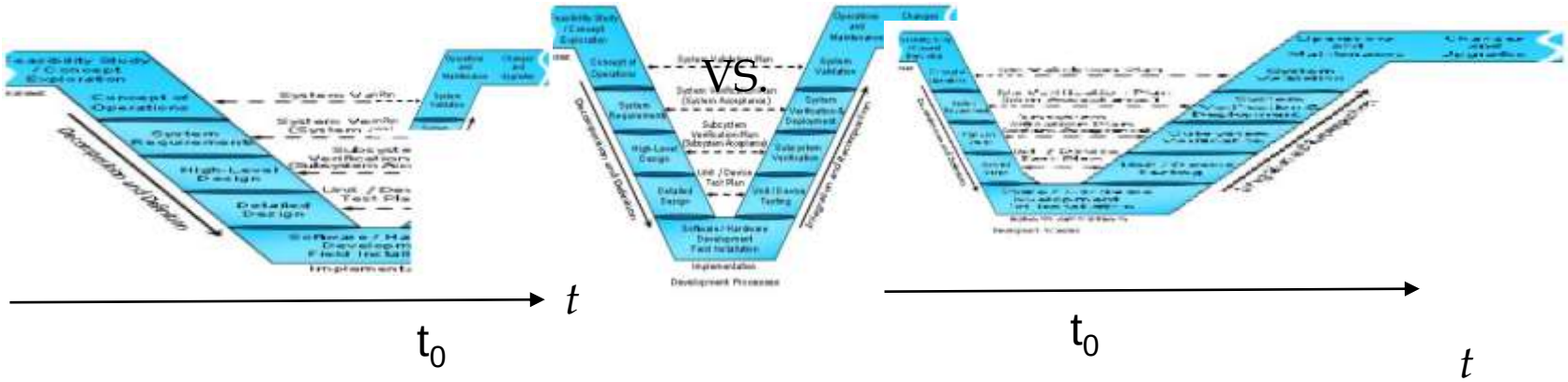
Expectation of T&E Roles in CxS & SoS Development Cycles

- V&V
- **Produce early assessments of the system's end-to-end performance and mission capabilities**

The Gap Between SE and T&E for CxS & SoS

Stakeholder and Developers' SE-V

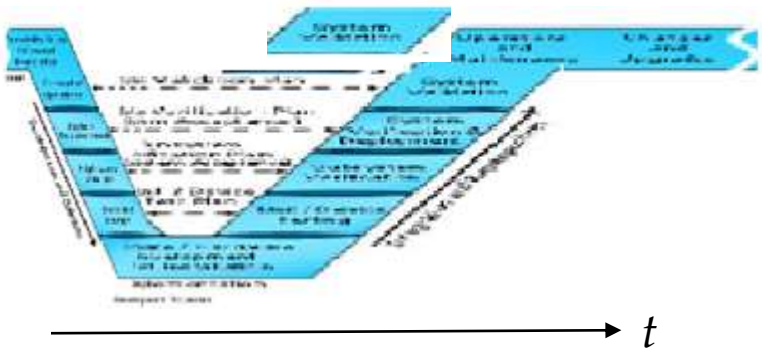
Testers' SE-V



The Potential Solution

The Scenario-Based Experimental Design (SBED) Test Approach

1. Continue with the existing bottom-up test implementation approach.
2. Execute the component- and subsystem-level test activities with **experimental design** (DoE) using operational-environment elements as common input factor
3. Aggregate the test results into **mission-representative scenario**(s) to forecast system-level performance and mission capabilities.



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II. The SBED Test Approach

(The Proposed Solution)

Assumptions

Assumptions

- Design specifications and requirements are already existing.
  - Requirements are testable and measurable
- User requirements are already existing or available through user elicitation.
- Initial verification activities are at component- and subsystem-level with the focus of independent functionality verifications.

The SBED Approach Methodology

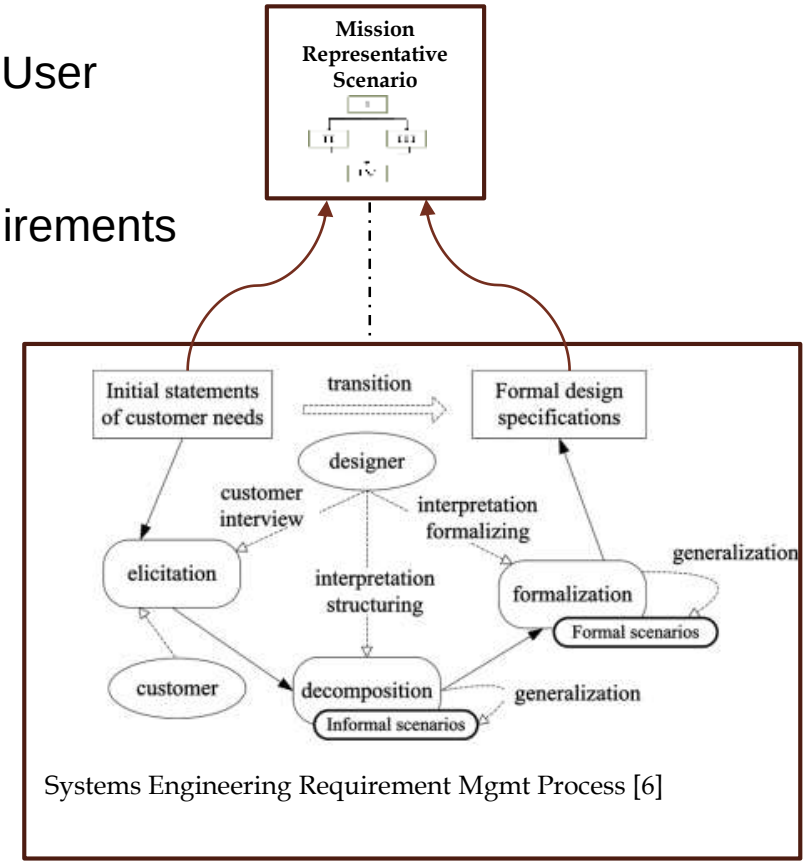
Step 1, **SB**ED (scenario-based):

- Generate Mission-Relative Scenarios from User Requirements
  - Tasks → Subtasks → Functions
- Populate Scenarios with defined design requirements
  - MBSE
  - UML / SysML
  - Manually [6]

Step 2, SB**ED** (experimental design):
Execute component- and subsystem-level functionality tests with Experimental Design

- Common Input Factors
  - Mission environment elements

Step 3, **SB+ED**:
Aggregate test results to forecast system performance & mission capabilities

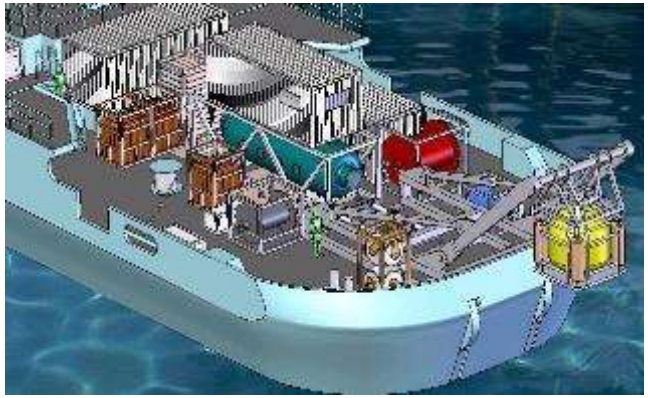


Systems Engineering Requirement Mgmt Process [6]

Case Study

Saturating Fly Away Diving System (SAT FADS)

US Navy's Experimental Diving Unit (NEDU)



Photographs courtesy of NEDU

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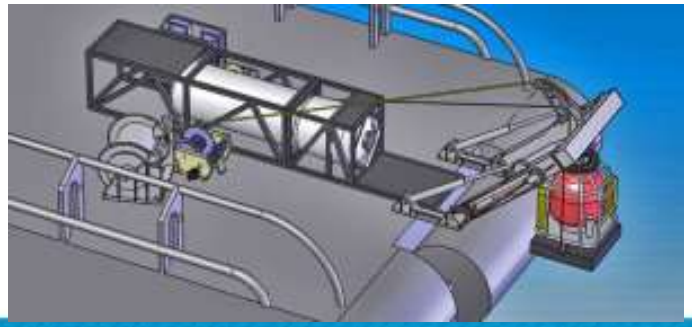
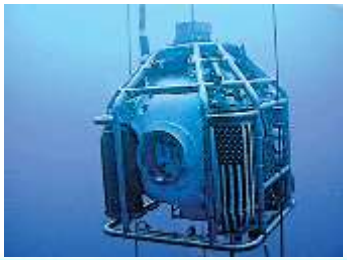
SAT FADS – CxS Subsystems

1. Main Deck Decompression Chamber (DDC)
   - including living quarters and air lock
2. 3-Man Diving Bell (DB)
3. DB Handling System
4. Bullet Control Van
5. (2) Auxiliary Support equipment Vans

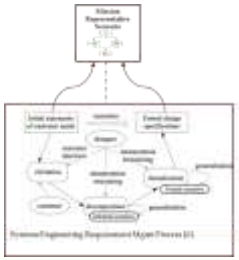




http://www.phnx-international.com/phnx/services/engineering/specialized-underwater-systems/saturation-fly-away-diving-system-satfads/ (SEP16)

The Scenario-Based Experimental Design Approach (Step 1)

1. Generate mission-representative scenario(s) from user requirements
2. Populate the scenario(s) with low-level design requirements.



SAT FADS User Requirement [7] [8]

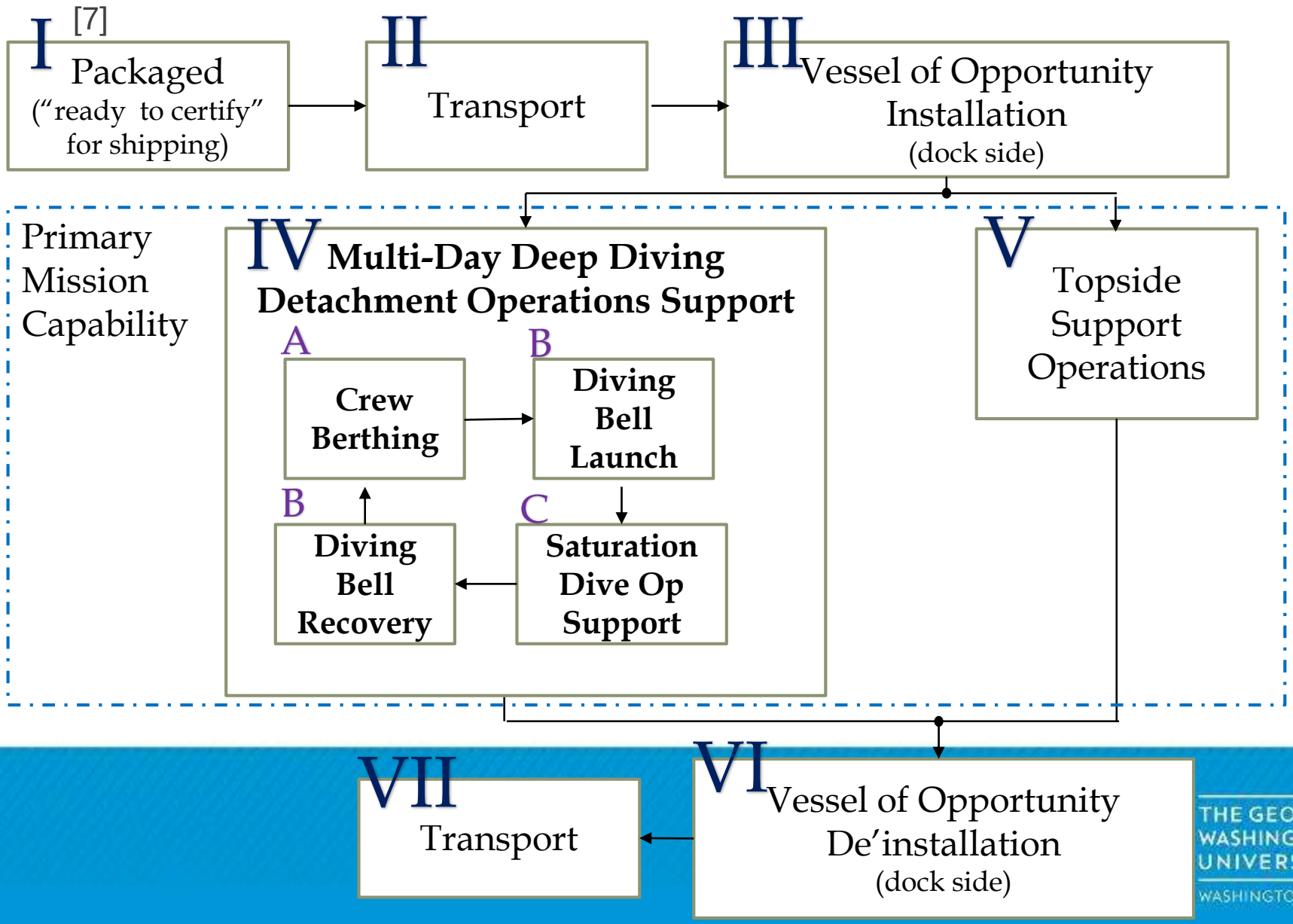
“The system will be air-transportable and be installed and operated from a vessel of opportunity (VOO).

“The SAT FADS will provide life support and habitability features capable of sustaining 6 saturation divers at 1,000 fsw (304.38 msw) and deployment of 3 divers in a diving bell with the ability to conduct in-water excursion to 1,000 fsw (304.8msw) during a 30-day mission profile.

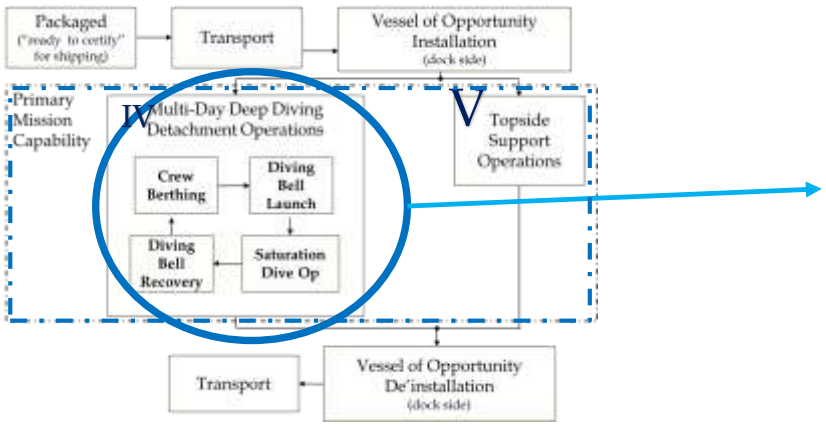
“The system will require fuel, potable water, sanitation disposal services, seawater, and crew subsistence and berthing.

“The system will have a 20 year service lie and utilize commercial-off-the-shelf (COTS) and non-developmental items (NDI) to the maximum extent possible. “

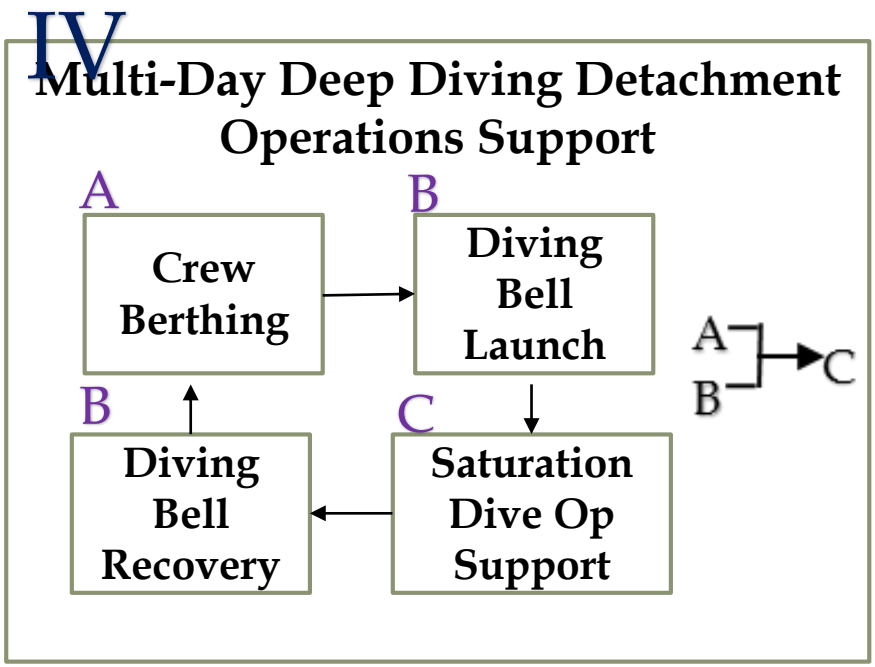
SAT FADS Mission-Representative Scenario



Scenario-Based Performance Estimations



SAT FADS mission scenario



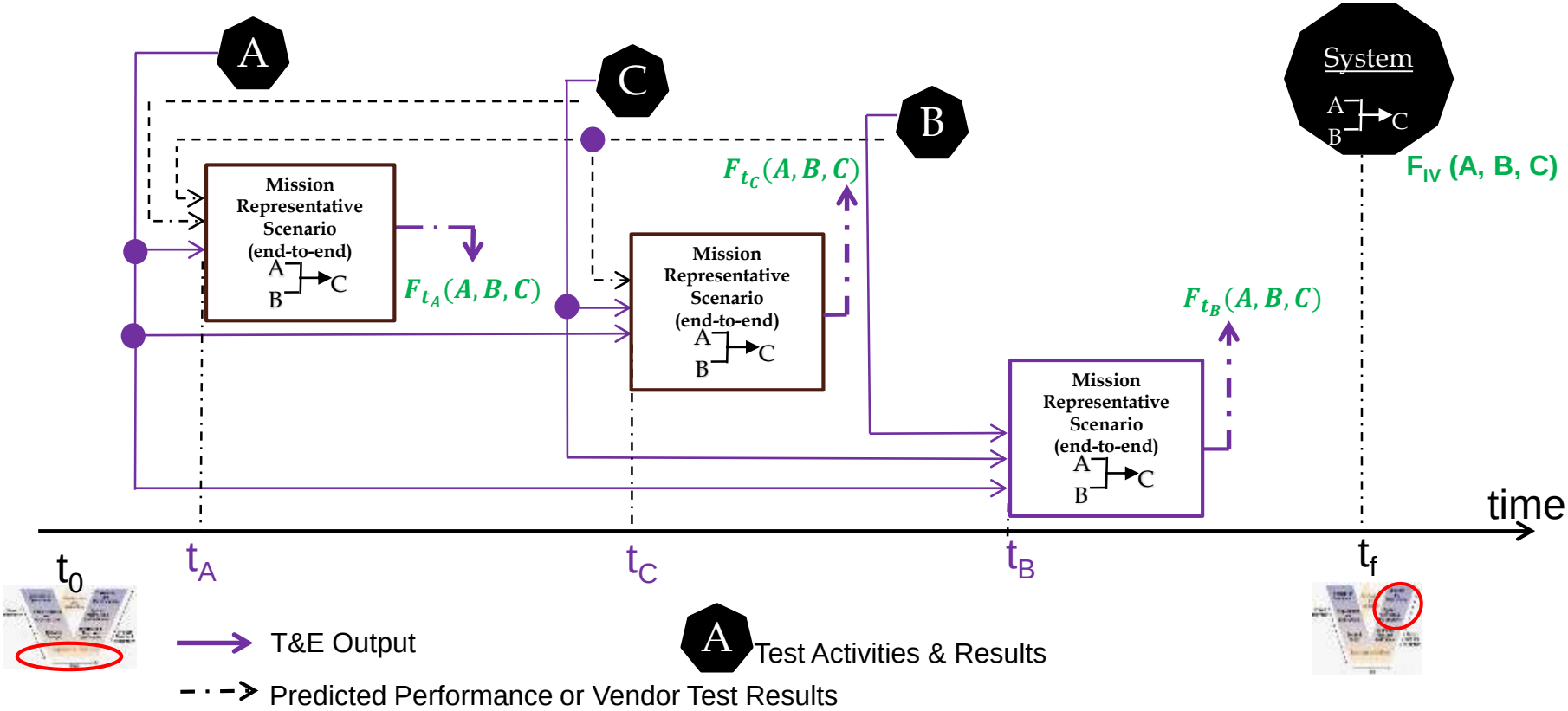
Primary Mission's End-to-End Performance

$$= F_{IV}\,(A \cap B \cap C) \cap F_V$$

The SBED Test Approach Comparison

(system end-to-end performance forecasting)

F_{IV} (A, B, C), where A = Crew Berthing, B = DB Launch/Recovery, C = Sat Dive Operation Support



$$H_o: \mu_{F_{t_f}} = \mu_{F_{t_A}} = \mu_{F_{t_B}} = \mu_{F_{t_C}} \quad and \quad \sigma_{F_{t_f}} = \sigma_{F_{t_A}} = \sigma_{F_{t_B}} = \sigma_{F_{t_C}}$$

Within an α value that is acceptable to the DoD T&E communities

- **typically ≤ 0.3 due to the low sample sizes**

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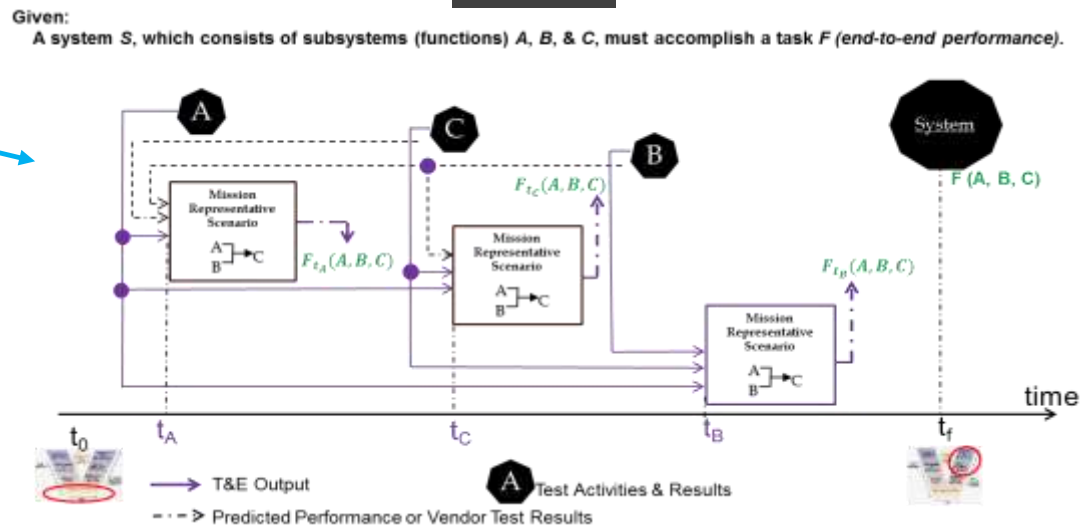
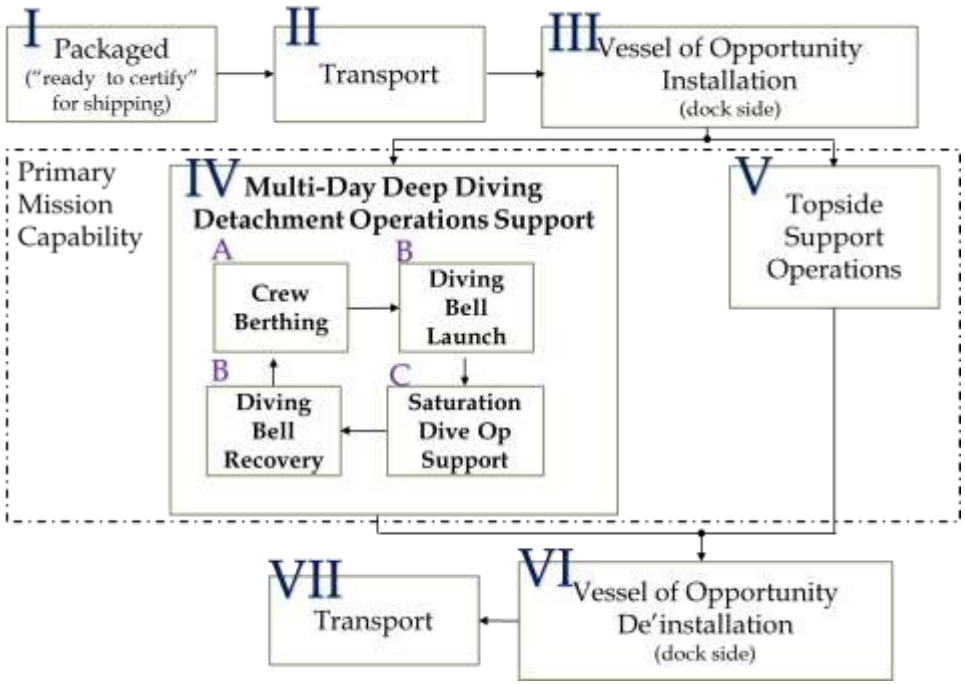
Applicability of the SBED Approach



- Applied from the lowest T&E functionality assessment level
- Use mission scenario to aggregate the individual requirements
  - **Functionalities → → End-to-end performance**

SAT FADS End-to-End Performance Characterization



$$\textit{SAT FADS Overall System End-to-End Performance} = F(f_{I}, f_{II}, f_{III}, f_{IV}, f_{V}, f_{VI}, f_{VII})$$

the SBED Approach Issues

- Lack of design requirements' commensurability
  - Units of measurements: mph ≠ F^o, ≠ psi
  - Verification Conditions: A ≠ B ≠ C

- End-to-end performance forecast ≠ Mission-Capability forecast

the SBED Approach -- Experimental Design

The SBED Approach (Step 2)

Plan & execute component- and subsystem-level functionality tests with Experimental Design

Operational Environment[7] & Experimental Design

Design parameters for all performance requirements

Controllable experimental-design input factors and levels universal to all component-, subsystem-, & system-level tests.

Parameter		Objective	Threshold
Divers			
	Deck Decompression Chamber	6	4
	Diving Bell	3	2
Sea State			
	Operational	6	5
	Launch	4	4
	Recovery	5	4
	Survivability	7	6
Air Temp (Operating) (F)			
	Max	120	100
	Min	0	0
Air Temp (Non Operating) (F)			
	Max	150	130
	Min	0	0
Water Temperature (F)			
	Max	88	82
	Min	28	29
Max Underwater Current (knots)		2.5	2

x_1: personnel = [2, 6]
x_2: Workload = [rest, light, heavy, severe]

x_3: sea state → [1, 6]
(e.g. wind speed, wave height)

x_4: surface air temp (F) →[0, 120]

x_5: water temp (F) → [28, 88]

x_6: u/w current (knots) → [0, 2.5]

x_7: depth (fsw) → [400, 1000]
(from User Requirement)

Component & Subsystem Testing Methodology

SB<u>ED</u>Test Approach

For Topside Functionality Verifications

- Use F_i (x_1, x_3, x_4) **for *i = 1, 2, 3, … , total number topside functionality tests***

where x_1 = # of divers (weight)

x_3 = sea state (wind & wave height)

x_4 = air temperature

For Underwater Functionality Verifications

- **F_j (x_5, x_6, x_7)** **for *j = 1, 2, 3, … , total number underwater functionality tests***

where x_5 = water temperature

x_6 = underwater current speed

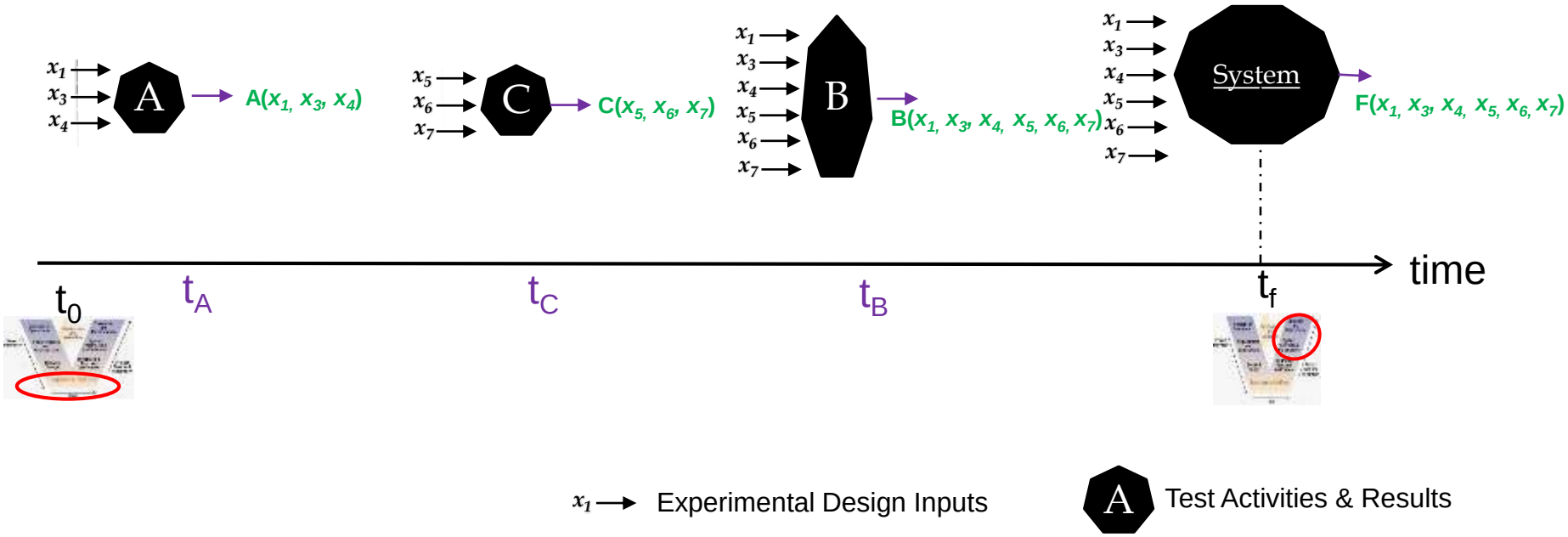
x_7 = operation depth

Regression surface plots, from actual test results, can quantifiably determine sections/volumes within the intended operational theater in which each individual functionality performs below the expected threshold.

The SBED Test Approach Comparison

(**for mission capability forecasting**)

F_{IV} (A, B, C), where A = Crew Berthing, B = DB Launch/Recovery, C = Sat Dive Operation Support



The SBED Approach (Step 3)

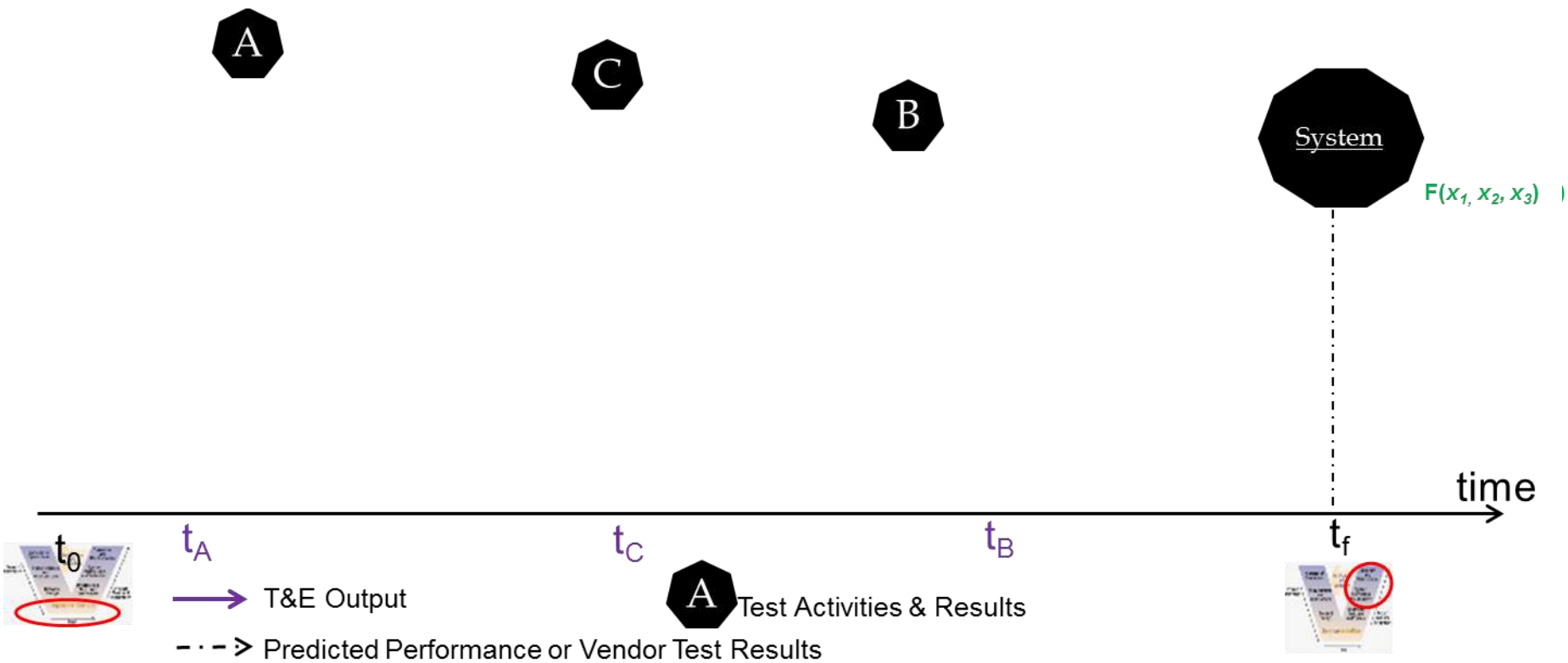
Aggregate (experimental design) test results to forecast system performance & mission capabilities

The SBED Test Approach Comparison

(Mission Capability forecasting)

Given:

A system *S*, which consists of subsystems (functions) *A*, *B*, & *C*, must accomplish a mission *F* ***under x_1, x_2, & x_3 environmental conditions.***



$$H_o\colon \mu_{F_{t_f}} = \mu_{F_{t_A}} = \mu_{F_{t_B}} = \mu_{F_{t_C}} \quad and \quad \sigma_{F_{t_f}} = \sigma_{F_{t_A}} = \sigma_{F_{t_B}} = \sigma_{F_{t_C}}$$

Within an α value that is acceptable to the DoD T&E communities

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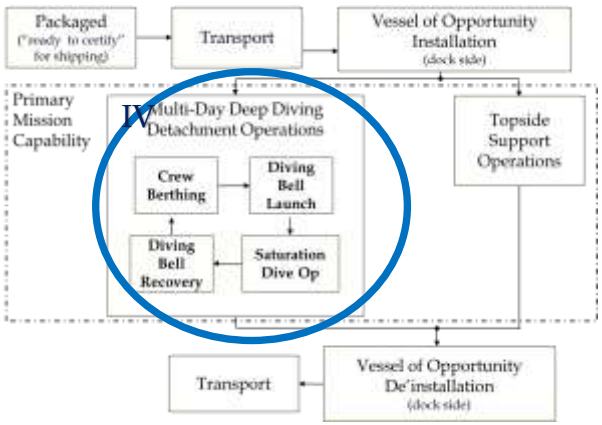
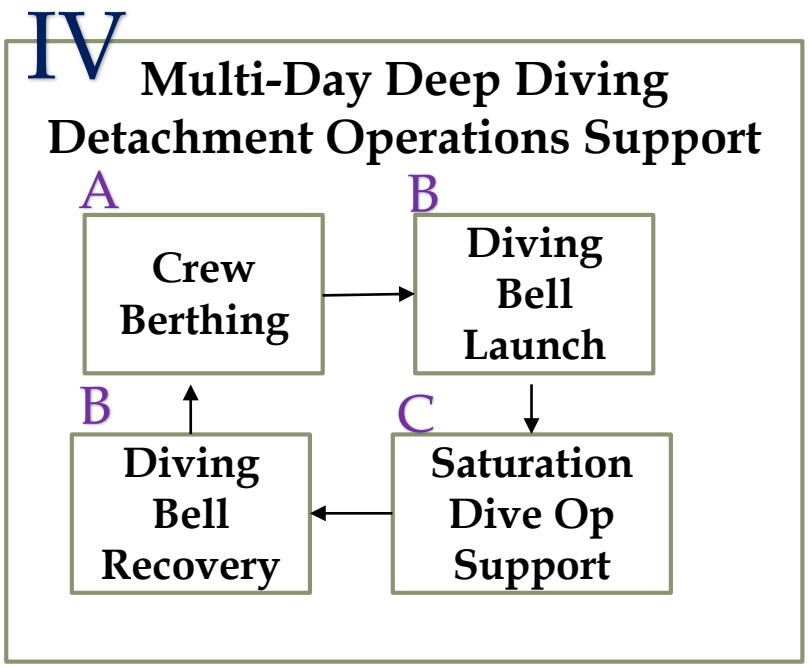
Capability Estimation

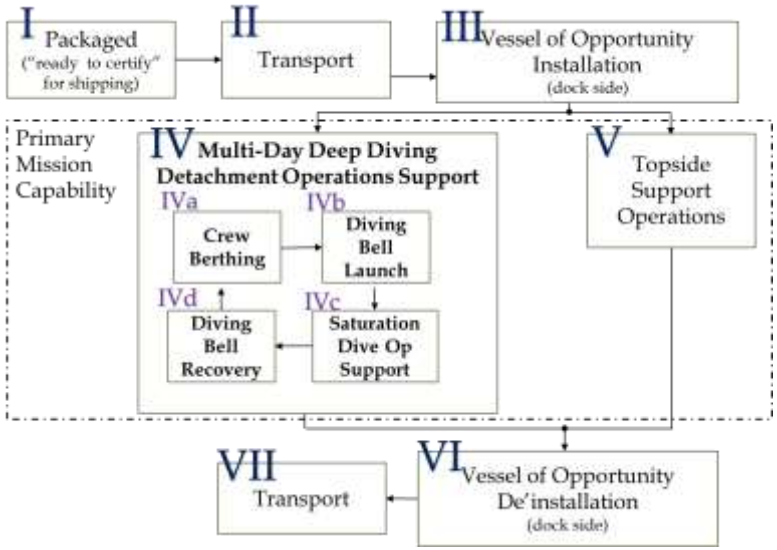


SAT FADS mission scenario



$$\textit{Multi-Day Saturation Dive Support Capability} = F_{IV}\left(f_A(x1, x3, x4),\ f_B(x1, x3, x6, x7),\ f_C(x5, x6, x7)\right)$$

SAT FADS Mission Capability Est



$$\textit{SAT FADS Mission Capability}$$
$$= F(f_I(x_1, x_3, x_4), \ldots, f_{IV}(x_1, x_2, x_3, x_4, x_5, x_6, x_7), \ldots)$$

Forecasting System-Level Mission Capabilities with Subsystem Functionality Test Results

(using the SBED Approach)

It is now possible with the SBED approach to forecast regions in which the system is expected to successfully carry out its intended mission, and regions that it is not.

- Using only component- and subsystem-level test data
- During early verification phase activities

Verification of low-level functionalities →

Keep the sponsors and external stakeholders informed →

References

References

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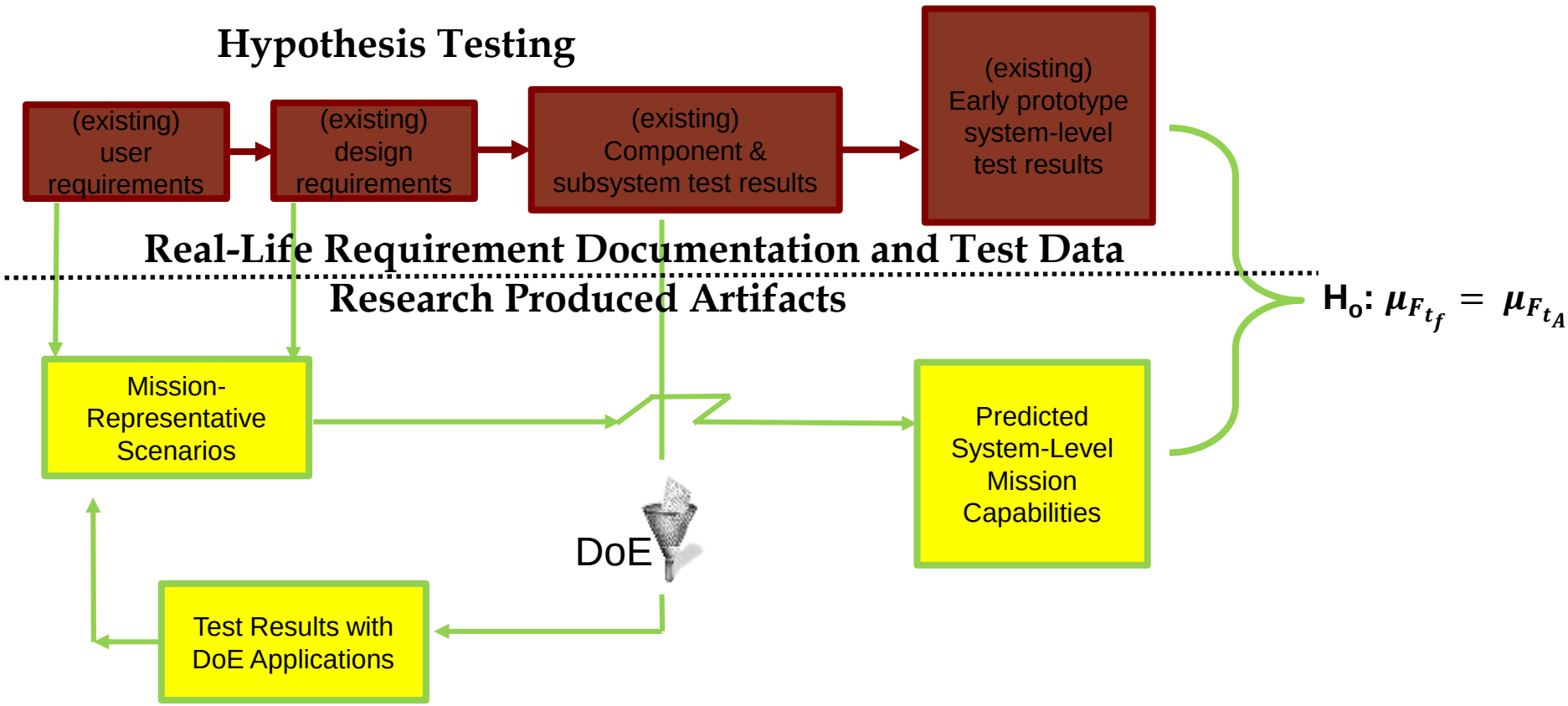
4. International Council on Systems Engineering (INCOSE) (2015). INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 4th ed. Hoboken, NJ: John Wiley & Sons, Inc.
5. Helle, P. & Schamari, W. (2013). Towards an Integrated Methodology for Development and Testing of Complex Systems. *5th International Conference on Advances in System Testing and Validation Lifecycle.*

6. Liu, Z., Zhang, Z. & Chen, Y. (2012). A Scenario-Based Approach for Requirements Management in Engineering Design. *Concurrent Engineering: Research and Applications*. 20(2), 99-109.
7. Office of the Supervisor of Salvage & Diving, NAVSEA 00C Program Office, USN (2008). *System Requirements for the Saturation Fly Away Diving System*. SAT-PGDM-001S-01.
8. Office of the Supervisor of Salvage & Diving, NAVSEA 00C Program Office, USN (2006). *Concept of Operations for the Saturation Fly Away Diving System*. SAT-PGDM-004P-00

Questions

Backups

Call for Data for Research Support



Lexicon

Complex Systems (CxS)

A highly structured system in which there is multiple interactions between many different components. It is a system that by design or function is difficult to understand and verify. [1]

System of Systems (SoS)

A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities. [2]

Differences

- Operational & Managerial Independence of constituent subsystems (SoS)
- SoS requires additional unique tailoring of the Systems Engineering (SE) process [3]

Similarities

- Requirements and design phases are developed from top to bottom
- Hierarchical nature of CxS & SoS
  - Complex System → Subsystems → Components
  - System of Systems → Constituent Systems → Components
- Hierarchical tasks of CxS & SoS
  - Mission Capabilities → System-Level Performance → Subsystem Performance → Subsystem/Component Functions
- **Both are introducing similar challenges to the T&E community**

Impediments to a Top-Down T&E Approach

Systems' Complexity

- Requires multi-disciplinary knowledge base
- Large T&E scope
- Sophisticate T&E management strategy

Solution: **Implement the Bottom-Up T&E Approach** (due to feasibility)

Independent & Asynchronous Subsystem Development Schedules

- Lack of full system available to test

Solution: **Implement the Bottom-Up T&E Approach** (due to practicality)

Systems' Evolutionary & Dynamic Development Strategy

- Lack of T&E-tailored Requirement-Management tools
- The need to identify and quantify performance failures at the lowest level

Solution: **Implement the Bottom-Up T&E Approach** (for traceability)

Existing Traditional T&E Strategies

Requirement-Based T&E

- Early tester participation in the SE requirements reviews
- Individually test the (quality) design requirements at the component and subsystem level
  - But does not assess the requirements themselves.
  - Cannot characterize system's end-to-end performance.

Early Prototyping with Incremental Test Approach

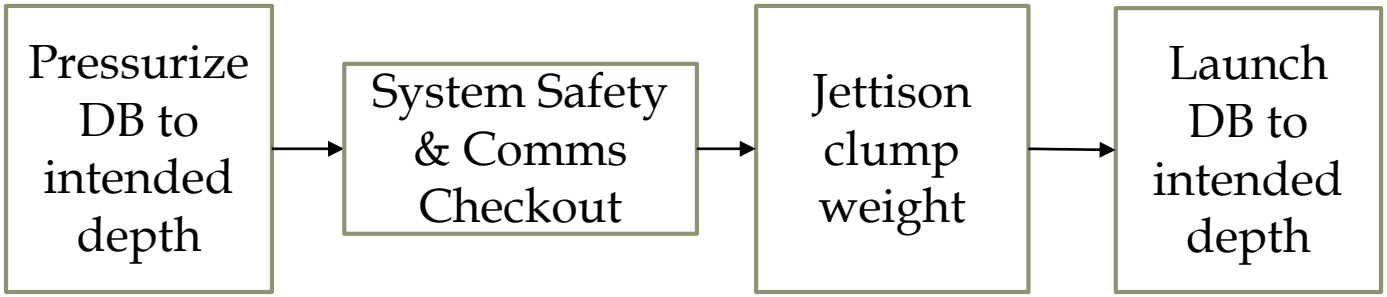
- System-level requirement-based T&E, plus partial Operational Testing (OT)
- Early (and partial) assessment of system OE and OS
  - Cannot characterize mission capability
  - Prototype rarely available during early verification phases

Early Prototyping with Experimental Designs

- Assess end-to-end performance across the entire operating spectrum
  - Prototype rarely available during early verification phases
  - To be emulated with the proposed SBED approach

Dive Bell Launch Task Performance Est.

Dive Bell Launch Scenario

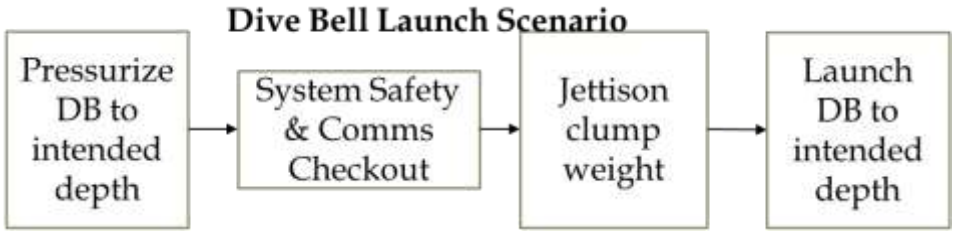


Associated Design Requirements & Tests [7]

A. Launch time vs. depth
B. Winch power
C. Winch wire strength
D. Weight wire strength
E. DB depth-report accuracy (gauge)
F. Hydraulic oil pressure stability & temperature
G. Weight depth-report accuracy (gauge)
H. DB orientation and indication
I. DB stability
J. DB wire line-out counter accuracy
K. Umbilical line-out counter accuracy

$$DB\ Launch\ Performance = f_{IV\text{-}b}\,(A, B, C, \ldots, K)$$

Dive Bell Launch Task Performance Est.



Associated Design Requirements & Tests

A. Launch time (x_1, x_3, , x_6 , x_7)
B. Winch power (x_1, x_3, , x_6 , x_7)
C. Winch wire strength (x_1, x_3, , x_6 , x_7)
D. Weight wire strength (x_1, x_3, , x_6 , x_7)
E. E (x_1, x_3, , x_6 , x_7)
F. F (x_1, x_3, , x_6 , x_7)
G. G (x_1, x_3, , x_6 , x_7)
H. H (x_1, x_3, , x_6 , x_7)
I. I (x_1, x_3, , x_6 , x_7)
J. J (x_1, x_3, , x_6 , x_7)
K. K (x_1, x_3, , x_6 , x_7)

DB Launch Task Capability Prediction =

$$F_{IV\text{-}a}\,(A(x_1, x_3, , x_6 , x_7), B(x_1, x_3, , x_6 , x_7), \ldots)$$