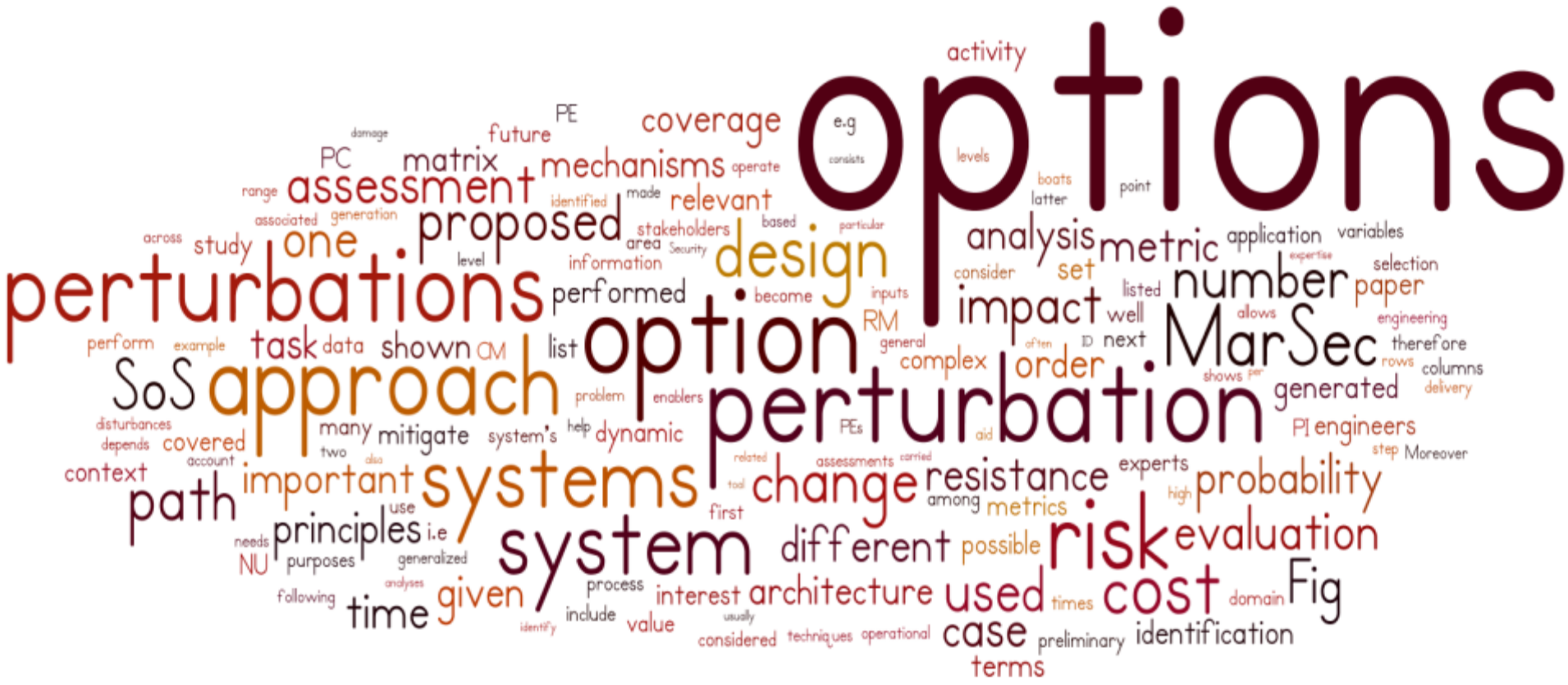
A Generalized Options-Based Approach to Mitigate Perturbations in a Maritime Security System-of-Systems

Nicola Ricci, Adam M. Ross, Donna H. Rhodes

CSER 2013

Atlanta GA

What is the Paper about?



The more a word was used in the paper, the bigger

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Outline

- Motivation
- Generalized Approach
  - Options Generation Process
  - Options Evaluation Process
    - Metrics for Evaluation of Options
  - Options Selection Process
- Discussion & Next Steps

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MOTIVATION

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Motivation

The world in which Systems Engineers practice has undergone a significant metamorphosis over the past twenty years

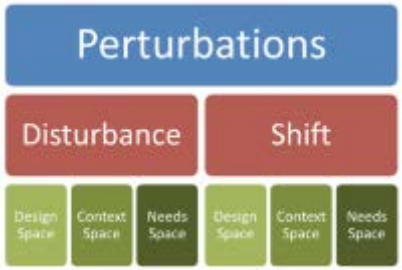
- *Advent of the internet* → great increase in amount of resources available
- *Information travels at the speed of light* → instantaneous communication
- *High-speed computation* → Performance of very complex analyses

Systems are subject to highly **dynamic operational environments**

- A multitude of exogenous uncertainties can impact a system
  - *Geo-political shifts* (e.g., policy/regulation changes)
  - *Disruptive technologies* (e.g., advent of GPS)
  - *Market variations* (e.g., price &demand variations)
- Unanticipated shifts in stakeholder needs
  - Change of *preferences*
  - Change of *mission objectives*
- Many options-based approaches for risk management
  - *Conceptually attractive, but with challenging effort and data requirements*
  - *May not be appropriate or difficult to apply to system of interest*

PERTURBATION

"Unintended state change in a system's design, context, or stakeholder needs that could jeopardize value delivery" (Beesemyer)



If focused solely on the present state of the world, engineers may encounter the problem of designing systems that may not be well positioned in the future, forced to operate in contexts for which they were not conceived, and delivering capabilities no longer of interest to stakeholders.

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Options

Problem	Perturbations introduce the **RISK** of interruption of value delivery
Solution	In the design of the system, include **“options”** that reduce the risk of interruption of value delivery

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Options

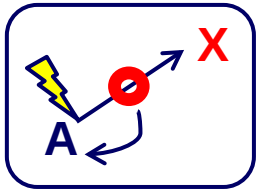
Problem	Perturbations introduce the **RISK** of interruption of value delivery
Solution	In the design of the system, include **"options"** that reduce the risk of interruption of value delivery

An **option**, in general, is *the ability to execute a design feature that will change or prevent change to the system in order to respond to perturbations and avoid interruption of value delivery*

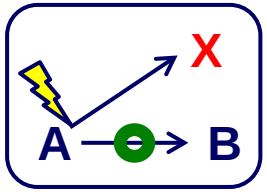
GENERALIZED OPTION

- **Resistance Option (RO)**
  - **Path Inhibitor (PI)**
  - **Resistance Mechanism (RM)**
- **Change Option (CO)**
  - **Path Enabler (PE)**
  - **Change Mechanism (CM)**

Having _____ allows you to _____
(path variable) (mechanism)



RO



CO

X = bad state
A,B = acceptable state

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Research questions

How should we find suitable options and decide what options to include?

Q1 How should we **generate** a list of interesting options?

Q2 How should we **evaluate** them? What metrics should we use?

Q3 How should we **select** the best options among those evaluated?

The socio-technical environment in which such systems are architected (and will eventually operate) can change rapidly, and therefore, in most cases, the identification and evaluation of options must occur in a timely manner

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GENERALIZED APPROACH

- Resist + Change
- Breath of Consideration
- Scalability w.r.t. Effort and Time

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Case Study

MarSec SoS

High-level Operational Needs Statement:

Provide maritime security for a particular littoral Area of Interest (AOI)

Stakeholders want a *system (SoS)* that:

- **Detects**, **identifies** and **boards** boats entering AOI
- Is capable of carrying out **search and rescue** missions upon request

Design variables and levels have already been defined…

Form

- Hermes
- Shadow
- Prop Plane
- Helicopter
- Manned Patrol Boat
- Satellite Relay
- Land Sensors

ConOps

- Tech Level Upgrade
- Info Sharing Use
- Task Assignment
- Geographic Segmenting
- Operators Per UAV
- Workforce Buffer
- Authority

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Case Study

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BUT…

We expect perturbations to occur and undermine the SoS value-delivery

It is now desired to find options that can be added to this current design space

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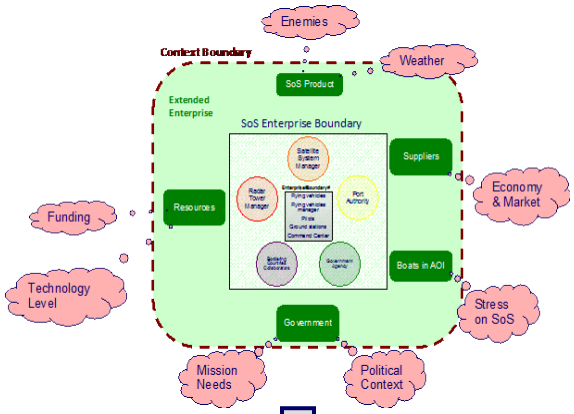
Inputs to Approach



Perturbations

Disturbances

- Serious Attack Occurrence
- Asset Unavailable
- Information Attack
- Storm
- Tsunami

Shifts

- Technology Level
- Workforce Availability
- Info Sharing Availability
- Boat Arrival Rate
- Pirate Percentage
- Smuggler Percentage
- Search and Rescue
- Jamming (Bad Com)

Value Sustainment

↓

Survivability

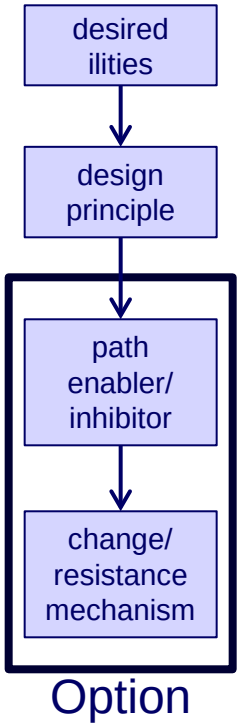
↓

Design Principles

- Preemption
- Avoidance
- Defensive Posture
- Deflection
- Hardness
- Heterogeneity
- Failure Mode Reduction
- Fail-safe
- Modification
- Containment
- Stable Intermediate Instances

…

(Richards)



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Generate a extensive list of options to be considered

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DP to Perturbation Mapping

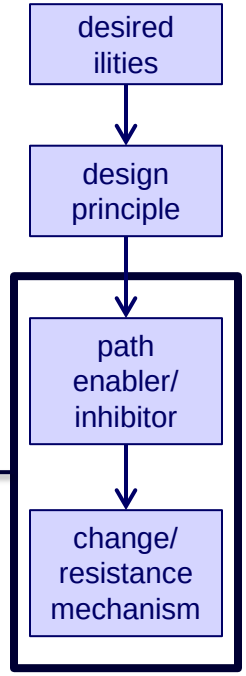
Generate as many options as possible

3 steps in this process

1. DP to perturbation mapping

Brainstorming activity: Perturbation-mitigating instantiations of design principles are considered options for systems engineers to include in the system design

	VALUE SUSTAINMENT	SHIFT					DISTURBANCE				
	DESIGN PRINCIPLES	S1	S2	S3	S4	S5	D1	D2	D3	D4	D5
ILITY 1	DP 1										
	DP 2										
	DP 3										
	DP 4										
	DP 5										
ILITY 2	DP 6										
	DP 3							■			
	DP 7										
	DP 8										
	DP 1										



Having _____ allows you to _____
(path variable) (mechanism)

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VALUE SURVIVABILITY FOCUS

	VALUE SURVIVABILITY / DESIGN PRINCIPLES	DISTURBANCES: Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack
SUSCEPTIBILITY	Prevention	Only use boats for intercept	Buy spares	Water repellant layer on windshield	Bring assets back to base promptly	
	Mobility	Vary flight paths and speeds		Enhanced control system	Move to non-affected region	
	Concealment	Higher Altitude				Higher altitude
	Deterrence					
	Preemption					
	Avoidance	Vary flight paths and speeds		Fast planes	Move to non-affected region	Vary flight paths and speeds
	Defensive Posture	Only use boats for intercept		Bring assets back to base promptly	Anchor boats to specific location	
	Deflection	Decoys	Decoys			
	Authentication					
	Reserves		Spares		Spares	
VULNERABILITY	Hardness	Armor		More stable structure	Armor	Double authentication
	Redundancy					
	Margin	Increase wing coefficient of lift (fly on one wing)	Use UAVs that are able to change role (detection/identification, etc.)			
	Heterogeneity		Multi-role asset		Multi-role asset	Satellite and direct links
	Failure Mode Reduction					
	Decentralization	Geographical distribution				Distribute/decentralize authority
	Fail-safe					
	Modification	UAV flight path change				
	Containment	Geographical distribution			Bring assets back to base	
	Stable Intermediate Instances	Training personnel in multiple tasks/irregular ops	Go to pre-validated design		Use only radar towers for detection	Training personnel in multiple tasks/irregular ops
RESILIANCE	Replacement	Spares	Replace unavailable asset with one at disposal		Train personnel for prompt vehicle replacement	
	Repair	Trained repair crews			Train personnel for prompt vehicle repair	Trained repair crews
	Adaptation	Change detection UAV to interception UAV	Use UAVs that are able to change role (detection/identification, etc.)	Enhanced control system		Training personnel in multiple tasks/irregular ops
	Contingency					
	Reversion					

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VALUE SURVIVABILITY FOCUS

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	Authentication					
			Spares		Spares	
VULNERABILITY				More stable structure	Armor	Double authentication
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	Contingency					
	Reversion					

Hardness → Armor

Decentralization → Distribute authority

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Pair CM-PE and RM-PI into Options

2. Discern among the four entries of the matrix and sort into lists → **3.** Match compatible PEs and CMs (and PIs and RMs) appropriately in order to generate a comprehensive list of change (and resistance) options

CHANGE OPTION		Path Enabler									Latent Path Enabler		
		Extra Interception UAV	Contract with Aircraft Supplier	Extra Cameras	Sea Planes	Pre-Validation Process	Long Range UAV	Workforce Buffer	Dispersed Com Network	Spares	Multi-Role Asset	Central Authority	Satellite Relay
Change Mechanism	Adding Vehicle	C1	C2	-	-	-	-	C3	-	C4	-	-	-
	Change Task Assignment	C5	-	C6	C7	-	-	-	C8	-	C9	-	-
	Change Geographic Segmentation	-	-	-	C10	-	C11	-	C12	-	-	-	C13
	Change Number of Operators per UAV	-	-	-	-	C14	-	C15	-	C16	-	-	-
	Go back to Pre-Validated Set	-	-	-	-	C17	-	-	-	-	C18	-	-
	Change Authority distribution	-	-	-	-	-	-	-	-	-	-	C19	C20
	Add extra features		C21	C22									

RESISTANCE OPTION		Path Inhibitor								Latent Path Inhibitor	
		Workforce Buffer	Armor on UAV	Better UAV Control System	Long range Signal Transimtter	Spares	Pre-Validation Process	High-Altitude UAV	Decoy	Multi-Role Asset	UAV Swarm
Resistance Mechanism	Overstaffing	R1	-	-	-	-	-	-	-	-	-
	Change Trajectory of Flight	-	-	R2	R3	-	-	R4	-	-	-
	Asset resistance to attacks	-	R5	-	-	-	-	-	-	-	-
	Disperse around AOI	-	-	R6	R7	-	-	-	-	-	R8
	Multiple Assets perform Same Function	-	-	-	-	R9	-	-	-	R10	R11
	Rapidly Recover against Asset Loss	-	-	-	-	R12	R13	-	-	R14	-
	Distract Hostile Attacks	-	-	-	-	-	-	-	R15	-	-
	Training Personnel for Multiple Tasks	R16	-	-	-	-	R17	-	-	-	-

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Adding Vehicle	C1	C2	-	-	-	-	C3	-	C4	-	-	-
Change Task Assignment	C5	-	C6	C7	-	-	-	C8	-	C9	-	-
Change Geographic Segmentation	-	-	-	C10	-	C11	-	C12	-	-	-	C13
Change Number of Operators per UAV	-	-	-	-	C14	-	C15	-	C16	-	-	-
Go back to Pre-Validated Set	-	-	-	-	C17	-	-	-	-	C18	-	-
Change Authority distribution	-	-	-	-	-	-	-	-	-	-	C19	C20
Add extra features		C21	C22									

RESISTANCE OPTION	Path Inhibitor								Latent Path Inhibitor	
Resistance Mechanism	Workforce Buffer	Armor on UAV	Better UAV Control System	Long range Signal Transimtter	Spares	Pre-Validation Process	High-Altitude UAV	Decoy	Multi-Role Asset	UAV Swarm
Overstaffing	R1	-	-	-	-	-	-	-	-	-
Change Trajectory of Flight	-	-	R2	R3	-	-	R4	-	-	-
Asset resistance to attacks	-	R5	-	-	-	-	-	-	-	-
Disperse around AOI	-	-	R6	R7	-	-	-	-	-	R8
Multiple Assets perform Same Function	-	-	-	-	R9	-	-	-	R10	R11
Rapidly Recover against Asset Loss	-	-	-	-	R12	R13	-	-	R14	-
Distract Hostile Attacks	-	-	-	-	-	-	-	R15	-	-
Training Personnel for Multiple Tasks	R16	-	-	-	-	R17	-	-	-	-

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In order to be able to differentiate among them

- Optionability
- Number of Uses
- Cost
- Perturbation Coverage

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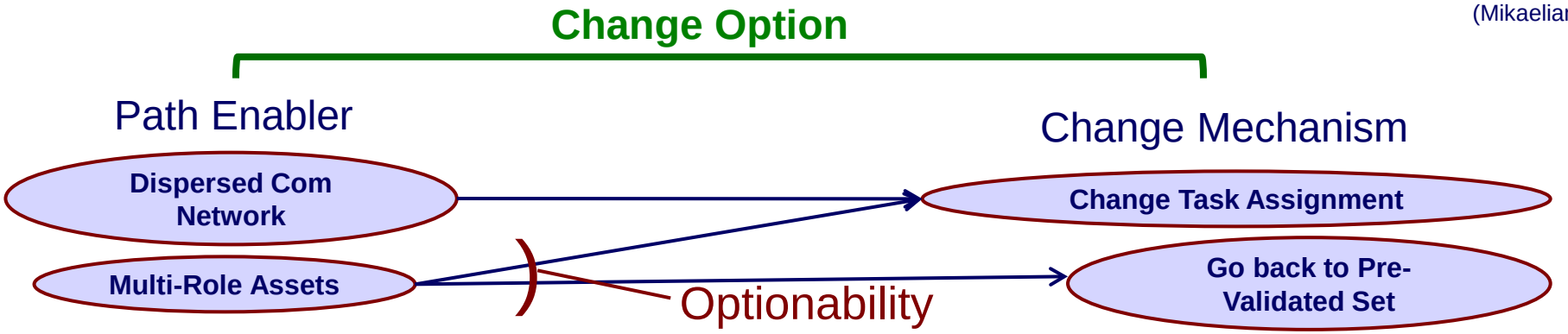
Evaluate Options: Optionability

Optionability: *the number of options that are connected to a particular path enabler/inhibitor*

(Mikaelian)



CHANGE OPTION		Path Enabler			Latent Path Enabler	
		PE 1	PE 2	PE 3	PE 4	PE 5
Change Mechanism	CM 1	C1	C2	-	-	-
	CM 2	C3	-	C4	C5	-
	CM 3	-	-	-	C6	-
	CM 4	-	-	-	-	C7
	CM 5	-	-	-	C8	-
Optionability Count		2	1	1	3	1

A highly "optionable" path enabler/inhibitor is a convenient one to include as it can enable different change/resistance mechanisms, in turn used to mitigate against perturbation

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Evaluate Options: Uses and Cost

Number of Uses: *the number of times a particular option can be employed* (related to its PE/PI).

Example:

- C4 (adding vehicle via spares) can be used a number of times (N) and has a high cost
- C17 (going back to pre-validated set using an already established pre-validation process) can be used for the entire existence of the SoS and has no cost

Number of uses:
- 1 = one time
- N = a finite number of times
- ∞ = for entire existence of SoS

Cost: *approximate cost of including the option in the system architecture.*

- Qualitative assessment carried out with the aid of domain experts
- Assessment for relative comparison

Cost:
- No cost
- Low cost
- Medium cost
- High cost

Change Option ___ Uses [1, N, ∞]

Option Number	Number of Uses	Cost
C1	1	high
C2	∞	low
C3	∞	medium
C4	N	high
C5	1	high
C6	N	low
C7	N	high
C8	∞	low
C9	∞	no
C10	N	high
C11	N	high
C12	∞	low
C13	∞	low
C14	∞	no
C15	∞	medium
C16	N	high
C17	∞	no
C18	∞	no
C19	∞	low
C20	∞	low
C21	∞	low
C22	N	low

Resistance Option ___ Uses [1, N, ∞]

Option Number	Number of Uses	Cost
R1	∞	medium
R2	∞	medium
R3	∞	low
R4	N	high
R5	∞	medium
R6	∞	medium
R7	∞	low
R8	∞	no
R9	N	high
R10	∞	no
R11	∞	no
R12	N	high
R13	∞	no
R14	∞	no
R15	1	medium
R16	∞	medium
R17	∞	no

Precision of the evaluation can vary widely, subject to:
- Expertise of people performing the task
- Level of detail they are willing to go into

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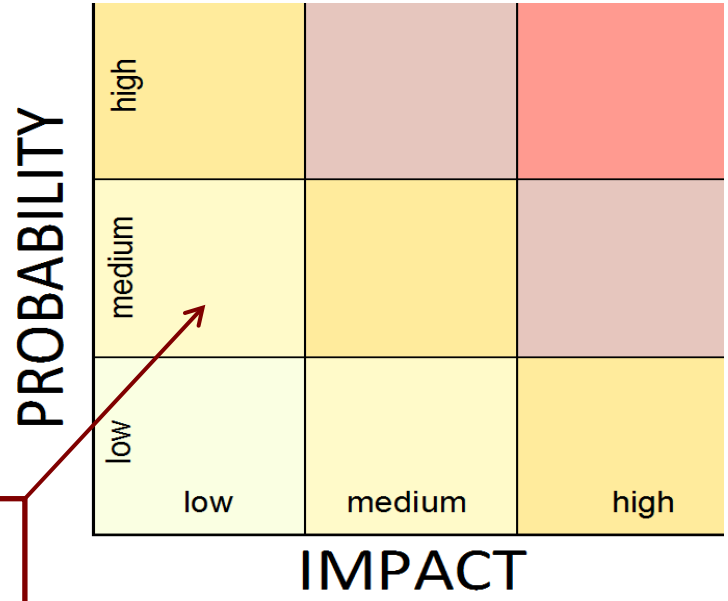
Evaluate Options: Perturbation Coverage

Assess Probability and Impact of Perturbation

Considerations in this step:

- A serious attack has a very low probability of occurrence, but it could have lethal consequences on the SoS
- Boat arrival rate is likely to change, and it can have moderate impacts on SoS



Fineness of the grid depends on level of competency of assessor and whether analytical tools are actually employed

Perturbation	SHIFT								DISTURBANCE				
	Tech Level	Workforce Availability	Info Sharing Availability	Boat Arrival Rate	Pirate Percentage	Smuggler Percentage	Search & Rescue	Jamming	Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack
Probability [High-Medium-Low]	low	medium	medium	high	medium	high	low	medium	low	medium	medium	low	medium
Impact [High-Medium-Low]	medium	medium	low	medium	high	medium	high	high	high	high	low	high	medium

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Evaluate Options: Perturbation Coverage

PERTURBATION			SHIFT			DISTURBANCE			Σ
			S1	S2	S3	D1	D2	D3	
Probability [High-Medium-Low]			low	medium	high	high	low	medium	
Impact [High-Medium-Low]			high	low	medium	low	medium	high	
Change Option Uses [1, N, ∞]	C1	1				1	1	1	3
	C2	∞	1		1	1	1		4
	C3	∞			1	1	1		3
	C4	N			1	1	1	1	4
	C5	1					1		1
Resistance Option Uses [1, N, ∞]	R1	∞		1	1				2
	R2	∞				1	1	1	3
	R3	∞							0
	R4	N				1	1		2
	R5	∞				1			1
Σ			1	1	4	7	7	3	

Perturbation coverage matrix, in which it is possible to identify **(a)** most *perturbation-mitigating options* and **(b)** most *commonly mitigated perturbations*

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Evaluate Options: Perturbation Coverage

Assess whether or not **perturbation is covered by option**

Perturbation			SHIFT								DISTURBANCE					Σ
			Tech Level	Workforce Availability	Info Sharing Availability	Boat Arrival Rate	Pirate Percentage	Smuggler Percentage	Search & Rescue	Jamming	Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack	
Probability [High-Medium-Low]			low	medium	medium	high	medium	high	low	medium	low	medium	medium	low	medium	
Impact [High-Medium-Low]			medium	medium	low	medium	high	medium	high	high	high	high	low	high	medium	
Change Option ___ Uses [1, N, ∞]	C1	1				1	1	1			1	1	1	1		7
	C2	∞	1		1	1	1	1	1		1	1		1		9
	C3	∞			1	1	1	1			1	1		1		7
	C4	N			1	1	1	1			1	1	1	1		8
	C5	1					1	1	1			1				4
	C6	N	1				1	1	1							4
	C7	N					1	1	1			1				4
	C8	∞	1				1	1	1			1				5
	C9	∞			1		1	1	1			1				5
	C10	N				1			1					1		3
	C11	N				1			1					1		3
	C12	∞				1			1	1					1	4
	C13	∞	1			1			1	1				1	1	6
	C14	∞		1							1	1	1			4
	C15	∞		1		1							1			3
	C16	N									1	1	1			3
	C17	∞		1							1	1		1		4
	C18	∞		1							1	1		1		4
	C19	∞							1	1				1	1	4
	C20	∞	1						1	1			1	1	1	6
	C21	∞					1	1					1			3
	C22	N					1	1	1				1			4
Resistance Option ___ Uses [1, N, ∞]	R1	∞		1	1	1	1	1								5
	R2	∞							1	1	1	1	1	1	1	7
	R3	∞							1	1				1	1	4
	R4	N								1	1	1		1	1	5
	R5	∞					1				1					2
	R6	∞					1						1	1		3
	R7	∞					1		1				1	1	1	5
	R8	∞					1		1						1	3
	R9	N				1				1	1	1		1		5
	R10	∞		1		1			1	1	1	1		1	1	8
	R11	∞							1		1	1			1	4
	R12	N					1				1	1		1		4
	R13	∞					1				1	1		1		4
	R14	∞		1			1				1	1		1		5
	R15	1					1				1					2
	R16	∞		1	1	1	1	1	1					1	1	8
	R17	∞		1			1	1	1				1	1	1	7
Σ			5	9	6	13	22	14	21	9	18	20	12	23	13	

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Evaluate Options: Perturbation Coverage

Assess whether or not **perturbation is covered by option**

			SHIFT								DISTURBANCE					
		Perturbation	Tech Level	Workforce Availability	Info Sharing Availability	Boat Arrival Rate	Pirate Percentage	Smuggler Percentage	Search & Rescue	Jamming	Serious Attack	Asset Unavailable	Storm (decreased situational awareness)	Tsunami (SoS seriously damaged)	Information Attack	Σ
		Probability [High-Medium-Low]	low	medium	medium	high	medium	high	low	medium	low	medium	medium	low	medium	
		Impact [High-Medium-Low]	medium	medium	low	medium	high	medium	high	high	high	high	low	high	medium	
Change Option ___ Uses [1, N, ∞]	C1	1				1	1	1			1	1	1	1		7
	C2	∞	1		1	1	1	1	1		1	1		1		9
	C3	∞			1	1	1	1			1	1		1		7
	C4	N			1	1	1	1			1	1	1	1		8
	C5	1					1	1	1			1				4
	C6	N	1				1	1	1							4
	C7	N					1	1	1			1				4
	C8	∞	1				1	1	1			1				5
	C9	∞										1				5
	C10	N												1		3
	C11	N												1		3
	C12	∞													1	4
	C13	∞												1	1	6
	C14	∞										1	1			4
	C15	∞											1			3
	C16	N									1	1	1			3
	C17	∞		1							1	1		1		4
	C18	∞		1							1	1		1		4
	C19	∞							1	1				1	1	4
	C20	∞	1						1	1			1	1	1	6
	C21	∞					1	1					1			3
	C22	N					1	1	1				1			4
Resistance Option ___ Uses [1, N, ∞]	R1	∞		1	1	1	1	1								5
	R2	∞							1	1	1	1	1	1	1	7
	R3	∞												1	1	4
	R4	N												1	1	5
	R5	∞														2
	R6	∞											1	1		3
	R7	∞											1	1	1	5
	R8	∞													1	3
	R9	N												1		5
	R10	∞		1										1	1	8
	R11	∞													1	4
	R12	N					1				1	1		1		4
	R13	∞					1				1	1		1		4
	R14	∞		1			1				1	1		1		5
	R15	1					1				1					2
	R16	∞		1	1	1	1	1	1					1	1	8
	R17	∞		1			1	1	1				1	1	1	7
Σ			5	9	6	13	22	14	21	9	18	20	12	23	13	

C2

Adding Vehicle – Contract with Aircraft Supplier

most perturbation-addressing change option

Tsunami

Most commonly addressed perturbation

(this is because its impact on the system is large and many things can be done to partially mitigate against it)

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Evaluate Options: Perturbation Coverage

Perturbation Coverage: *proxy for risk (of disrupting value delivery) attenuation*.

v1 (simple) →

$$PeC(option) = n \quad (1)$$

n is number of perturbations covered by option

v2 (more complex) →

$$PeC(option) = \sum_{i=1}^{n} P_i^{\gamma} I_i \quad (2)$$

n is number of perturbations covered by option
i is the given perturbation considered
P is the assessed probability for perturbation *i* to occur
I is the impact on value delivery caused by occurrence of perturbation *i*
γ is the risk aversion factor for assessment of perceived probability

***Note**: PeC can be *normalized* against the sum of $P^{\gamma}_i I_i$ across *all* perturbations

This metric is computed for a given option.
Higher scores are considered to be better.

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Downselect list of desired options from initial list

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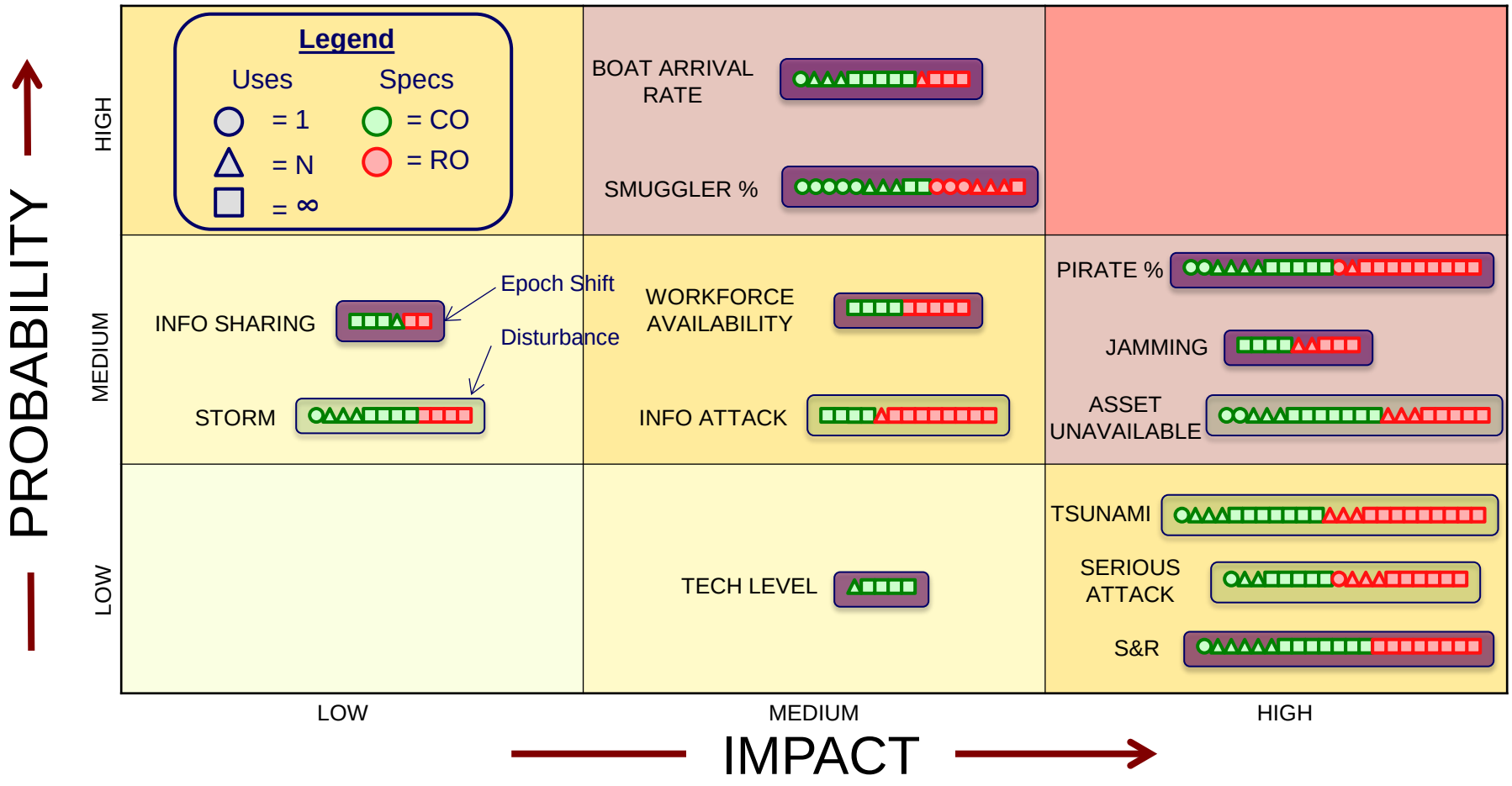
Select Options: Visualization Aid



There are other analytical tools that can be used to inform final selection decision

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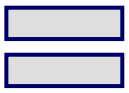
Finalize List of Options

For evaluation, four different metrics are considered:

- **OPTIONABILITY**: *the number of options a path enabler/inhibitor is linked to.*
- **NUMBER OF USES**: *how many times can a path enabler/inhibitor be used.*
- **COST**: *the cost of acquiring and using a particular path enabler/inhibitor.*
- **PERTURBATION COVERAGE**: *metric that takes into account impact and probability of perturbations covered by path enabler/inhibitors when paired with change/resistance mechanism*

For selection criteria, two tools will be developed:

- **VISUALIZATION TOOLS**: *look at different metrics at once.*
- **ANALYTICAL TOOLS**: PC vs. *cost tradespace exploration*



Final list of options to consider for:

1. Direct inclusion into system (if time is a concern)
1. Model and simulation for more detailed analysis and better informed decision

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DISCUSSION & NEXT STEPS

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Final Remarks and Important Assumptions to Address

- The approach is a **first order attempt** to tackle a problem that is very broad!

- The assessment of certain metrics, such as perturbations' probability and impact, as well as cost, strongly depends on the **level of knowledge** and expertise of the people involved in the evaluation task.

- The **perturbation coverage quantification** problem is not a simple one.
  - First, options do not usually mitigate the ***full impact*** of a perturbation. They often mitigate a portion of the total damage a perturbation causes.
  - Considerations related to the ***lifetime of a perturbation*** and option utilization ***timing*** ought to be made in order to incorporate partial damage coverage in the analysis

- it is important that one be able to consider the **approximate number of occurrences of a perturbation** through time as well. This way, a **dynamic** analysis of perturbation coverage could be performed.
  - Throughout the approach presented, this issue was tackled only by the number of uses (NU) metric.

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Next Steps

- Exploration of the **dynamics** of the PeC vs. Cost tradespace using Number of Uses metric, as options are executed over time
- Delineation of risk attenuation metric for a portfolio of options
- General portfolio analysis, inspired by financial portfolio theory (Markowitz), could be performed to identify **PORTFOLIOS** of options that, through diversification:
  - Maximize PeC, given a desired Cost.
  - Minimize Cost, given a desired PeC.
- Inclusion of all types of costs associated with an option: i.e., **acquisition** cost, **carrying** cost, **execution** cost, **disposal** cost, as well as **switching** costs for portfolios of options
- Consideration of the **upside** of uncertainty (i.e., *opportunity*)

Overall, the approach:

- Enables the **identification of options** that can improve system's performance, as well as lifecycle properties (e.g., flexibility, robustness).
- Is **scalable** with regard to effort required, time invested, and data availability needs (when using mostly qualitative assessments).
- Contributes to Systems Engineering **risk-benefit** techniques, and provides **structure** to dealing with uncertainty in modern-day systems.

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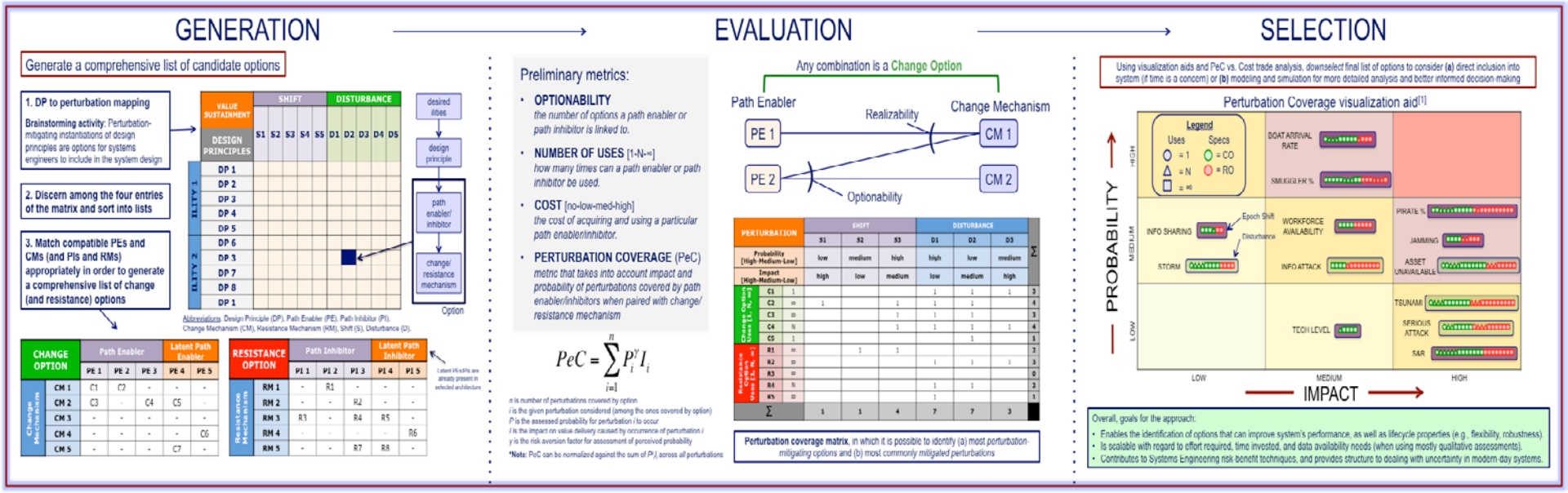
QUESTIONS?



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Appendix

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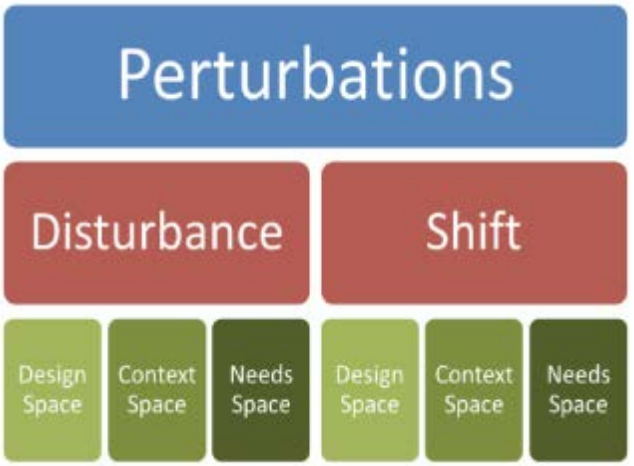
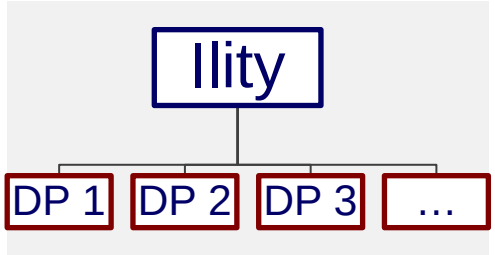
Perturbations & Design Principles

1. **PERTURBATIONS**: *"Unintended state change in a system's design, context, or stakeholder needs that could jeopardize value delivery"*
   - **Shift**: *"Long-lasting changes in design (i.e., form and operations), context, or needs [that could affect value delivery]"* (Ross, Rhodes, and Hastings 2008)
   - **Disturbance**: *"Finite-(short) duration changes of a system's design, context, or needs [that could affect value delivery]"* (Richards 2009; Mekdeci 2012)



(Beesemyer 2012)

1. **DESIGN PRINCIPLES**: *"Guiding thoughts [for design] based on empirical deduction of observed behaviour or practices that prove to be true under most conditions over time"* (Wasson 2006)
   - They serve to help intentionally create desirable properties in a system.



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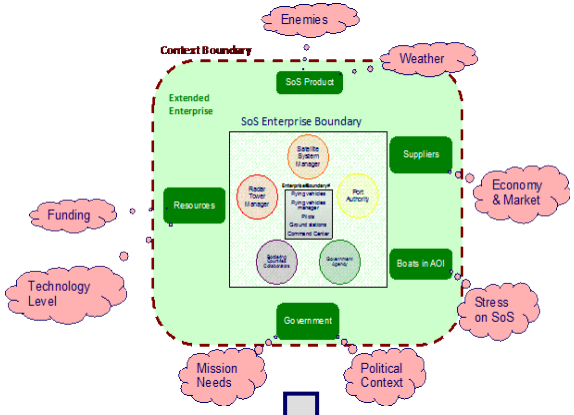
Inputs to Approach



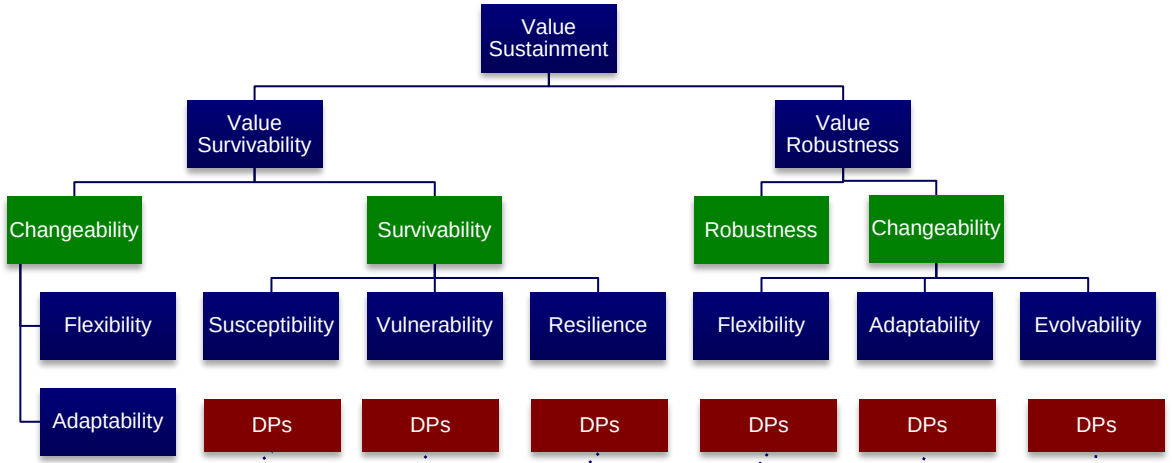
Perturbations

Disturbances

- Serious Attack Occurrence
- Asset Unavailable
- Information Attack
- Storm
- Tsunami

Shifts

- Technology Level
- Workforce Availability
- Info Sharing Availability
- Boat Arrival Rate
- Pirate Percentage
- Smuggler Percentage
- Search and Rescue
- Jamming (Bad Com)



Design Principles

- Prevention
- Mobility
- Concealment
- Deterrence
- Preemption
- Avoidance
- Defensive Posture
- Deflection
- Authentication
- Reserves

- Hardness
- Heterogeneity
- Failure Mode Reduction
- Fail-safe
- Modification
- Containment
- Stable Intermediate Instances

- Replacement
- Repair
- Adaptation
- Contingency
- Reversion

- Targeted Modularity
- Integrability
- Standardization
- Interoperability
- Excess Capacity
- Redundancy
- Reconfigurability
- Margin
- Slack

- Targeted Modularity
- Integrability
- Agility
- Redundancy
- Reconfigurability
- Situational Awareness
- Critical Thinking

- Targeted Modularity
- Integrability
- Scalability
- Decentralization (=“Distribution”)
- Redundancy
- Architecture changeability
- Reconfigurability
- Margin
- Slack
- Proper Documentation
- Leverage Ancestors
- Mimicry
- Disruptive Architectural Overhaul
- Resourceful Exaptation

Note: DPs in red are common to all three

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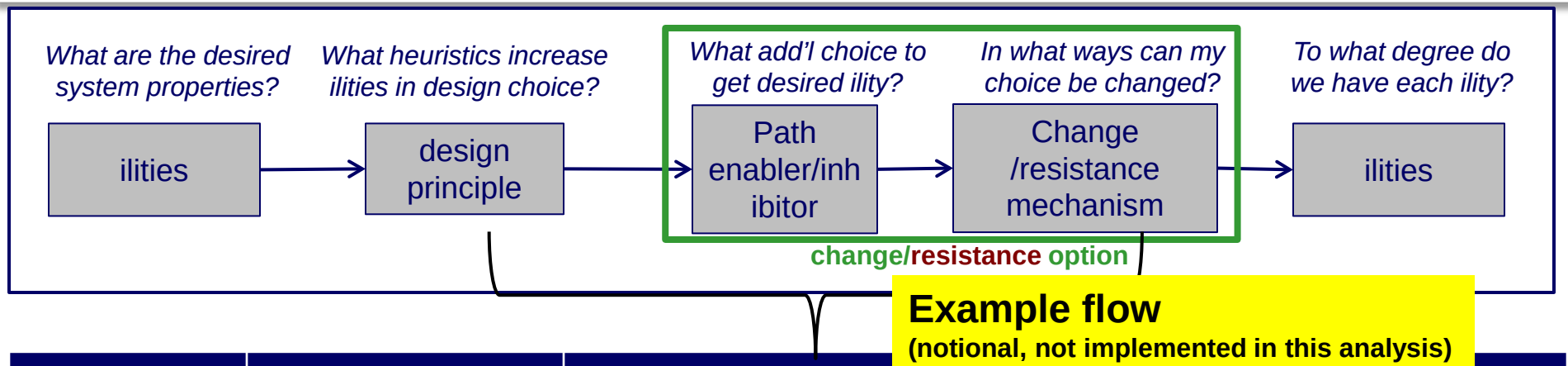
Generating Change/Resistance Options from DPs



Ility	Design Principle	Change/Resistance Mechanism	Path Enabler/Inhibitor
Survivability	Concealment	Operating UAVs at higher altitudes	Long range communication
Survivability	Hardness	Ability to absorb a hit	Armor
Evolvability	Targeted Modularity	Easily upgrading and adding new sensors/ sensor technology	Modularized sensor set
Evolvability	Decentralization	Updating constituent without disturbing other SoS constituents	Dispersed communication network
Survivability	Heterogeneity	Using multiple means for detection/ interception	Selection of multiple different UAVs that can perform similar functions

Using design principles to generate path variables and change mechanisms is an exercise in creative design, leveraging domain expertise and historical examples

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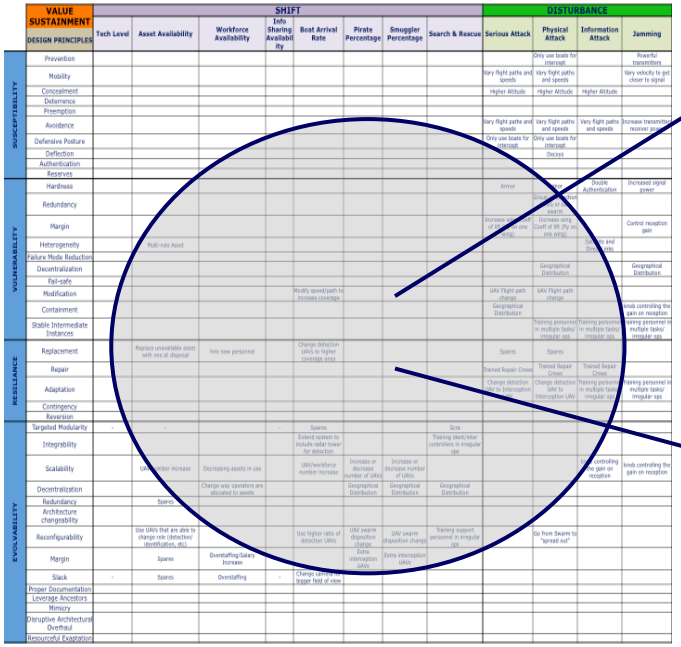
Generate "Resistance Mechanism" and Path Inhibitor Set

2. Discern among the four entries of the matrix and sort into lists



Resistance Mechanism

- Overstaffing
- Vary velocity of flight
- Increase armor
- Disperse around AOI
- Training personnel for multiple tasks
- Have multiple constituent systems perform the same task
- Training maintenance crew
- Oversizing SoS
- Distract hostile attacks
- Rapid recovery against asset/component loss
- …

Path Inhibitor

- Extra personnel
- Armor on UAVs
- Strong software architecture
- High-altitude UAV
- Decoys
- Extra feature for Constituent systems
- Extra constituent systems
- Spares
- Versatile Constituent System
- Better control system
- …

Change Mechanism

- Add vehicle
- Change the function of an Asset
- Disperse around AOI
- Change velocity and position of a specific asset
- Add extra feature to asset
- Go back to pre-validated set
- Change task assignment
- Change authority distribution
- Change geographic segmentation
- Change # of operators per UAV
- …

Path Enabler

- Multi-role asset
- Extra UAV capable of performing interception
- Central authority
- Port authority boats
- Satellite
- Acquiring faster UAV
- Contracts with aircraft suppliers
- Sea planes
- Spares
- Pre-validation process
- Dispersed communication network
- Long range UAVs
- Workforce buffer
- …

Implementing a Path Enabler/Inhibitor allows for the use of a Change/Resistance Mechanism

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CO and RO Lists

Change Options		
	Mechanism	Path Enabler
1	Adding vehicle	Extra interception UAV
2	Adding vehicle	Contract with aircraft supplier
3	Adding vehicle	Workforce buffer
4	Adding vehicle	Spares
5	Change task assignment	Extra interception UAV
6	Change task assignment	Extra cameras
7	Change task assignment	Sea planes
8	Change task assignment	Dispersed Com network
9	Change task assignment	Multi-role asset
10	Change geographic segmentation	Sea planes
11	Change geographic segmentation	Long Range UAV
12	Change geographic segmentation	Dispersed Com network
13	Change geographic segmentation	Satellite Relay
14	Change number of operators per UAV	Pre-validation process
15	Change number of operators per UAV	Workforce buffer
16	Change number of operators per UAV	Spares
17	Go back to pre-validated set	Pre-validation process
18	Go back to pre-validated set	Multi-role asset
19	Change authority distribution	Central authority
20	Change authority distribution	Satellite relay
21	Add extra features to assets	Contract with aircraft supplier
22	Add extra features to assets	Extra cameras

Resistance Options		
	Mechanism	Path Inhibitor
1	Overstaffing	Workforce buffer
2	Change trajectory of flight	Better UAV control system
3	Change trajectory of flight	Long range signal transmitter
4	Change trajectory of flight	High altitude UAV
5	Asset resistance to attacks	Armor on UAV
6	Disperse around AOI	Better UAV control system
7	Disperse around AOI	Long range signal transmitter
8	Disperse around AOI	UAV swarm
9	Multiple assets perform same function	Spares
10	Multiple assets perform same function	Multi-role asset
11	Multiple assets perform same function	UAV swarm
12	Rapidly recover against asset loss	Spares
13	Rapidly recover against asset loss	Pre-validation process
14	Rapidly recover against asset loss	Multi-role asset
15	Distract hostile attacks	Decoy
16	Training personnel for multiple tasks	Workforce buffer
17	Training personnel for multiple tasks	Pre-validation process

3. Match compatible PEs and CMs (and PIs and RMs) appropriately in order to generate a comprehensive list of change (and resistance) options

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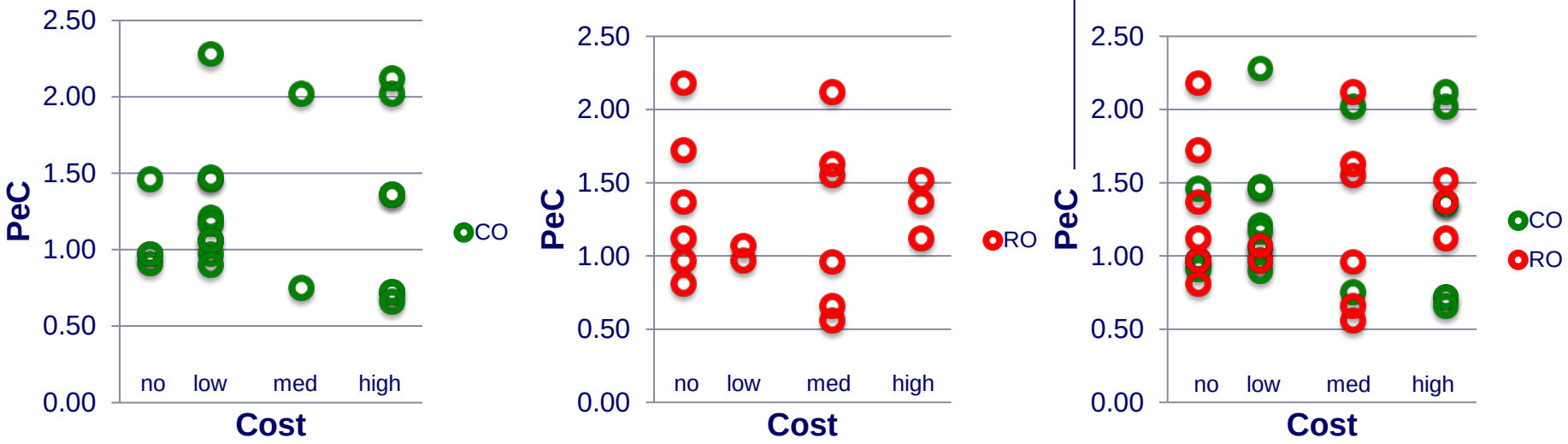
Select Options: Analytical Tools

Perturbation Coverage vs. Cost tradespace

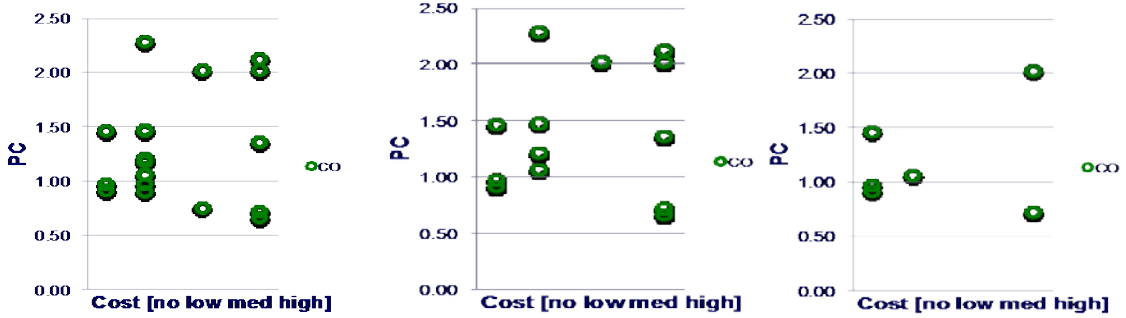
$$PeC = \sum_{i=1}^{n} P_i^{\gamma} I_i$$



Can be thought as trading **risk** (*inverse* of PeC) versus **benefit** (*inverse* of Cost)

Exploration of the **dynamics** of the Perturbation Coverage vs. Cost tradespace using Number of Uses metric

- Must have knowledge of **approximate number of occurrences of a perturbation**



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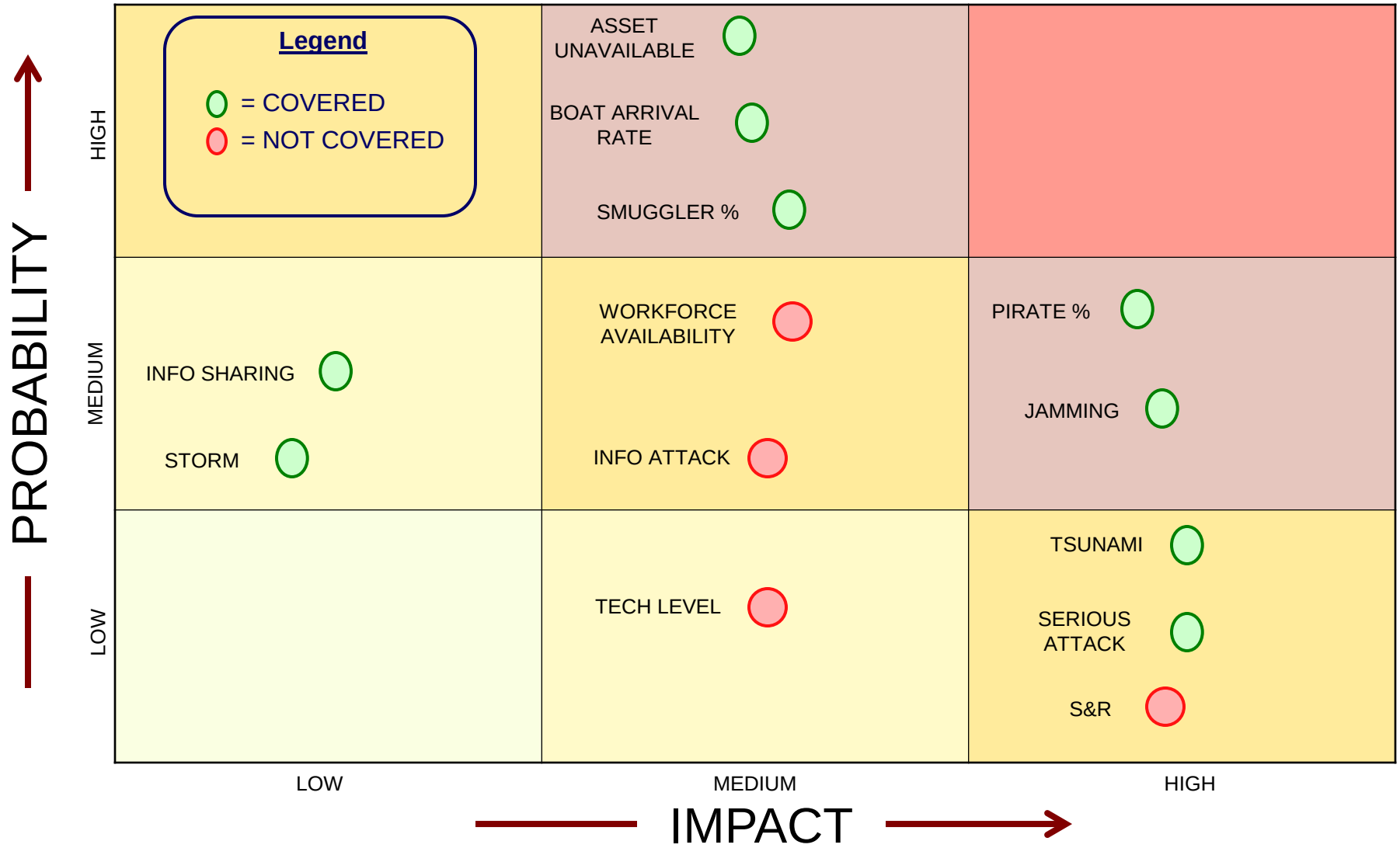
Select Options: Visualization Tools



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