A Systems Engineering Approach to Architecture Development

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Discussion Objectives

- ***Using a simple extension of basic systems engineering (SE) practices***

  1) *Describe what a mission area architecture (MAA) is and show how it integrates into a Notional Civil Space (NCS) Architecture Framework*

  2) *Describe an effective approach for developing an MAA*

- ***Note: The NCS Architecture is notional and is for illustration & context only – no such architecture has been defined***

  ➢ *But, for this discussion imagine there is an NCS architecture*

Architecture Studies - Beginning Thoughts

- ***Conducted prior to Pre-Phase A of project life cycle***
  - *Scope broader & shallower than scope for concept design studies in Pre-Phase A*

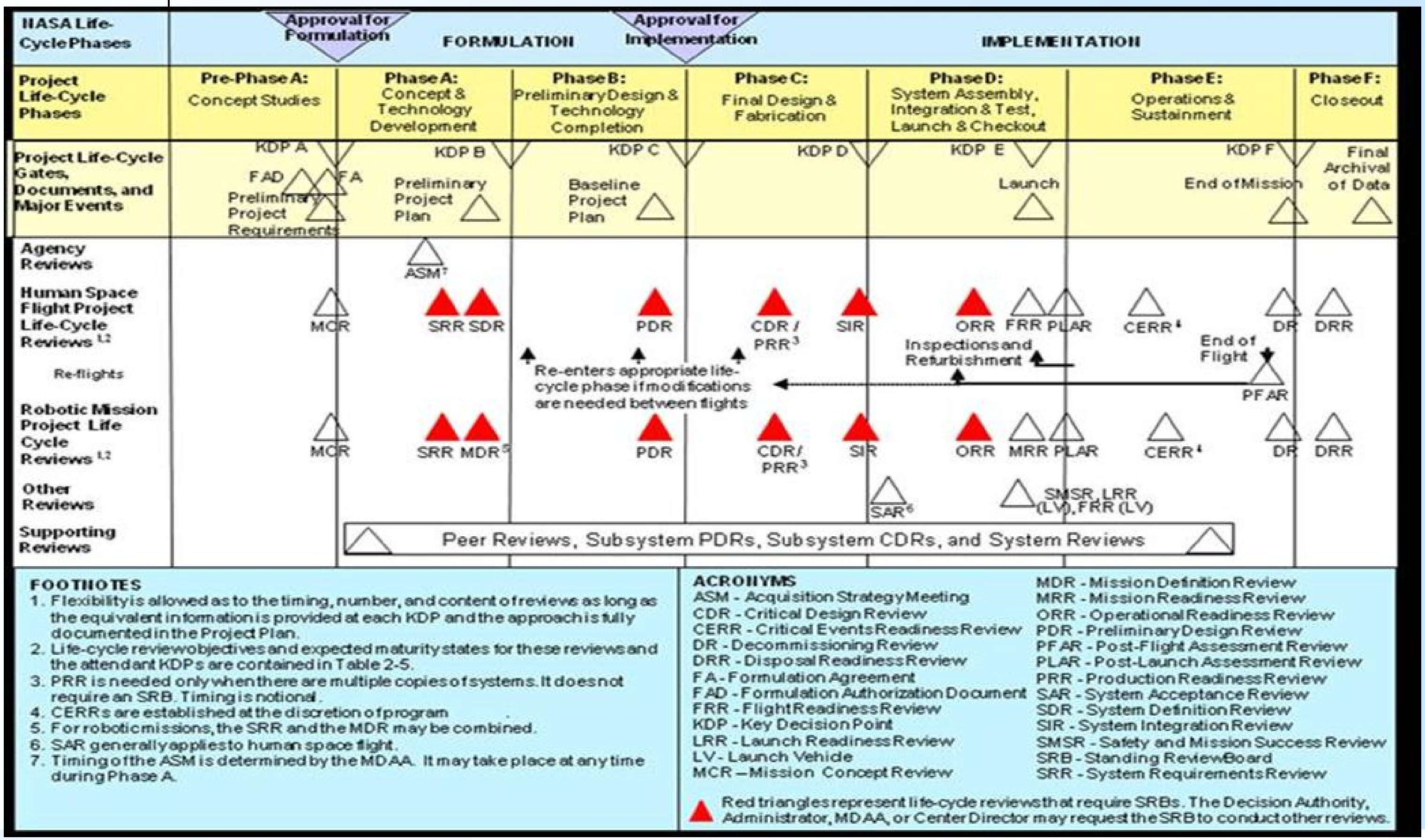
- ***Can be conducted at mission area or mission level***
  - ***MAA Studies:***
    - *Address best-value mix (number, capability, rough cost, etc.) of collection of MAA assets that work together in specific scenarios & time frames to accomplish mission area objectives*
    - *Inform planners on recommended capabilities & investment profile across mission area*
  - ***Mission Architecture Studies:***
    - *Address approaches to meet objectives for single mission*
    - *Done when little is known of mission & significantly different approaches exist*
      - *e.g.,1st time expedition to study moon of Saturn*
    - *Scope narrower & deeper than MAA*
    - *Inform planners on most cost effective approach for mission*

Architecture Development Precedes System Level Concept Design Studies in Project Life Cycle

Figure 1

Architecture Development

NASA Project Life Cycle Example - NASA Procedural Requirements (NPR) 7120.5E



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Architecture Frameworks

- ***Many architecture frameworks reported developed or in use***
  - *A survey of over 60 frameworks is at ref. (a), including those for:*
  - *Enterprise, defense, information, software, automotive, business, security, etc.*

Objective 1

- ***Describe what an MAA is and show how it integrates into the NCS architecture framework***

Beginning Definitions

- ***Before getting started, just what is an “architecture”?***

Beginning Definitions (Cont'd)

- ***New Webster Dictionary (1975) defines "Architecture" as:***
  - *1) the art or science of building; specif. the art or practice of designing and building structures and esp. habitable ones*
  - *2) formation or construction as, or as if, the result of conscious act*
  - *3) architectural product or work*
  - *4) a method or style of building*

- ***New Webster Dictionary (1975) defines "Architect" (from Latin "architectus", from Greek: "architekton" or master builder) as:***
  - *1) one who designs buildings & superintends their construction*
  - *2) one who plans and achieves a difficult objective (e.g., a military victory)*

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What is the "NCS Architecture"?

- **From these definitions, it's clear architecting involves some level of design & orchestration, but**
  - What level of design?
  - What does an architecture look like, and what does it do?

- **To answer these questions, we'll need a common view of:**
  - NCS Architecture & its constituent MAAs
  - Core elements of NCS architecture

Core Elements of an NCS Architecture

1) *The set of **functional capabilities** that characterizes actual or forecast capabilities of NCS physical assets & human command & control (C2) entities*
   - *Includes "what" capability will be delivered along with measures of performance (MOPs), e.g.,*
     - *Quality, quantity, timeliness, interoperability, & robustness (QQTIR) (Note: this is not an exclusive list)*

2) *The set of NCS **physical assets** (hardware/software) that is, (or is forecast to be) available along with their interconnectivities*
   - *Shows "how" architecture functional capabilities will be delivered*

3) *The set of NCS **human C2** operator / decision maker **entities** available along with their interconnectivities*
   - *Note: Automated C2 assets are considered part of physical assets*

Core Elements of an NCS Architecture (Cont'd)

4) *The concept of operations (**<u>CONOPS</u>**) that identifies how NCS physical assets & human C2 entities will be employed in time sequence to meet a defined mission*
   - *Used to evaluate effectiveness, etc., as function of environment & scenario*

5) *The set of **<u>constraints</u>** , i.e., rules / policies & standards / protocols, that constrain use of NCS assets & human C2 entities*

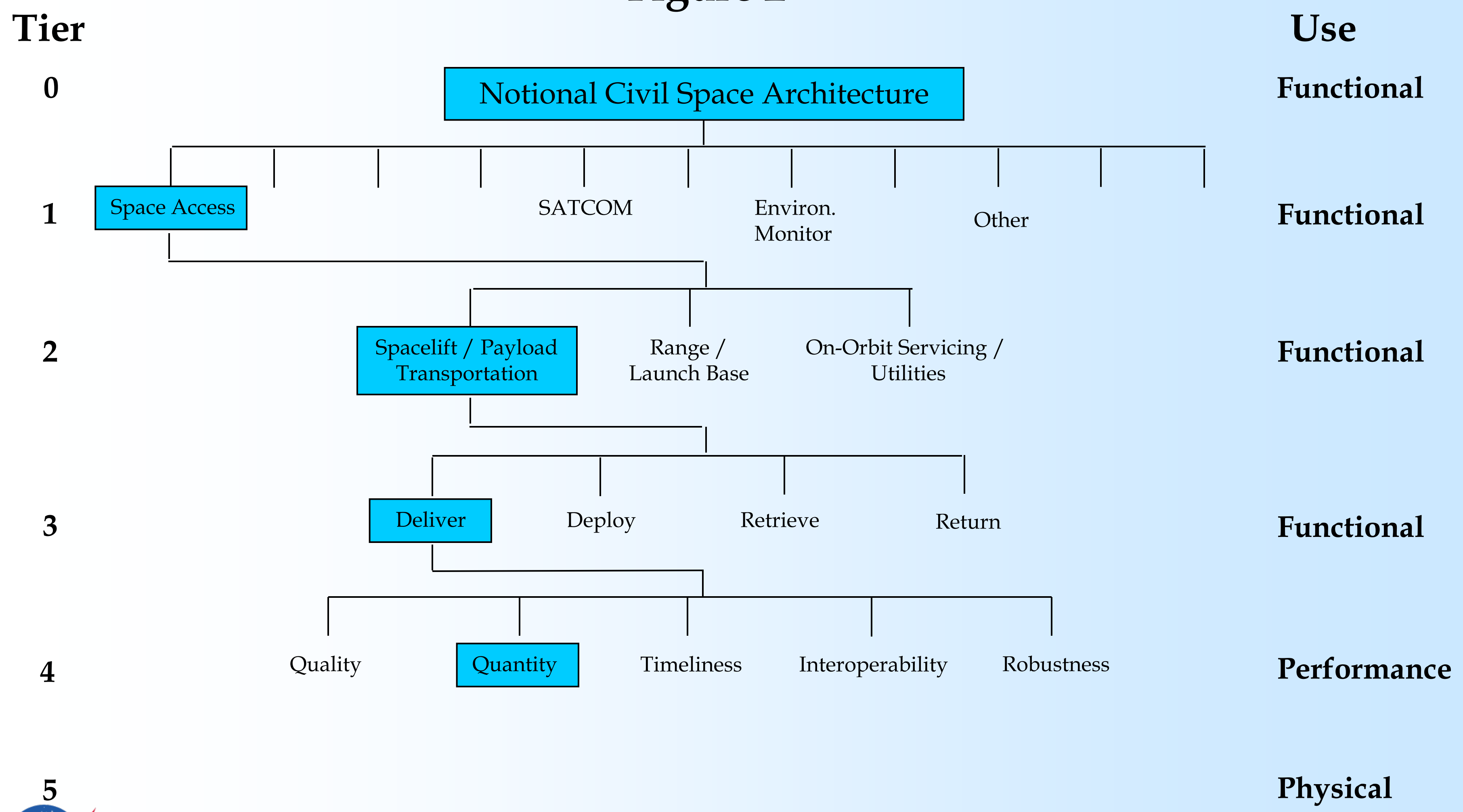
- ***Each** element above pertains to **<u>specific period in time</u>, or "epoch"***

NCS Architecture Framework Example

- ***Framework is established by functional decomposition***
  - *Standard systems engineering (SE) technique*
- ***Enables means to identify***
  - *Vertical flowdown of guidance*
  - *Horizontal interfaces within & among architectures*

NCS Architecture Framework Example
Space Access Mission Area (Epoch = 20xx)

Figure 2



Functional Decomposition Example

Space Access Mission Area (Epoch = 20xx)

- ***Tier 0:*** *NCS architecture functions applicable to all mission areas*
- ***Tier 1:*** *Allocates Tier 0 functions to mission areas, e.g., provide **Space Access***
- ***Tier 2:*** *Allocates Tier 1 functions to sub mission area functions (e.g., provide **Spacelift / Payload Transportation**, etc.)*
- ***Tier 3:*** *Allocates Tier 2 functions to more detailed functions (e.g., **deliver, deploy, retrieve, return,** etc.)*
- ***Tier 4:*** *Allocates Tier 3 functions to metrics (**QQTIR**) & **MOPs**, e.g., for "**deliver**" function*
  - *Example quantity metric* = *x payloads of y,000 kg to z,000 km circular orbit at i° inclination*
  - *Example MOP (adds specific values)* = *2 payloads of 2,000 kg to 400 km circular orbit at 51.6° inclination*
- ***Tier 5:*** *Allocates Tier 4 to physical assets & human C2 entities*

Note: Number of tiers can vary among mission areas

Role of Tier 0 & 1 Guidance

- ***Tier 0: Provides guidance for all mission areas, e.g.,***
  - *Environmental (e.g., power / fuel sources, orbital debris, planetary protection, etc.) policy*
  - *Interoperability standards*
  - *Criticality categories which drive level of robustness (or fault tolerance needed); might pertain to those that assure:*
    - *1) Human survival*
    - *2) Specific mission operational capabilities*
    - *3) Specific technology capabilities*

- ***Tier 1: Adds guidance unique to each Tier 1 mission area***

- ***Note:***
  - *A fault means loss of capability for any reason (component failure, hostile action, etc.)*
    - *Severity of potential fault depends on severity of threat*

Functional Decomposition Table Example

Space Access Mission Area (Epoch = 20xx)

Supports Figure 2

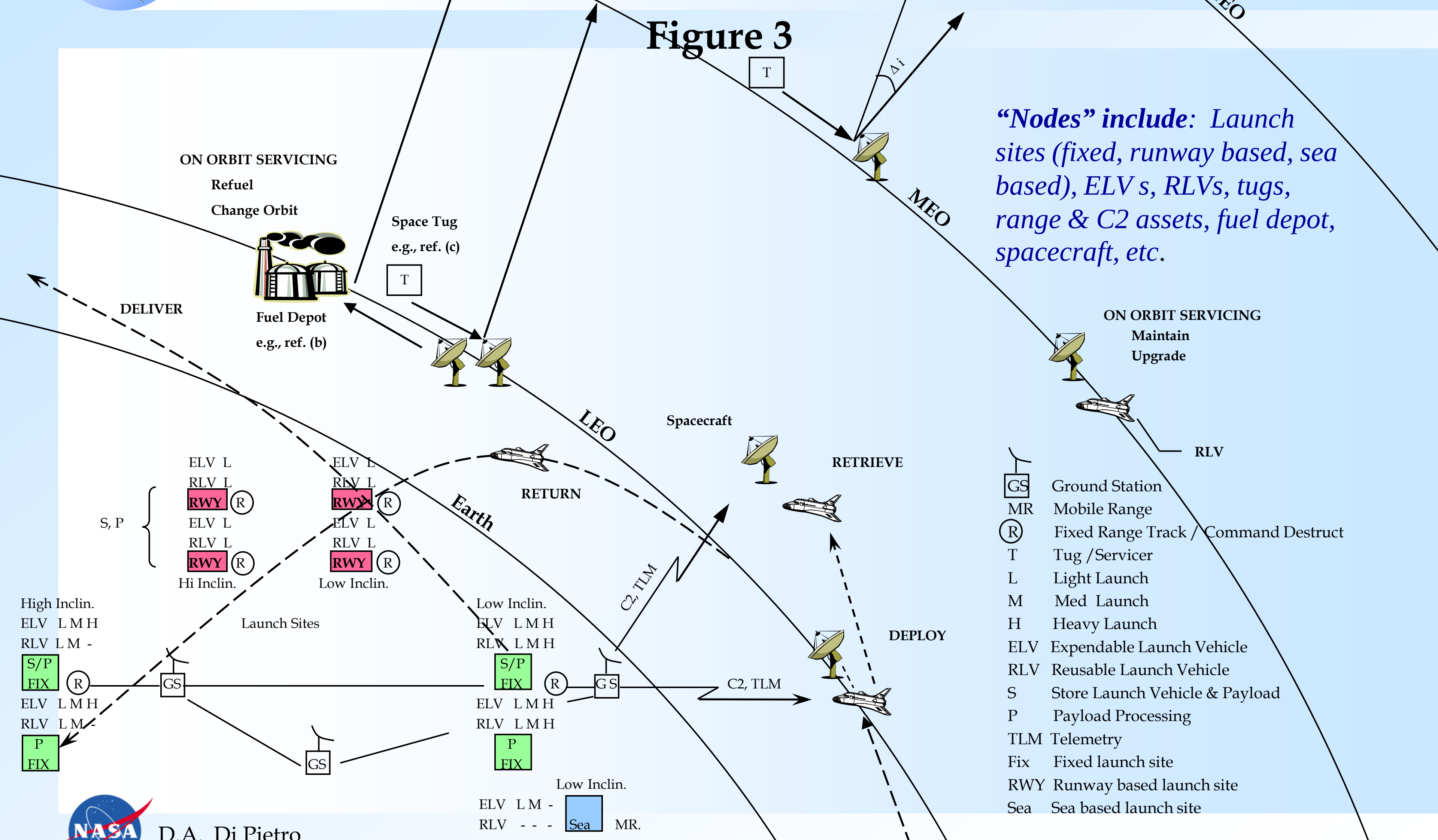
Table 1

Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Notes
1.0 Provide NCS capabilities	1.1 Provide Space Access capabilities	1.1.1 Provide Spacelift / Payload Transportation capabilities	1.1.1.1 Provide capability to **deliver** payload(s) to orbit	**1.1.1.1.1 Quality**	
				1.1.1.1.2 Quantity	
				1.1.1.1.3 Timeliness	
				1.1.1.1.4 Interoperability	
				1.1.1.1.5 Robustness	
			1.1.1.2 Provide capability to **deploy** payload(s) on orbit	**1.1.1.2.1 Quality**	
				1.1.1.2.2 Quantity	
				1.1.1.2.3 Timeliness	
				1.1.1.2.4 Interoperability	
				1.1.1.2.5 Robustness	
			1.1.1.3 Provide capability to **retrieve** payload(s) on orbit	**1.1.1.3.1 Quality**	
				1.1.1.3.2 Quantity	
				1.1.1.3.3 Timeliness	
				1.1.1.3.4 Interoperability	
				1.1.1.3.5 Robustness	
			1.1.1.4 Provide capability to **return** payload(s) from orbit	**1.1.1.4.1 Quality**	
				1.1.1.4.2 Quantity	
				1.1.1.4.3 Timeliness	
				1.1.1.4.4 Interoperability	
				1.1.1.4.5 Robustness	
		1.1.2 Provide Range / Launch Base Capabilities	Use construct similar to 1.1.1	Use construct similar to 1.1.1	
		1.1.3 Provide On-Orbit Servicing / Utilities Capabilities	Use construct similar to 1.1.1	Use construct similar to 1.1.1	

NCS Space Access Physical View (20xx)

Addresses Functional Decomposition
Excludes Assets beyond GEO

"Nodes" include: Launch sites (fixed, runway based, sea based), ELV s, RLVs, tugs, range & C2 assets, fuel depot, spacecraft, etc.



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NCS Architecture Framework Example
Mission Area Functions Allocated to Multiple Organizations

Figure 4

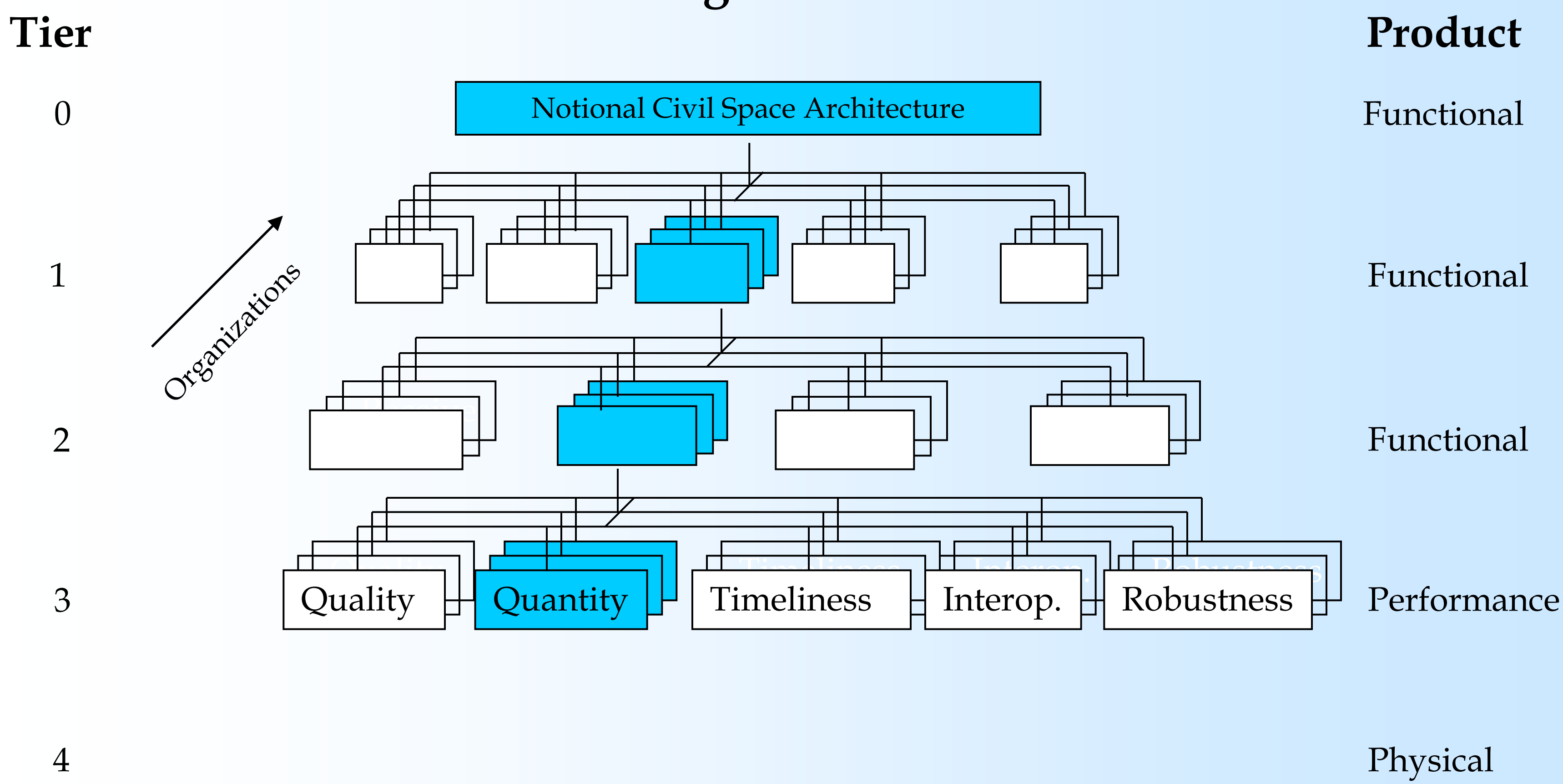
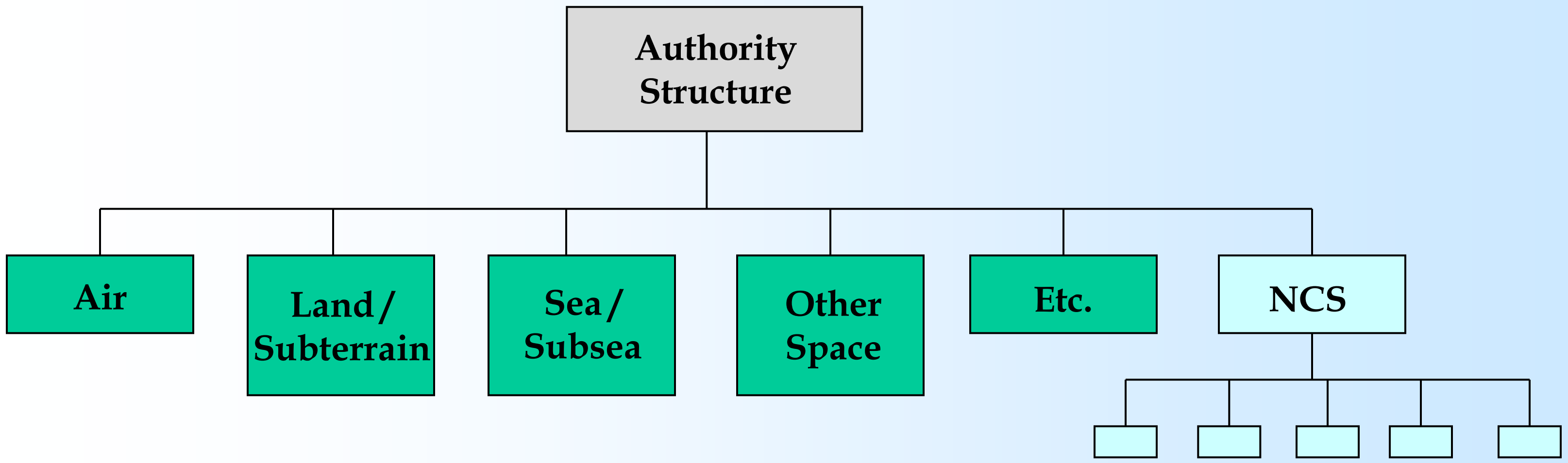


Figure 4 illustrates an NCS architecture framework wherein mission area functions are performed by more than one civil organization

NCS: Just One Domain of Many Domains

Figure 5



- *NCS architecture may be part of larger architecture that crosses domains & stakeholders*
- *Integration with larger architecture may impose additional constraints*

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Example Level of "Design" Work in MAA Development

- ***MAA technical analysis typically limited to 1st principles***

- ***For space access MAA with tugs that maneuver spacecraft, ADT might size tugs at rocket equation level***
  - *Tug mass might scale to 1st order via rocket equation & other relationships, e.g., dry mass to propellant mass ratio, etc.,*

- ***No detailed tug subsystem design conducted***

Measures Of Effectiveness (MOEs)

- ***MOEs - typically address effectiveness at architecture level & differ from MOPs, e.g.,***
  - *MOP might pertain to sizing nodes for spacelift, range, & on-orbit servicing functions*
  - *MOE might pertain to how well these nodes combine to meet an operational objective of a scenario at MAA level*

- ***MOEs typically need to be decomposed into measurable terms in order to be useable by ADT***
  - *Need early & continued customer / user engagement to develop & refine*

Architecture Scenarios & Environments

- **_Scenarios_**
  - *Include driving operational cases at architecture level*
- **_Environments typically are assumed conditions in which architecture will be developed & / or operate, e.g.,_**
  - *Stable / cooperative vs. unstable / uncooperative governments*
  - *Stable vs. unstable budgets*
  - *Contested vs. uncontested space operations*
  - *Orbital debris / space weather, etc.*
- **_Key enabler for NCS architecture level effectiveness analysis_**
  - *Consistent scenarios & environments at MAA & NCS levels for given epoch*

Interface Identification

- ***Horizontal interfaces (within or among MAAs) can be highlighted on functional decomposition***
  - *e.g., transmit data rate / frequency from remote sensing node (Environmental Monitoring MAA) to ground station (SATCOM MAA)*
- ***Some physical interfaces may need to be standardized***
  - *e.g., for some on-orbit servicing nodes*
- ***Horizontal integration analyses across MAAs validate interfaces are compatible***

Mission Area CONOPS Development & Use

- ***Each MAA has CONOPS that applies to particular scenarios, environments & epoch***
  - *Used to evaluate MAA effectiveness*

- ***CONOPS is specific to architecture design***
  - *i.e., scenario is met differently by space access MAA having RLVs & on-orbit servicing than by MAA having only ELVs*
    - *RLV = Reusable launch vehicle*
    - *ELV = Expendable launch vehicle*

Some Uses for an NCS Architecture Framework

- ***Establishes common lexicon for functions, metrics, & products***
- ***Allows synthesis of Tier 0 Architecture (as-is, to-be, should-be)***
  - *Provides coherent context & relationships among architecture elements*

- ***Provides structured flowdown of policy & guidance into MAAs***
- ***Highlights whether studies are for:***
  - *a) One mission area across all QQTIR metrics*
  - *b) All mission areas for only one metric, e.g., timeliness*

- ***Facilitates horizontal (& cross organizational) integration of MAA interfaces at NCS level***
- ***Exposes gaps / overlaps that can be used to select follow-on architecture studies***

- ***Facilitates identifying Tier 0 CONOPS & conducting effectiveness analysis of Tier 0 Architecture in set of scenarios & environments***

Objective 2

- ***Describe an effective approach for developing an MAA***

Terms of Reference (TOR)

- ***TOR is top level study charter, approved by customer***
  - *ADT leadership may assist in developing*
- ***TOR should clearly identify***
  - *Who, what, where, why, when of study process & products*
    - *Incl. resources, participants, roles & responsibilities*
- ***TOR typically will include***
  - *Problem background (incl. relationship to relevant past studies)*
  - *Problem statement: Concise & clear*
  - *Study scope & product depth, i.e.,*
    - *Functional boundaries (e.g., include spacelift, exclude on-orbit servicing)*
    - *Stakeholders*
    - *Domains*
    - *Epoch*
    - *Mission area guidance (e.g., relevant policy directives, etc.)*
  - *Guidance for establishing MOEs*
  - *Definitions for key unique terms*

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Terms of Reference (TOR) (Cont'd)

- *Assumptions, Constraints, Groundrules*
  - *System (x) from stakeholder (y) is out of scope*
  - *Use data from source (z) as principal input*
  - *Scenarios & environments*
  - *Technology readiness date*
  - *Policy, Cost*
- *Guidance on how to select recommended architecture*
  - *e.g., single best value architecture within cost constraint, etc.*

- ***TORs are deceptively difficult, but worth time to develop well***
  - *Meaningful TOR can save ADT's significant time*
  - *Weak TOR can leave ADT to define purpose, scope, deliverables, etc. while designing MAA*
    - *ADT view may not match customer view*

Mission, Domain, & Stakeholder Space

Figure 6

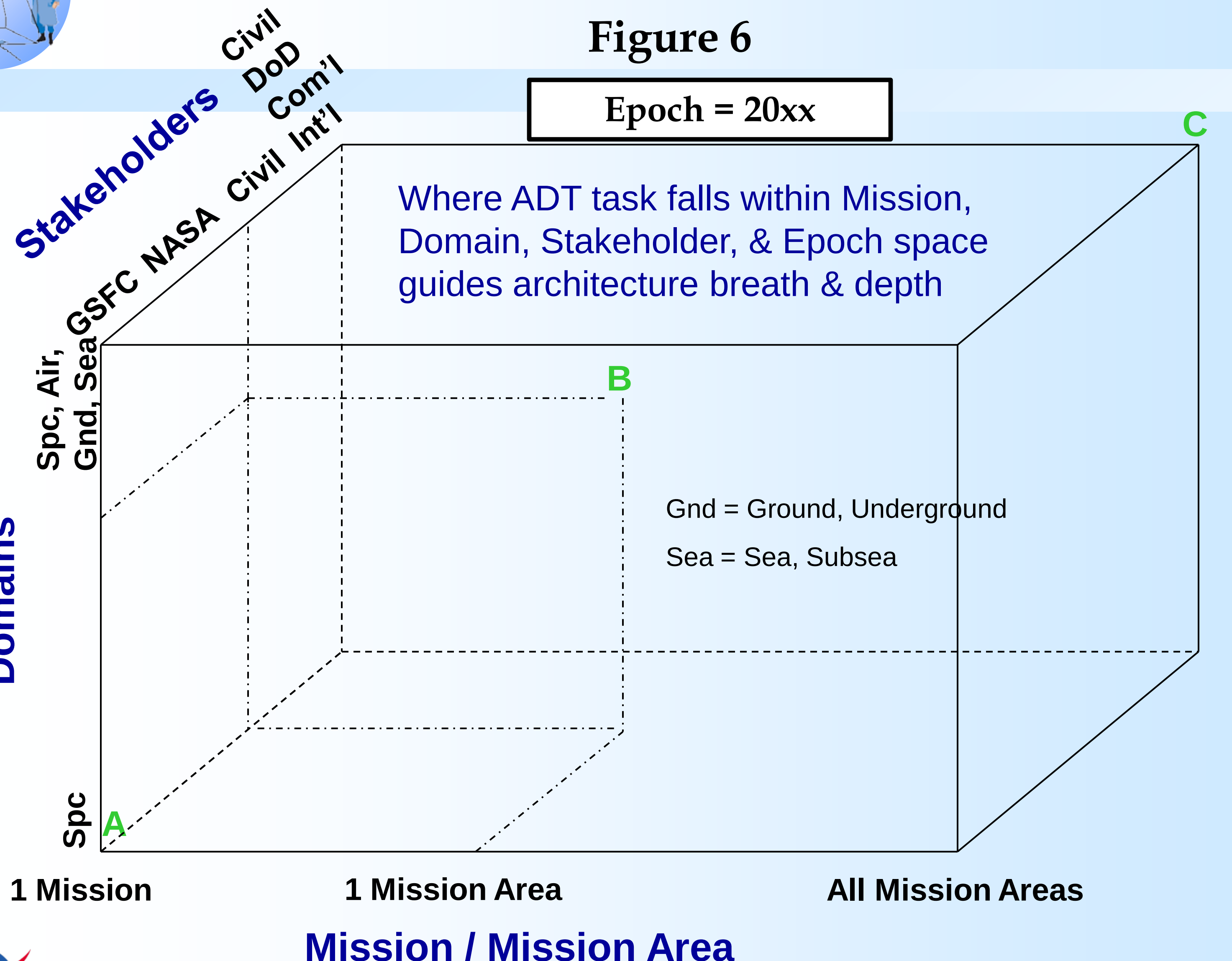

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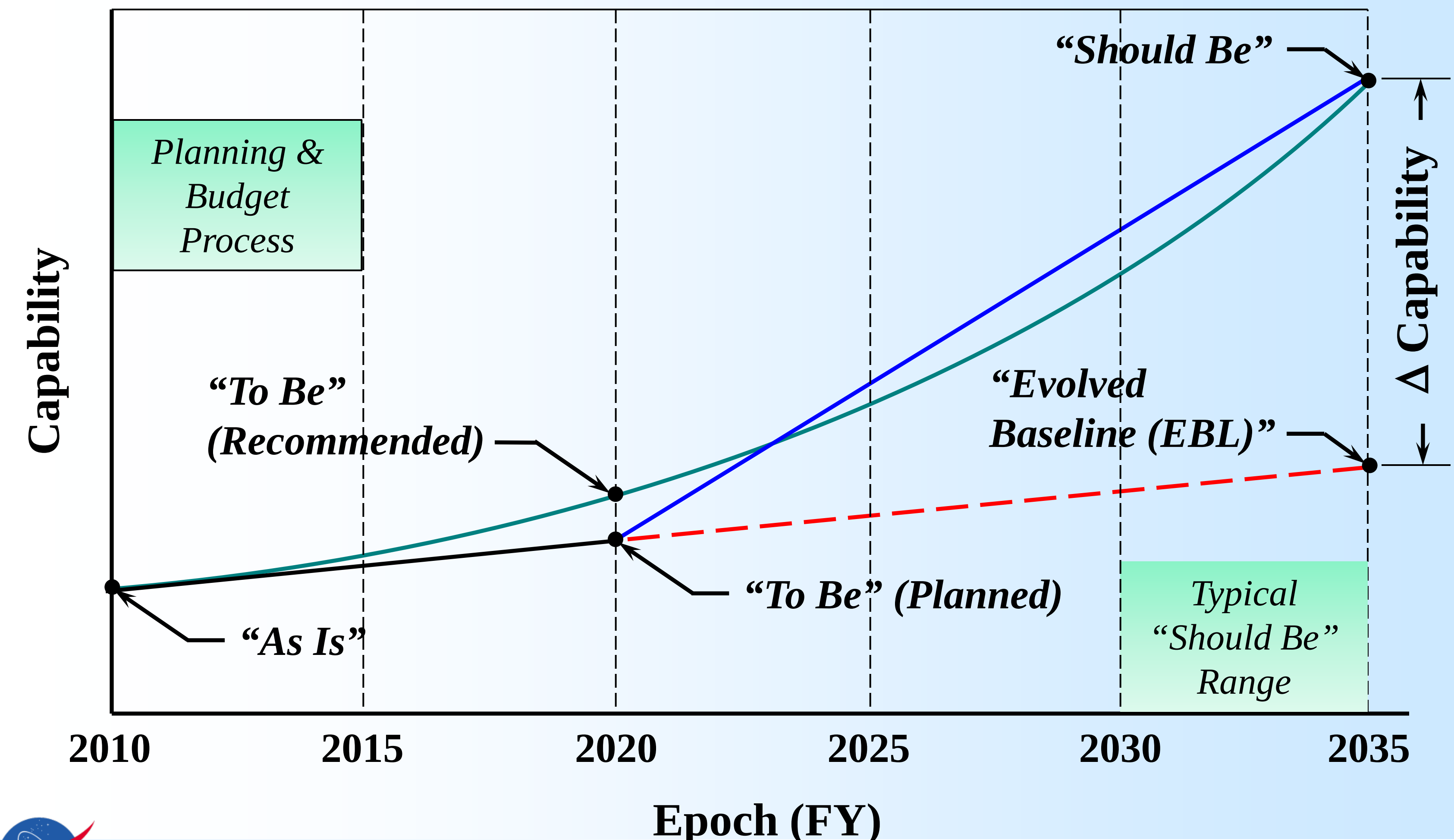
Illustration of "As-Is", "To-Be", "Should-Be", & Evolved Baseline" Architectures

Ref. (d)

Figure 7



Conducting Effective Architecture Studies

- ***Lets now look at one way to effectively conduct an MAA study***
  - *A generic, iterative "design cycle" process*

- ***Important Note:***
  - *MAA studies can be conducted more than one way*
    - *Typically, however, they involve synchronized, iterative process with active systems engineering (SE) leadership*
    - *"Art" is in enabling & orchestrating highly dynamic & creative efforts to produce products of sufficient scope & fidelity within allotted time*

Introduction to Design Cycle Process for Architecture Studies

- ***Design cycle process is structured, iterative approach***
  - *Based on standard SE technique for conducting requirements development, design, & analysis*
  - *Brings products to common, coherent reference point in each cycle*
    - *Accelerates start of architecture design, surfaces unknowns early*
    - *Provides discrete opportunities for stakeholder / management review*
    - *Maintains synchronization of assumptions, trades & analyses*
    - *Facilitates systems level integration*
    - *Improves final report & reduces work required to produce it*

- ***Other process models (e.g., waterfall, ad-hoc iterative, etc.), less effective for studies with high uncertainty***
  - *Waterfall (i.e., linear, unidirectional) processes more effective for tasks that are well understood*
  - *Ad-hoc iterative processes difficult to keep in synch*

Introduction to Design Cycle Process for Architecture Studies (Cont'd)

- ***First time MAA developments are inherently exploratory & uncertain***
  - *Teams learn at high rate, unknown-unknowns (UUs) dominate early*
- ***Can't plan all study details at outset***
  - *Outline general plan (incl. major activities & milestones) early*
  - *Plan cycle details iteratively within general plan constraints*
    - *Plan & execute Cycle 1, plan & execute Cycle 2a, etc.*
- ***Starting design work early accelerates learning***
  - *Helps surface UUs early*
  - *Allows adjustments when there is still time to resolve*

Design Cycle Approach Overview
Conducted in 3 Cycles

- ***Cycle 1: Pathfinder; learn & assess readiness for design***
  - *a) requirements characterized in form usable for analysis*
  - *b) metrics compatible with modeling tools*
  - *c) modeling tools can analyze design to provide desired product set*
  - *d) desired product set suffices to answer questions in TOR*
  - *Analyze a few architectures that span solution space*
  - *Surrogates can be used for requirements, technology forecast*

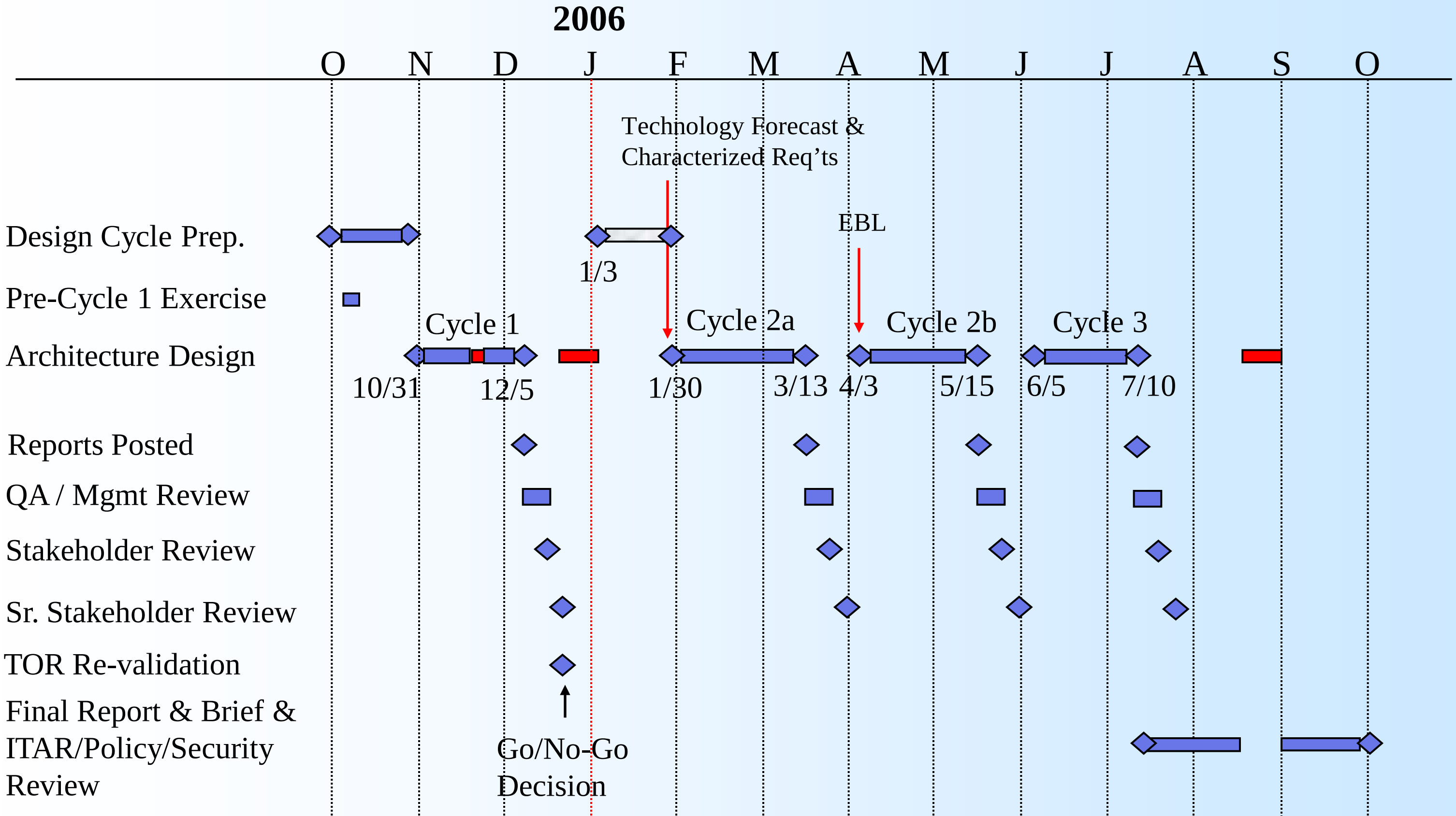
- ***Cycles 2a & 2b:***
  - *Conduct comprehensive investigations for broad range of candidate architectures*
  - *Determine most promising architectures across trade space*

- ***Cycle 3:***
  - *Refine designs & analyses on most promising representative architectures of solution space*
  - *Recommend single best-value architecture*

12-Month MAA Study Design Cycle Template

CY 2005/2006 Example with Pre-Design Products Available

Figure 8



1) Assume no scheduled work during: 1) Thanksgiving week, 2) last 2 weeks of August & December. Assume partial week during Spring Break
2) End of Cycle 1 presents opportunity to assess whether study should be continued (e.g., is problem well posed, is scope realistic, etc.) and to revalidate TOR.

Pre-Design Products
Draft Products Developed before Cycle 1

- ***Pre-Design Products Accelerate Cycle 1 start***
  - *Functional decomposition through performance metrics*
  - *Generic scalable physical nodes*
    - *Prepare for modeling use, incl. governing equations / relationships*
  - *Generic "threads" (see next chart)*
  - *Types of modeling tools available to analyze nodes*
  - *Technology forecast (to degree readily available in roadmaps, etc.)*
  - *Summary of known mission area guidance & relevant studies*
  - *MOEs previously used or identified for mission area*

- ***Pre-design products may also include***
  - *Data collection templates that support development of technology forecast and as-is, to-be planned, and EBL architectures*

Architecture Trade Case Matrix
Space Access Example

- ***Analyses of individual nodes combine to determine performance / effectiveness of "threads"***
  - *Threads contain all elements to deliver an end-to-end service, e.g.,*
    - *Deliver payload to orbit includes: launch base, ground station, range, launch vehicle, human C2 entities*
  - *Nodes are main elements (e.g., launch vehicle) within thread*

- ***Analyses of individual "threads" combine to determine performance / effectiveness of MAA***
  - *ADTs assign combinations of threads to a range of candidate MAAs*

- ***Functional decomposition for final MAA solution transferred into NCS functional decomposition table***
  - *Formats similar*

Architecture Trade Case Matrix
Leverages Functional Decomposition Table
Space Access Example

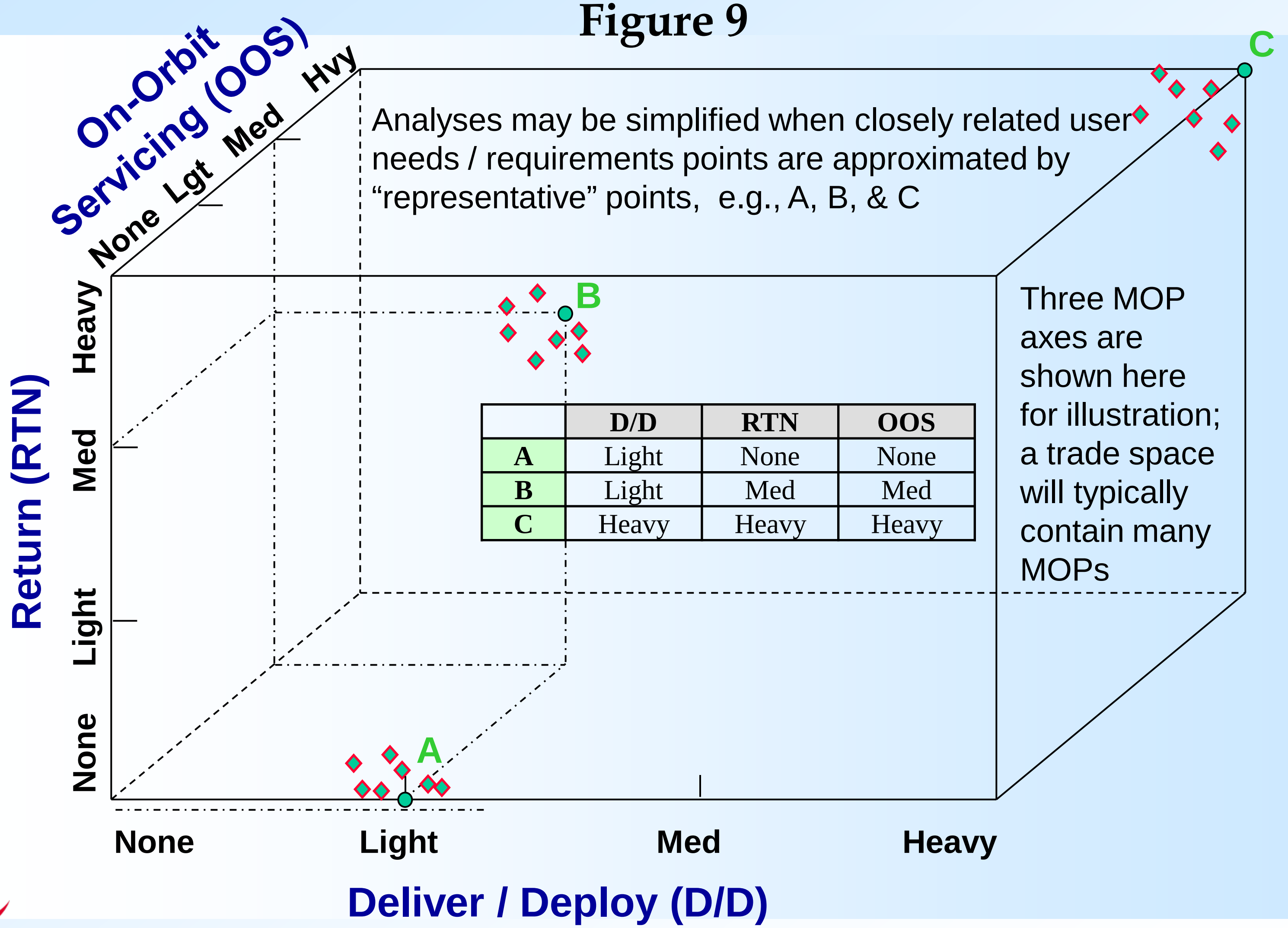
Table 2

Architecture Solution (How's) => Functions / MOPs (What's)	1a	1b	1c	2a	2b	2c	3a	3b	3c	4a	4b	4c	5a	5b	5c	6a	6b	6c
PROVIDE Space Access Capabilties	**All ELV**			**Mix ELV / RLV**			**All RLV w/Tugs**											
Provide Spacelift / Payload Transportation Capabilities																		
- Deliver																		
- Quality										**Each "architecture" is a composite of several "threads" designed to meet MOPs (QQTIR)** **Architecture 1** represents an all ELV solution where threads 1a, 1b, & 1c might be light, medium, & heavy ELVs, respectively. **Architecture #3** represents an all RLV solution with tugs, where threads 3a, 3b, & 3c might be light RLVs, medium RLVs, & medium tugs, respectively.								
- Quantity																		
- Timeliness																		
- Interoperability																		
- Robustness																		
- Deploy (QQTIR as above)																		
- Retrieve (QQTIR as above)																		
- Return (QQTIR as above, etc.)																		
Provide Range / Launch Base Capabilties										Expand as done for Spacelift / Payload Transportation								
Provide On-Orbit Servicing / Utilities Capabilities										Expand as done for Spacelift / Payload Transportation								

Example Requirements Trade Space

Space Access Example

Figure 9



	D/D	RTN	OOS
A	Light	None	None
B	Light	Med	Med
C	Heavy	Heavy	Heavy

Typical Design Cycle Products (1 of 2)

Table 3

No	Product	Cycles
1	Functional Decomposition (& MOPs / Interface Req'ts)	1, 2a, 2b, 3
2	Needs / Requirements Classes & Bounding Cases	*, 2a, 2b, 3
3	Trades and Tradespace Report	1, 2a, 2b, 3
4	EBL	2b, 3
5	Technology Forecast & Plan	*, 2a, 2b, 3
6	Architecture Alternative (AA) Point Designs	1, 2a, 2b, 3
7	Scenarios	1, 2a, 2b, 3
8	Threat / Alternative Future Environments	1, 2a, 2b, 3
9	MOEs	1, 2a, 2b, 3

Note: Shading aggregates products into ADT subteam reports

1) Operations:	Green shading
2) Systems:	Blue shading
3) Analysis:	Yellow shading
4) Architecture SE:	Grey shading

* Surrogates may be used for Cycle 1

Typical Design Cycle Products (2 of 2)

Table 3 (Cont'd)

No	Product	Cycles
10	Performance / Utility Analyses Report	1, 2a, 2b, 3
11	CONOPS	1, 2a, 2b, 3
12	Vulnerability Assessment	1, 2a, 2b, 3
13	Doctrine / Policy Assessment	1, 2a, 2b, 3
14	Work Breakdown Structure	1, 2a, 2b, 3
15	Cost Analysis	1, 2a, 2b, 3
16	Risk Assessment	1, 2a, 2b, 3
17	Subteam Technical Reports	1, 2a, 2b, 3
18	Systems Engineer Report	1, 2a, 2b, 3

Some Recommended Practices for MAA Development

- **_Develop Strong TOR_**
  - ➢ *Sound understanding of objectives, scope, product, etc.*
- **_Set "Should-Be" epoch far enough out for candid discussion_**
  - ➢ *25 years: Allows candid discussion of future architecture*
  - ➢ *15 years: Discussion highly constrained by current budget*
- **_Conduct ADT in cycles vs. single, waterfall step_**
  - ➢ *Keep Cycle 1 short, but apply concerted effort – high value learning*
  - ➢ *Avoid pressure to use results from Cycle 1 for budget inputs*
- **_Don't retrofit architectures from prior cycles_**
  - ➢ *Just apply what's been learned to future cycles*
- **_Exercise full solution space in Cycles 1, 2a & 2b_**
  - ➢ *Cycle 1 will have few architectures, but will span solution space to exercise thought paths*

Some Recommended Practices for MAA Development (Cont'd)

- ***Engage stakeholders with coherent products periodically***
  - *Don't wait until end of study to engage*
- ***Begin writing ADT report in Cycle 1, refine in Cycles 2 & 3***
  - *Write reports first (documents of record), then translate to briefings*
- ***Assign architecture systems engineer experienced in successfully conducting MAA studies***
- ***Remain objective & impartial***
  - *Recognize unknown unknowns dominate early*
- ***Respect the clock***

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Questions ?

References

a) http://www.iso-architecture.org/ieee-1471/afs/frameworks-table.html

b) http://en.wikipedia.org/wiki/Propellant_depot

c) http://en.wikipedia.org/wiki/Space_tug

d) Adapted from model used by Mr. H. E. Hagemeier, Deputy Director, National Security Space Office, 2009

Backup

Use of the Term "Requirements" for MAAs

- ***"Requirements" as used by an ADT have a different context than in project management***
  - *An ADT uses "requirements" to reflect classes of user needs while conducting MAA trade study cases prior to Pre-Phase A*
  - *In project management, "requirements" aren't baselined until System Requirements Review (SRR), normally near the end of Phase A, for a specific mission concept*

NCS CONOPS Development & Use

- ***At NCS level, a CONOPS is developed using scenarios, environments, & epoch consistent with those evaluated for each MAA***
  - *Assumes MAA's within NCS have significant operational interrelationships*
- ***Effectiveness of NCS architecture is periodically evaluated using this CONOPS with "frozen" architecture design***
- ***Output of effectiveness assessment highlights parts of NCS architecture that underperform either due to shortfall in capability or due to interface incompatibility***
  - *These areas may be candidates for study in next cycle of NCS architecture design*

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Current, Mid-Term, & Far Term Architectures, Detail for Figure 7
Ref. (d)

- ***Architectures are developed for three periods in time, current, mid-term, & far-term***
  - *Current architecture is referred to as **"as-is"** architecture*
  - *Mid-term architecture is referred to as **"to-be"** architecture*
  - *Far-term architecture is referred to as **"should-be"** architecture*

- ***Figure 7 shows these architectures; where "as is" is FY 2010***
  - ***"Should-be"** architecture*
    - *Associated with systems & capabilities determined by ADT to be needed in **"should be"** epoch of FY 2035*
  - ***"To-be planned"** architecture*
    - *Associated with systems & capabilities that would result from proceeding on current development path (i.e., includes efforts funded in any year of current budget) until "to-be" epoch of FY 2020*

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Current, Mid-Term, & Far Term Architectures, Detail for Figure 7 (Cont'd)
Ref. (d)

- ***"Evolved baseline"**, or **EBL***
  - *Linear extrapolation of **"to-be planned"** architecture out to **"should-be"** epoch*
  - *Assumes no: non-linear breakthroughs afforded by new technologies, new operational doctrine, new policies, etc.*

- ***ADT compares "should-be" & EBL architecture capabilities to identify changes needed***
  - *ADT translates those changes into capability improvements for **"to-be recommended"** architecture that enables gradual, continuous improvement toward **"should-be"** capability*
  - *ADT identifies corresponding funding adjustments in budget to meet **"to-be recommended"** capability*