International Council on Systems Engineering
A better world through a systems approach

Sustainment of Navy Assets: A Case study of Post-Production Design Change Process and Documentation of Archetypical Sources of Inefficiency

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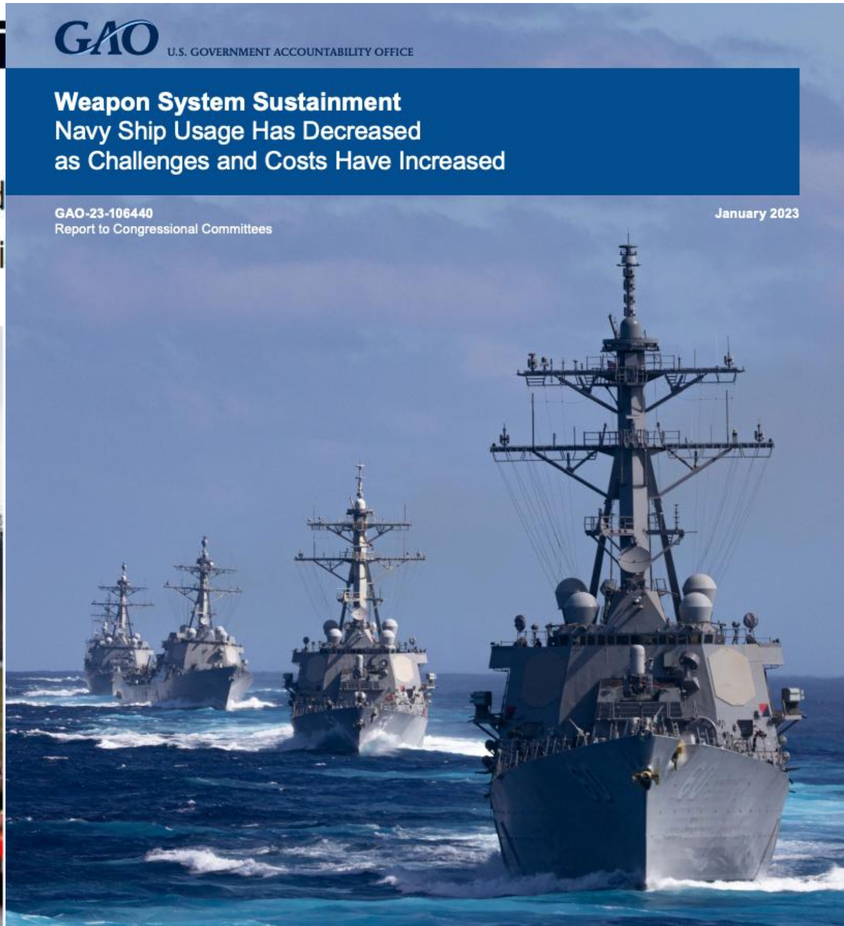
The Sustainment Challenge of Complex Engineered Systems

- **Complexity** (Simon '62, de Weck et al. '11), is blamed for schedule and cost overruns (Henning et.al. '21)
- A significant chunk of costs & benefits arise during sustainment (Fricke '05; Walden et al., '15)



Digital Engineering (DE) as a “Cure”?

The Research GAP

Despite high expectations for **DE Transformation,**

its **VALUE** is poorly **UNDERSTOOD**

Questions in Pursuit of Understanding the Value of DE Transformation

- **RQ1: WHY** post-production design change projects exceed their planned schedule?

- **RQ2: WHERE** in the process does time loss occur and **HOW** substantial are these deviations?

- **RQ3:** If the organization were digitally transformed, **WHERE** and to **WHAT EXTENT** would it help?

Research Setting, Data, & Methods

- **A case study** of an Integrated Design Team **(IDT)** at a NAVY Agency designing the top-side of Navy Assets (Eisenhardt '89, Singh & Szajnfarber, 2024; Topcu et al., 2021)
- **Research Frame:** Preliminary design where IDT explores how to integrate new systems to existing assets, collaborating with stakeholders & coordinating effort
- **Data:** Site observations and semi-structured interviews
- A Mixed Methods Research Approach with 3 complementary thrusts:

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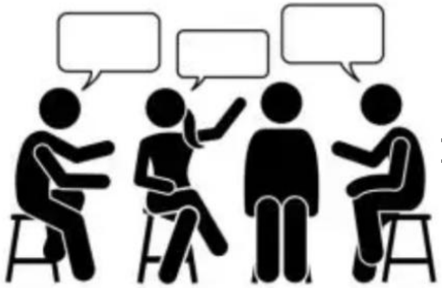
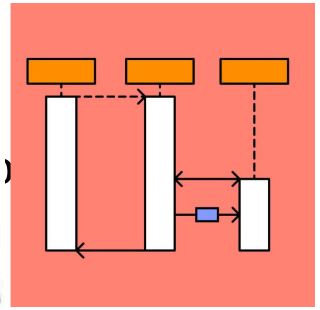
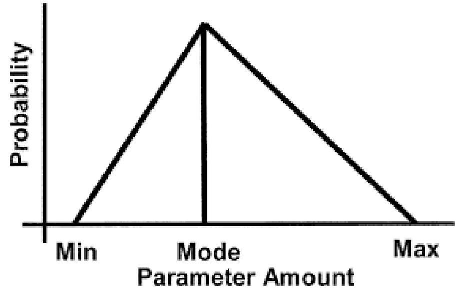
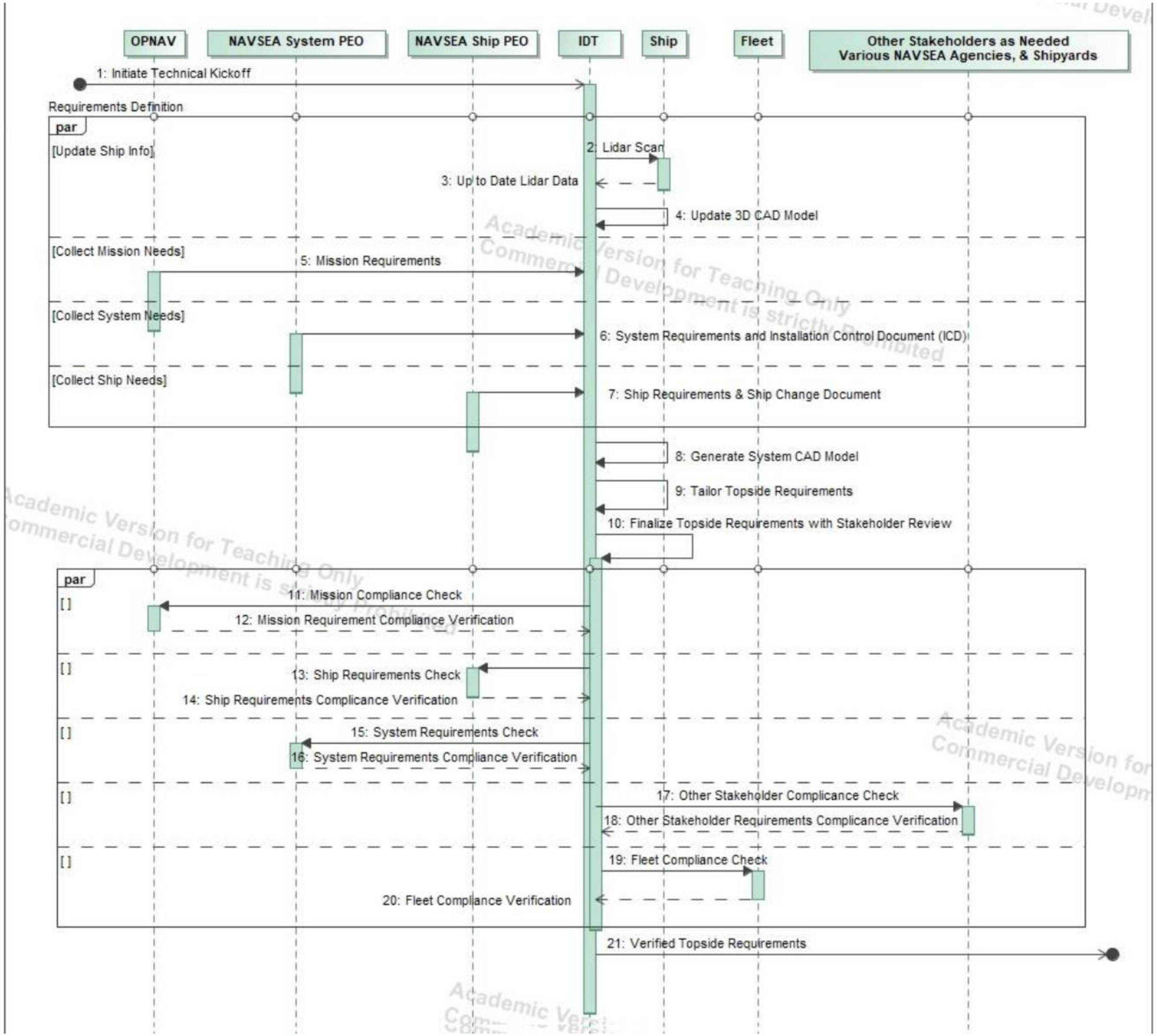


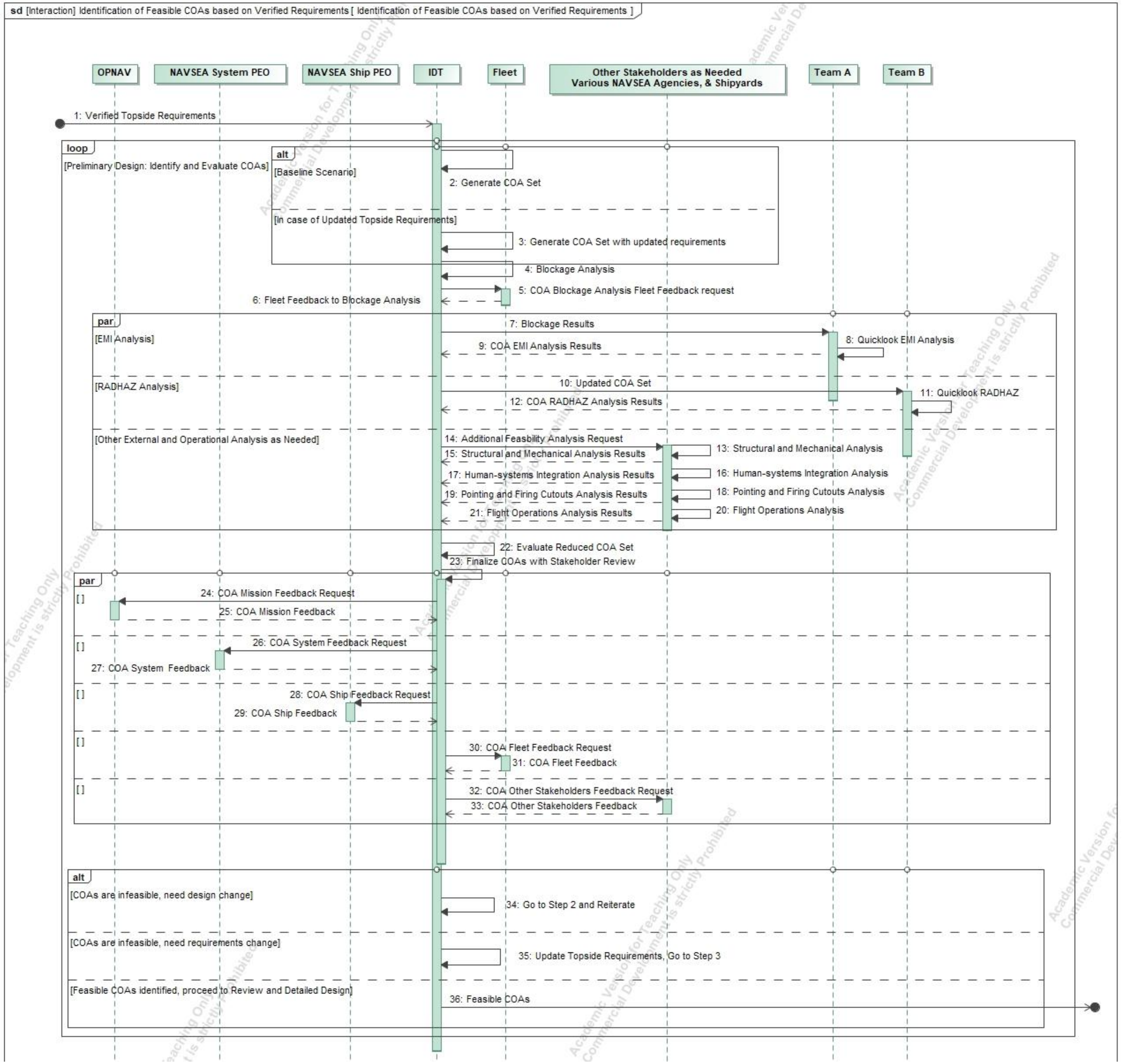




Sequence 1
Requirements Elicitation & Verification



Sequence 2
Identification of Feasible Courses of Action (COAs) and Selection



Questions in Pursuit of Understanding the Value of DE Transformation

RQ1: **WHY** post-production design change projects routinely deviate from their planned schedule?

RQ2: **WHERE** in the process does time loss occur and **HOW** substantial are these deviations?

RQ3: If the organization were digitally transformed, **WHERE** and to **WHAT EXTENT** would it help?

Findings: Why Schedule Slips Occur?

Questions in Pursuit of Understanding the Value of DE Transformation

RQ1: WHY post-production design change projects deviate from their planned schedule?

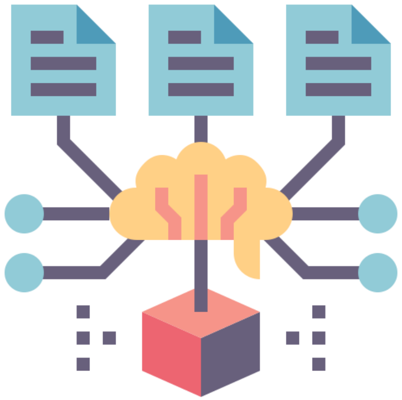
RQ2: WHERE in the process does time loss occur and **HOW** substantial are these deviations?

RQ3: If the organization were digitally transformed, **WHERE** and to **WHAT EXTENT** would it help?

Mapping of Task Categories

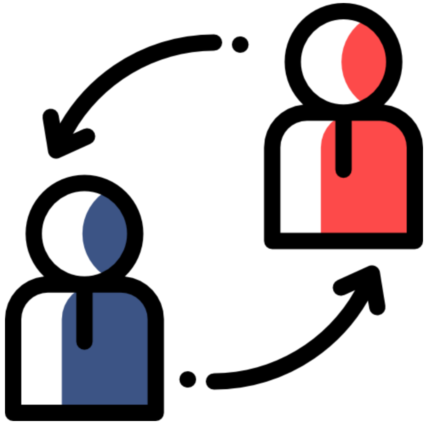
Coded tasks based on what engineers do during preliminary design

Eliciting Requirements



System-Level Modeling & Analysis

Disciplinary Modeling & Analysis



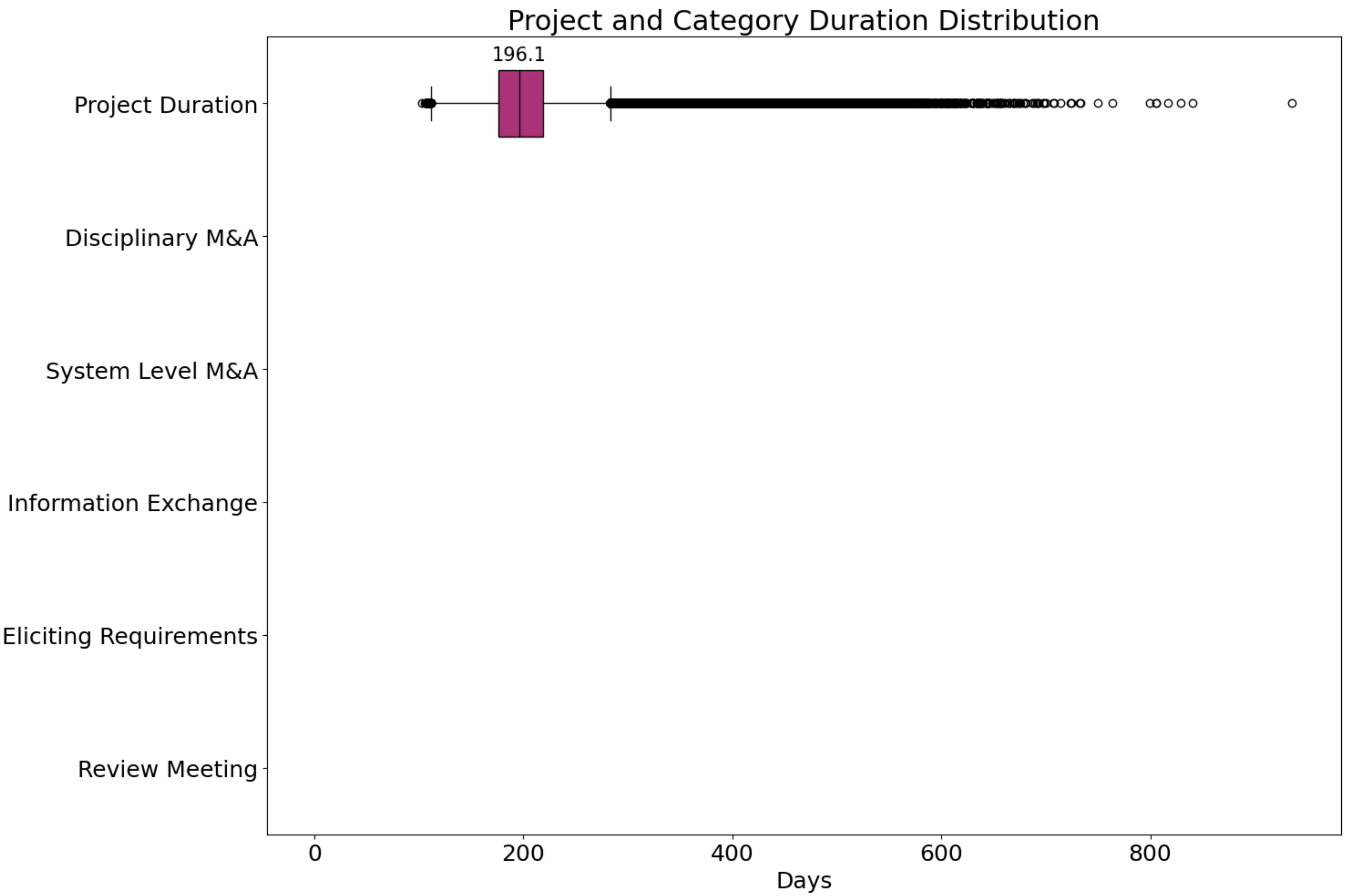
Information Exchange

Review Meetings

We then associated expert beliefs for each function, and conducted a simulation study to quantify time commitments

DES Findings for Task Duration

the AS-IS (current) case



Questions in Pursuit of Understanding the Value of DE Transformation

RQ1: WHY post-production design change projects deviate from their planned schedule?

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RQ3: If the organization were digitally transformed, **WHERE** and to **WHAT EXTENT** would it help?

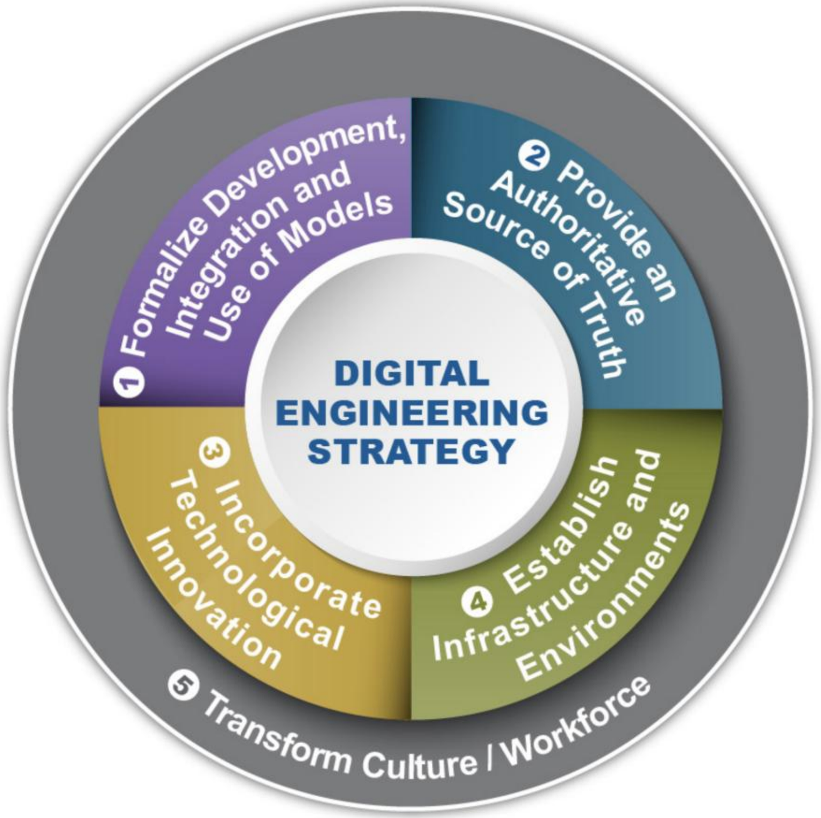
Imagining SE after DE Transformation

AS-IS

TO-BE

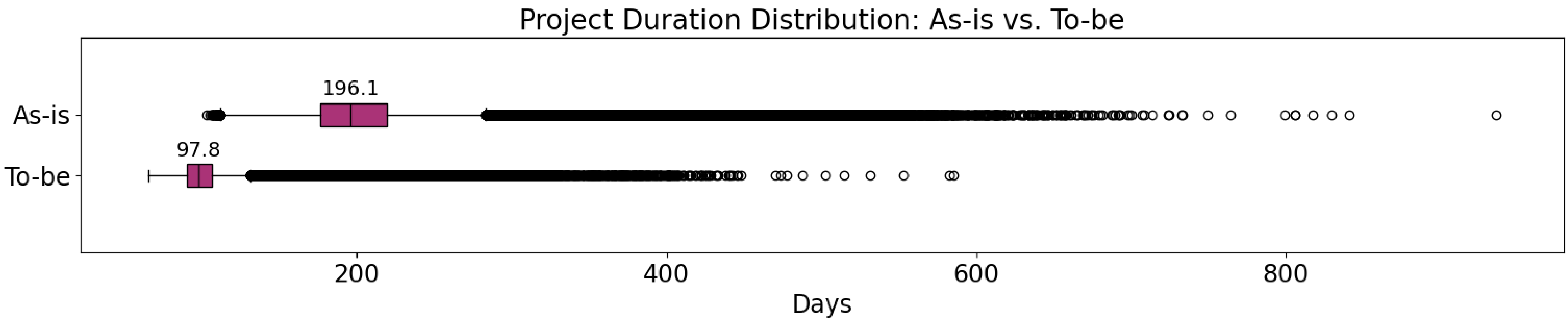
Assumptions for the “To-be” case (after DE adoption)

1. There exists an Authoritative Source of Truth (ASOT) of the SOI, that is accessible to IDT.
2. DE has been adopted across the NAVY enterprise, enabling free flow between collaborators.
3. Secure & up-to-date sharing among authorized stakeholders, ensuring consistent and timely exchange of data & analytical models across organizational boundaries.
4. DE enables proactive and concurrent consideration of multi-disciplinary technical constraints.



VIRGINIA TECH

AS-IS vs TO-BE Comparison: Project Schedule



Significantly Shorter Cycles: ~50% reduction in preliminary design duration

More Predictable Spread:~40% reduction in Std Deviation

OK BUT WHERE ARE THE GAINS?

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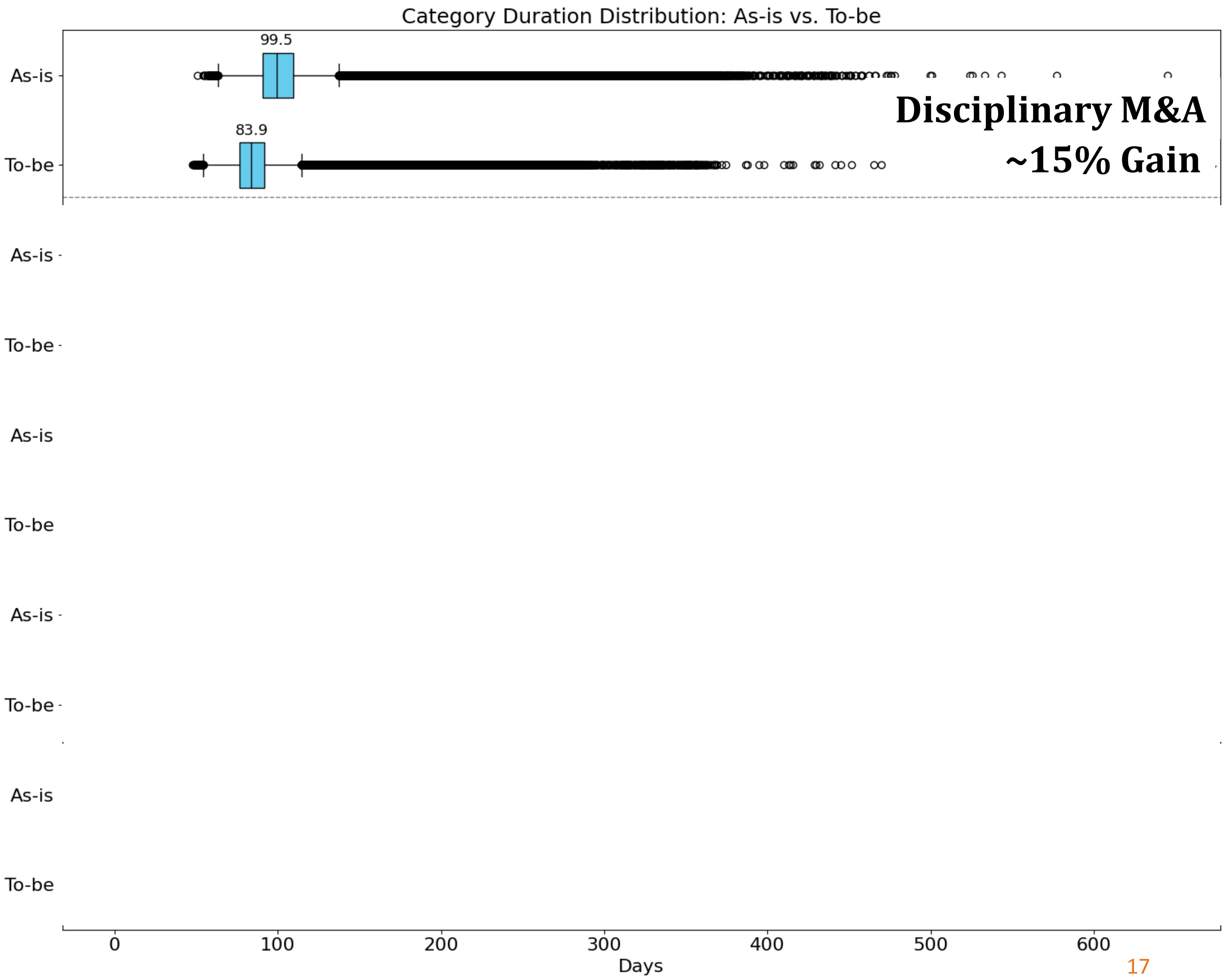
DES Findings for the AS-IS vs. TO-BE case

Category Duration Distribution



So WHAT?

Discussion: Contributions

- The first study that quantifies **WHERE** and **HOW** DE could provide value.
- **The benefits are NOT UNIFORM *but are significant!**
  - Some see significant growth (i.e., System-level M&A, information exchange, and reviews)
  - Others (i.e., Disciplinary M&A and eliciting requirements) exhibit limited gains
  - Gains seem to be concentrated in categories that are arguably most dreaded by engineers
- Qualitative analysis documents **WHY** post-production design change projects experience schedule overruns.
  - **4** inefficiency archetypes that outline why delays occur, these might be generalizable to other post-production design change projects, particularly for large Systems of Systems such as Navy Assets

Discussion: Limitations & Future Work

- **Limitations**
  - We studied only a single team within a single organization conducting a single "process", and only schedule (time is not always equal to cost).
    - Yet even here, DE showed notable benefits.
    - Scaling this across the enterprise could yield exponential returns.
  - Inherent variations due to varying project scope and complexity.
  - Strong assumptions but conservative in structure – hence results should be taken as a grain of salt.
  - **% gains don't generalize, but insights do.**
- **Future work**
  - Sensitivity analysis based on different DE adaptation scenarios.
  - **What about the Golden Triangle?** Cost-benefit analysis of DE adaption

Closure

- SE community is inefficient at designing and sustaining complex systems
- There is optimism DE will help, here we provided some insight on the **ROI;** more specifically on **WHERE, HOW,** and **TO WHICH EXTENT** it could help.
- Nevertheless, DE transformation will not be a frictionless path…
  - Challenges include resistance from leadership and operational staff who see DE as disruptive to established workflows and significant upfront investment for enabling the transformation.
  - **Help US:** We are conducting a survey to learn more about these obstacles

Survey on Digital Engineering Barriers

- Do you currently work for an organization that is involved in the design, development, management, maintenance, or sustainment of engineered systems?
- If 'Yes', please consider taking our "Barriers to Digital Engineering Transformation" survey.
- The survey takes approximately 20-25 minutes.
- Incentives: Participants will enter a raffle to win one of two $50 gift cards.
- Survey link: https://virginiatech.questionpro.com/t/AcAVUZ6icb
- **Or Contact Me: ttopcu@vt.edu**

Thank you! Questions are most Welcome!

"If one is interested in the relations between fields which, according to customary academic divisions, belong to different departments, then s/he will not be welcomed as a builder of bridges, as s/he might have expected, but will rather be regarded by both sides as an outsider and troublesome intruder." ***Rudolph Carnap***

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Contact Me!

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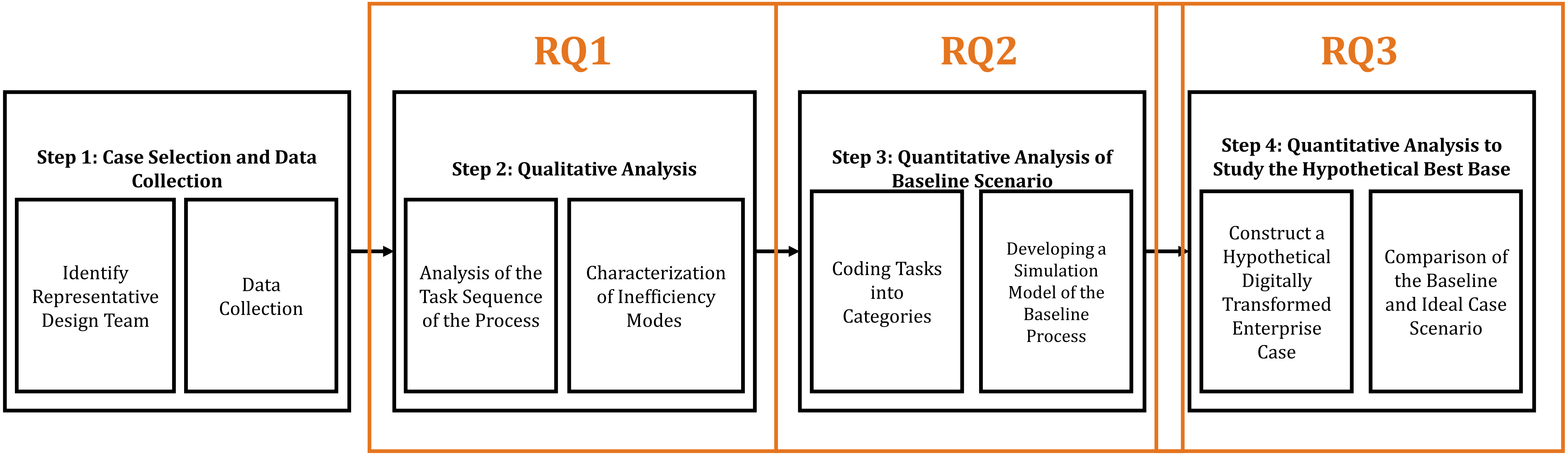
Extras

Systems of Systems: An Even Greater Challenge

- Managing change in SoS environments demands more adaptive and robust approaches than single-system contexts.
- **Key Challenges:**
  - Constituent systems are independently acquired, managed, and operated and must work together seamlessly (Jamshidi, 2008).
  - SoS configurations evolve as constituent systems are upgraded or replaced asynchronously (Nielsen et al., 2015).
  - Differing stakeholders, ownerships, and priorities lead to coordination challenges and delayed decision-making (Gorod et al., 2008).
  - Failures or upgrades in one system can propagate unpredictably across the SoS (Keating et al., 2003).

Research Design



Research Design Step 1 – Case Selection, Data Collection, & Organization

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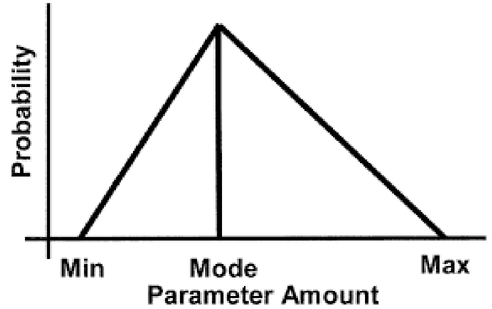
- **Method:** Case study
  - Are especially valuable for understanding the *how* and *why* questions as well as the nuanced interactions and dynamics within real-world contexts, such as complex engineering systems (Singh & Szajnfarber, 2024; Topcu et al., 2021)
- **Research Setting and Framing**
  - The Integrated Design Team (IDT) at a U.S. Naval Surface Warfare Center manages 80+ post-production design change projects annually
  - Top-side design of Navy Platforms
  - Focus is on preliminary design phase: IDT integrates new topside systems balancing performance, safety, and mission constraints.

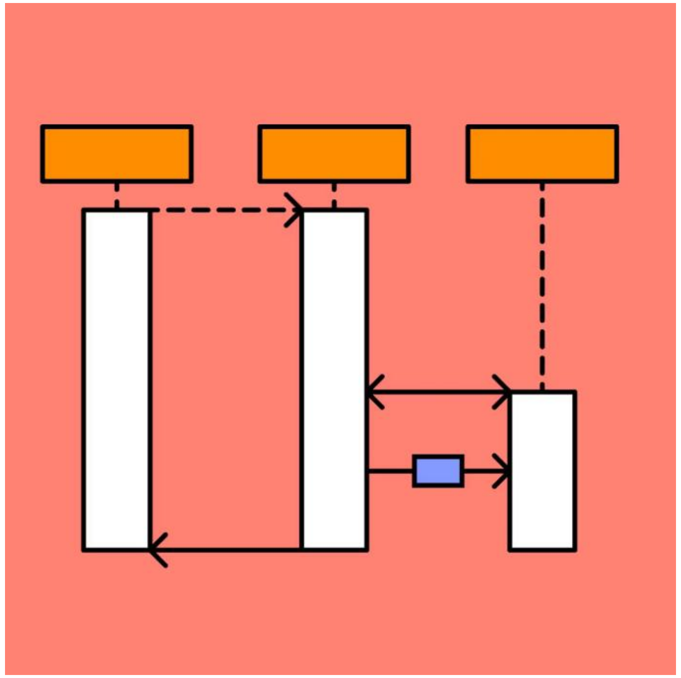
- **Data Collection Methods**
  1. Site observations & Semi-structured interviews with key stakeholder to understand the task sequence and sources of inefficiencies
  2. Triangular distributions (min, mode, max) were used to capture task durations, as this format was easier to communicate with various stakeholders (Topcu & Mesmer, 2018).



Research Design – Step 2

Step 2: Qualitative Analysis

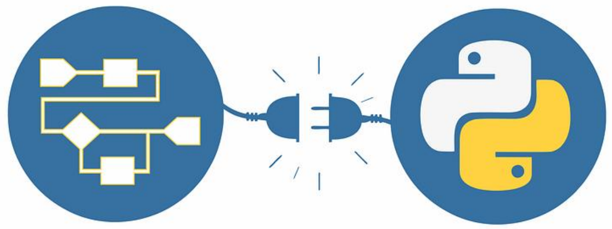
- From interview and observation data, sequence diagrams were constructed to represent
    - Tasks
    - Interactions between these tasks (energy, material, and information flow), and
    - Stakeholder groups to conduct each task.
- This visualization reveals task dependencies and hand-offs between the tasks
- Next, inefficiency archetypes were identified capturing recurring patterns that cause rework or delays in the process.



Research Design – Step 3

Step 3: Quantitative Analysis of Baseline Scenario

- **Simulation-Based Analysis:**
  - Developed a discrete-event simulation of the task flow using stochastic time data (triangular distributions).
  - Ran Monte Carlo simulations (number of runs: 10,000) to model process variability and expected durations.
- **How designers spend their time?**
  - Using literature, the tasks are categorized into the following categories:
    1. System-Level Modeling & Analysis (O'Neil & Petty, 2013; Rahman et al., 2021)
    2. Disciplinary Modeling & Analysis (Robinson, 2012; Wu et al., 2016)
    3. Eliciting Requirements (Mohedas et al., 2014; Wu et al., 2016)
    4. Information Exchange (Mesmer-Magnus et al., 2011; Wildman et al., 2012)
    5. Review Meeting (D'Astous et al., 2004; Fernando et al., 2013)

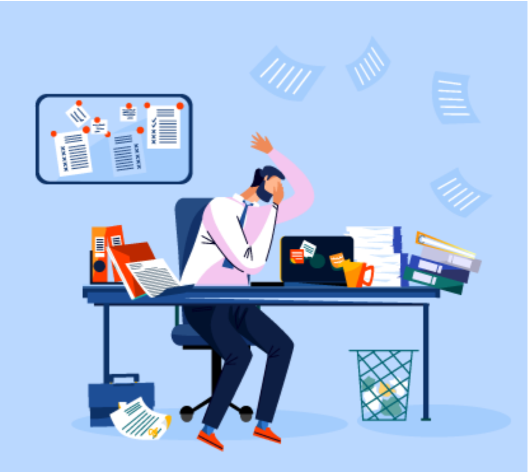


Research Design – Step 4

Step 4: Quantitative Analysis to Study the Hypothetical Best Case

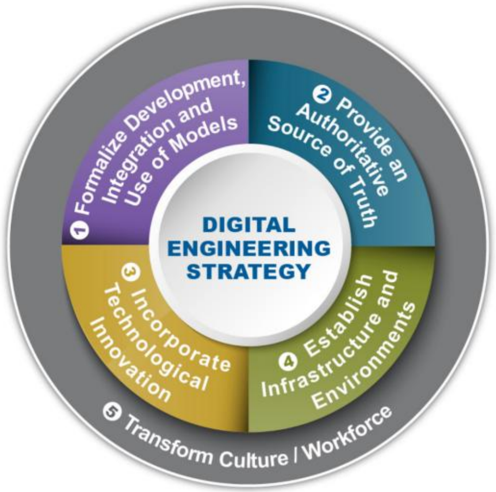
- Constructed an idealized digitally transformed To-be scenario based on DoD's Digital Engineering Strategy (DoD, 2018).
- Compared this simulation performance against the baseline (As-is) scenario.

As-is



vs.

To-be



Summary Statistics (in Days)

Label	Min	Max	Mean	Median	Std Dev
Project Duration (As-is)	103.2	935.9	205.2	196.1	48.2
Project Duration (To-be)	65.3	585.5	104.2	97.8	28.2
Information Exchange (As-is)	31.4	172.9	55.2	54	9.6
Information Exchange (To-be)	13.1	56.9	25.3	25.1	3.9
Eliciting Requirements (As-is)	14.3	341.2	32.2	28.7	15.2
Eliciting Requirements (To-be)	12.4	173.7	26.1	24.5	8.2
System Level M&A (As-is)	20.3	193	87.2	86.6	23.8
System Level M&A (To-be)	2.9	63.6	10.5	9.8	3.9
Disciplinary M&A (As-is)	51	645.1	107.3	99.5	31.6
Disciplinary M&A (To-be)	47.7	469.6	89.5	83.9	25.7
Review Meeting (As-is)	1.2	34.6	11.1	11	3.4
Review Meeting (To-be)	0.2	29.1	7.3	7.2	2.3

Task Classification – Phase 1

No.	Task	Category	Sub-category
1	Initiate technical kick-off	-	
2	Lidar scan	Information Exchange	
3	Up-to-date lidar data	Modeling and Analysis	System-level
4	Update 3D CAD model	Modeling and Analysis	System-level
5	Mission requirements	Information Exchange	
6	Systems requirements and ICD	Information Exchange	
7	Ship requirements and ship change documents	Eliciting Requirements	
8	Generate system CAD model	Modeling and Analysis	Disciplinary
9	Tailor topside requirements with stakeholder review	Eliciting Requirements	

Task Classification – Phase 1

No.	Task	Category
10	Finalize topside requirements with stakeholder review	Review Meeting
11	Mission compliance check	
12	Mission requirements compliance verification	
13	Ship requirements check	
14	Ship requirements compliance verification	
15	System requirements check	
16	System requirements compliance verification	
17	Other stakeholder compliance check	
18	Other stakeholder requirements compliance verification	
19	Fleet compliance check	
20	Fleet compliance verification	
21	Verified topside requirements	

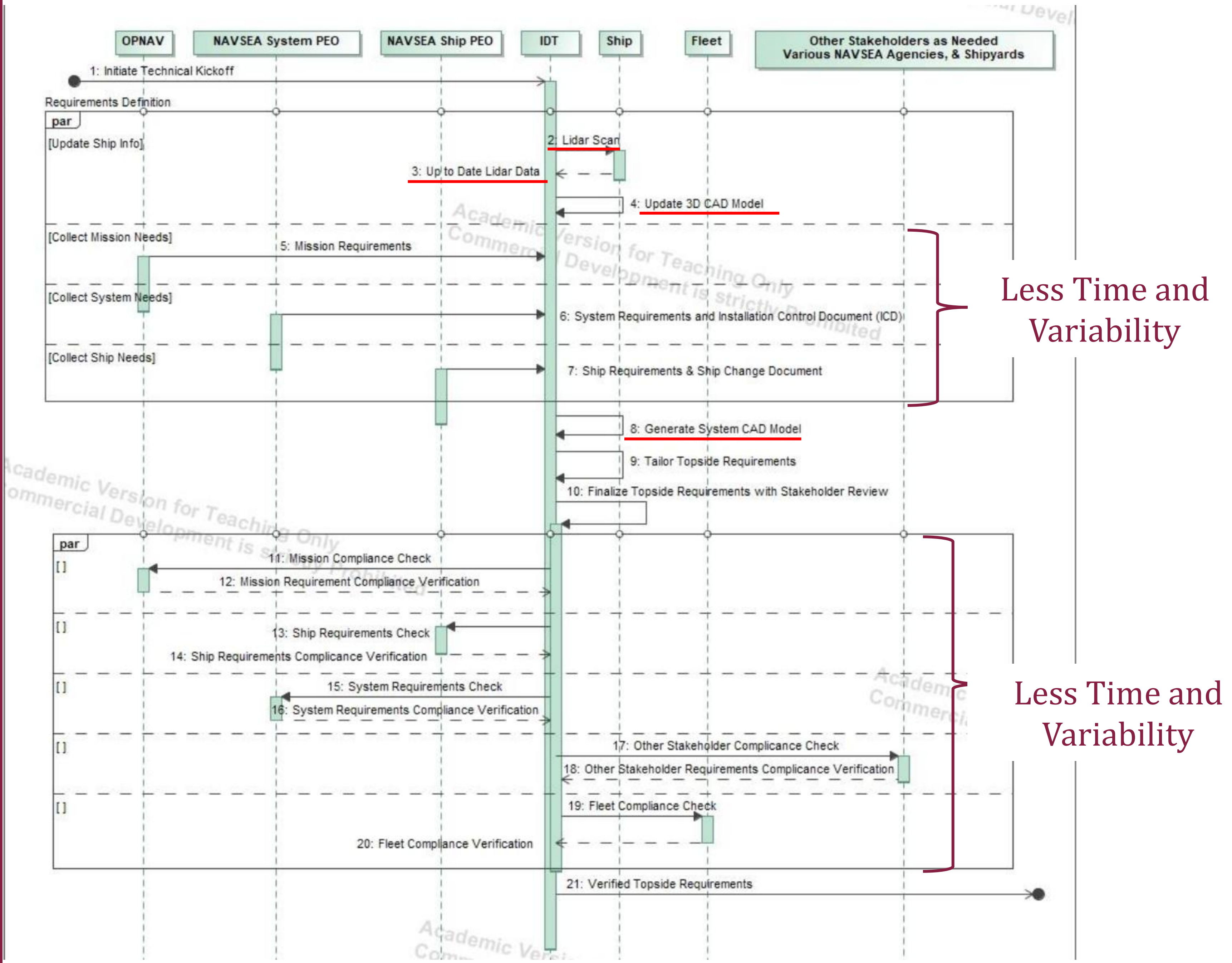
Task Classification – Phase 2

No.	Task	Category	Sub-category
1	Verified topside requirements	-	-
2	Generate COA set	Modeling and Analysis	System - level
3	Generate COA set with updated requirements	Modeling and Analysis	System - level
4	Blockage Analysis	Modeling and Analysis	Disciplinary
5	COA Blockage Analysis Fleet Feedback Request	Information Exchange	
6	Fleet feedback to blockage analysis	Information Exchange	
7	Blockage results	Information Exchange	
8	Quicklook EMI analysis	Modeling and Analysis	Disciplinary
9	COA EMI analysis results	Information Exchange	
10	Updated COA set	Information Exchange	
11	Quicklook RADHAZ	Modeling and Analysis	Disciplinary
12	COA RADHAZ analysis results	Information Exchange	
13	Additional feasibility analysis request	Information Exchange	Time
14	Structural and mechanical Analysis	Modeling and Analysis	Disciplinary
15	Human- systems integration analysis	Modeling and Analysis	Disciplinary
16	Pointing and firing cutouts analysis	Modeling and Analysis	Disciplinary
17	Flight operations analysis	Modeling and Analysis	Disciplinary
18	Evaluate reduced COA set	Modeling and Analysis	System - level

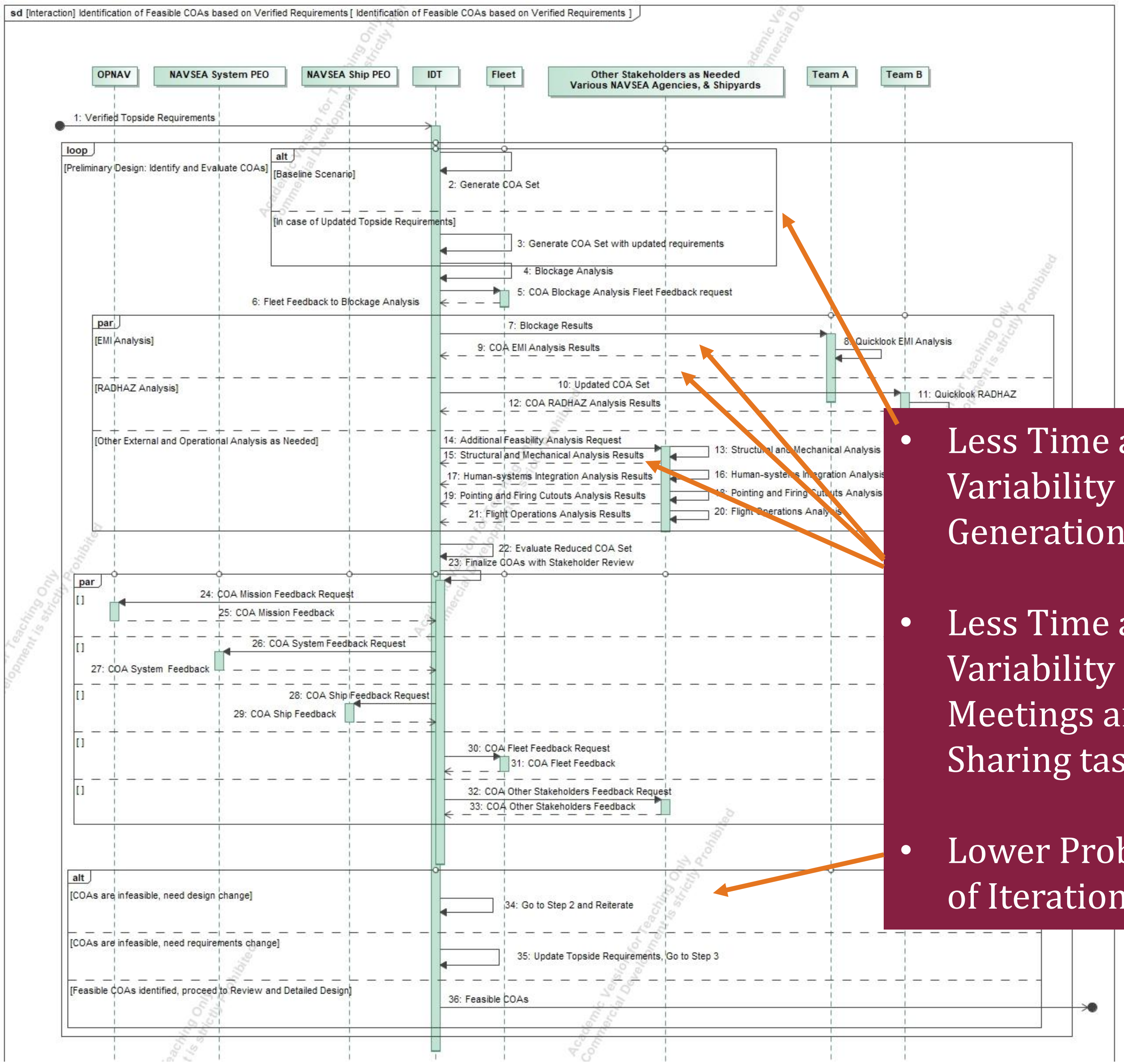
Task Classification – Phase 2

No.	Task	Category
19	Finalize COAs with stakeholder review	Review Meeting
20	COA mission feedback request	
21	COA mission feedback	
22	COA system feedback request	
23	COA system feedback	
24	COA ship feedback request	
25	COA ship feedback	
26	COA fleet feedback request	
27	COA fleet feedback	
28	COA other stakeholders feedback request	
29	COA other stakeholders feedback	
31	Update Topside requirements	Eliciting Requirements

Requirements Verification Phase: DE Scenario



Identification of Feasible COAs: DE Scenario



- Less Time and Variability in COAs Generation
- Less Time and Variability in Review Meetings and Info-Sharing tasks
- Lower Probabilities of Iterations

Assumption 1

There exists a comprehensive and up-to date digital representation of the operational system of interest (SOI), in this case, the Navy vessel, as well as the relevant processes, systems, and operational context in which the SOI functions. The digital models are assumed to reside within an ASOT, which plays a critical role in managing and maintaining digital artifacts across the system lifecycle.

- With an ASOT in place, a validated and current digital representation of the ship would already be accessible.
  - Task involving docking the vessel, dispatching IDT personnel for LIDAR scanning, and processing that data into updated CAD models does not needs to be conducted by IDT during the design change process.
  - The digital CAD model will be delivered to IDT and the team does not need to invest time to create the CAD model.

Figure 1. DOD Digital Engineering Goals (DOD, 2018)

Assumption 2

The digital transformation is adopted across the entire organization, including all relevant stakeholders, systems, and processes.

- With an organization-wide ASOT, IDT can access mission, ship, and system information from a centralized, validated source of truth.
  - Requirement elicitation tasks is assumed to become faster, less variable.
- Stakeholders continuously have access to IDT's ongoing analyses, and IDTs remain updated with any changes in requirements or operational data.
  - The time required to schedule meeting and to converge on a viable solution during review meetings is assumed to be reduced.
  - This will also reduce the probabilities of reiterations.

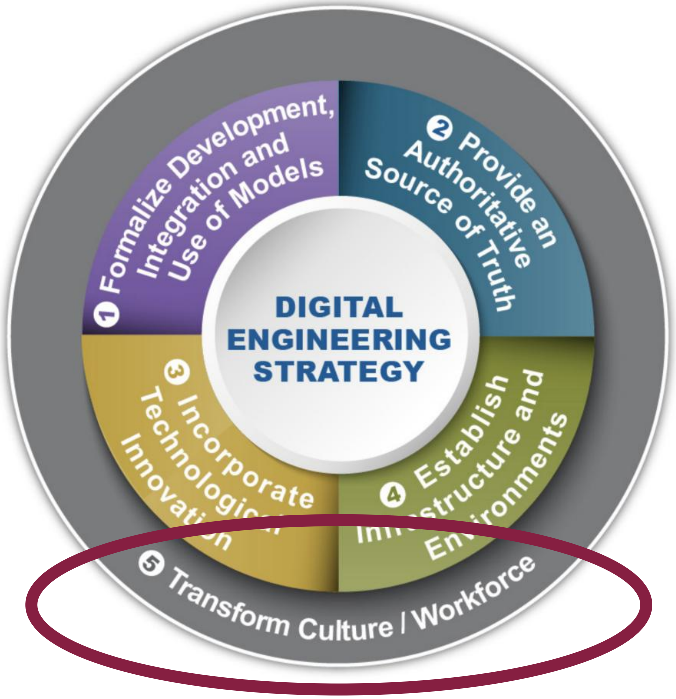


Figure 1. DOD Digital Engineering Goals (DOD, 2018)

Assumption 3

The ASOT enables secure, up-to-date digital data sharing among authorized stakeholders, ensuring access to up-to-date and consistent models across the system lifecycle and organizational boundaries.

- Currently, information sharing is conducted manually, which works as the *time sinks* specially involving the tasks executed by multiple stakeholder groups.
  - Digital data sharing within the ASOT is assumed reduce the time in information exchange steps.
- The availability and access to digital information are also assumed to reduce the time and variability in collecting mission and system requirements.
- The digital data sharing capability withing the ASOT can also enable digital review of the requirements and courses of action (COA) sets.
  - We assume faster, and less variable time spent in the review meetings.

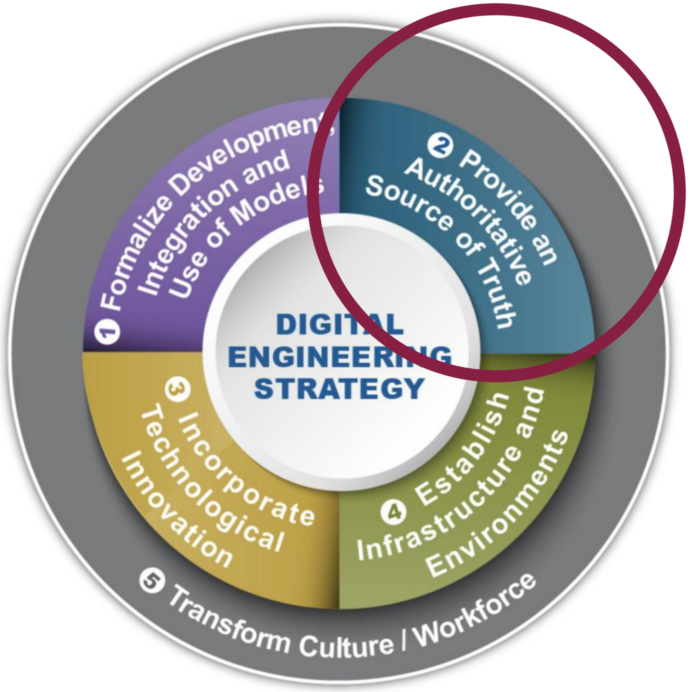


Figure 1. DOD Digital Engineering Goals (DOD, 2018)

Assumption 4

The digital transformation will provide more informed analysis capabilities in a digitalized and connected environment.

- The digital transformation enables more concurrent and proactive consideration of system characteristics that may not be identified ahead of time due to their complex and interdisciplinary nature in the current capacity.
- This ensures conformation to the constraints, operational realities of the the ship and mission as well as requirements of the system being installed.
  - This is assumed to help to produce COAs in reduced time and better alignment with mission
  - This will further reduce the probabilities of reiterations

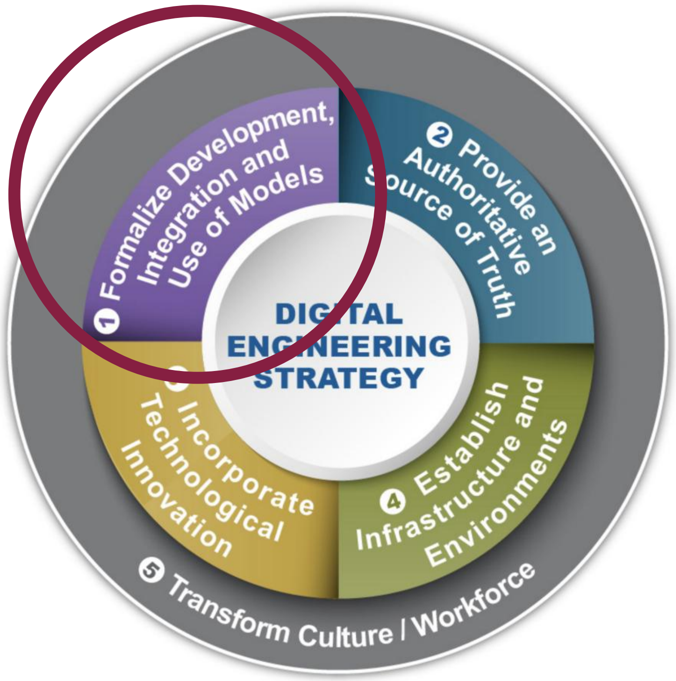


Figure 1. DOD Digital Engineering Goals (DOD, 2018)