A Method for Selecting Affordable System Concepts: A Case Application to Naval Ship Design

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Motivation

- Massive cost overruns, schedule delays, failure to anticipate future requirements and ultimately unrealized capabilities (Cordesman and Frederiksen, 2006)

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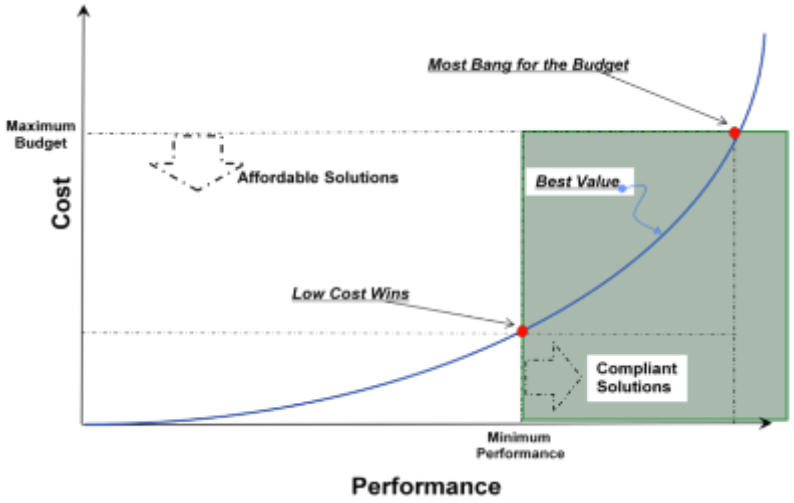
- Weaknesses in initial program definition and costing (IDA, 2009)
- Affordability mandated as a requirement at all milestone decision points of program development (Carter, 2010a, 2010b)

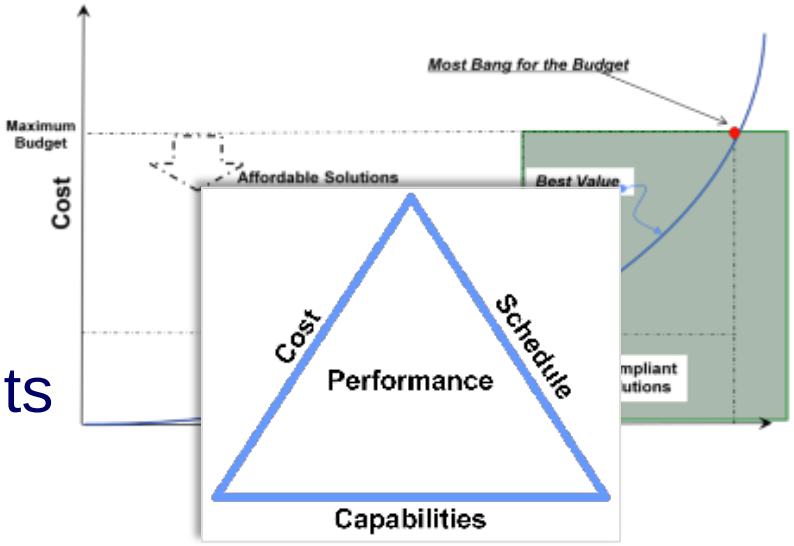
Motivation

- Determining affordable solutions (Tuttle and Bobinis, 2012)



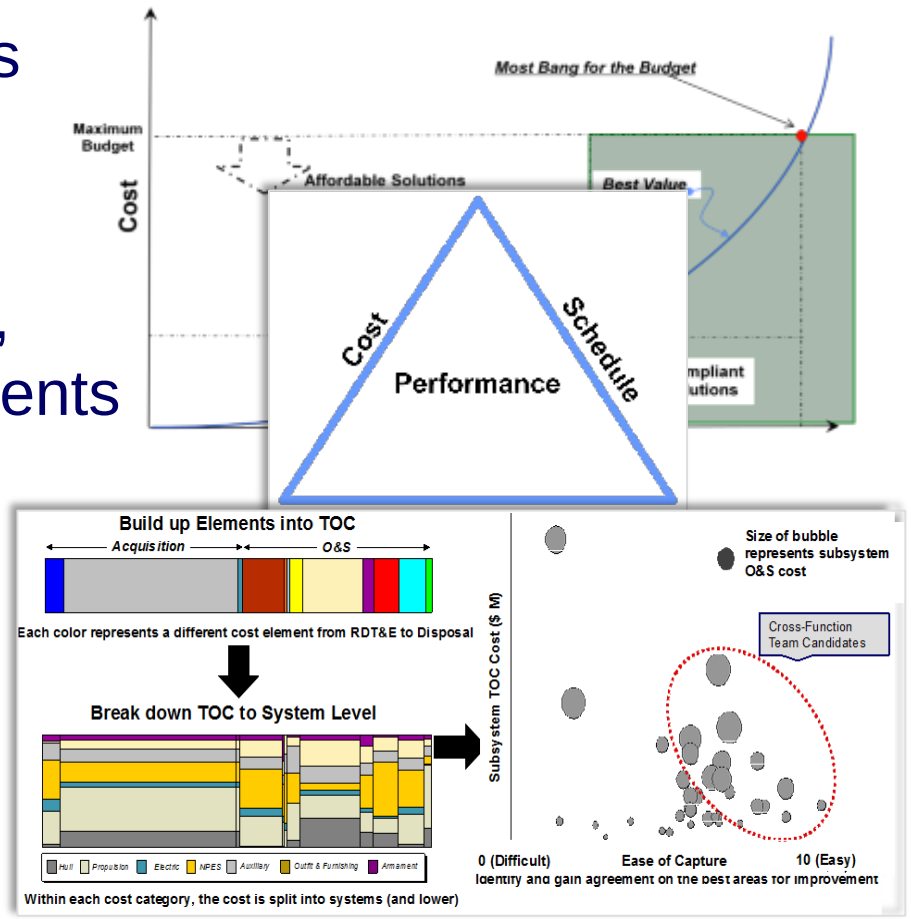
Motivation

- Determining affordable solutions (Tuttle and Bobinis, 2012)
- Balancing performance, budget, and schedule for fixed requirements (Tuttle and Bobinis)



Motivation

- Determining affordable solutions (Tuttle and Bobinis, 2012)
- Balancing performance, budget, and schedule for fixed requirements (Tuttle and Bobinis)
- Breakdown of Total Ownership Cost into constituent costs (Booz Allen Hamilton, 2011)



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Absence of mature metrics and systematic frameworks for comprehensive affordability analysis.

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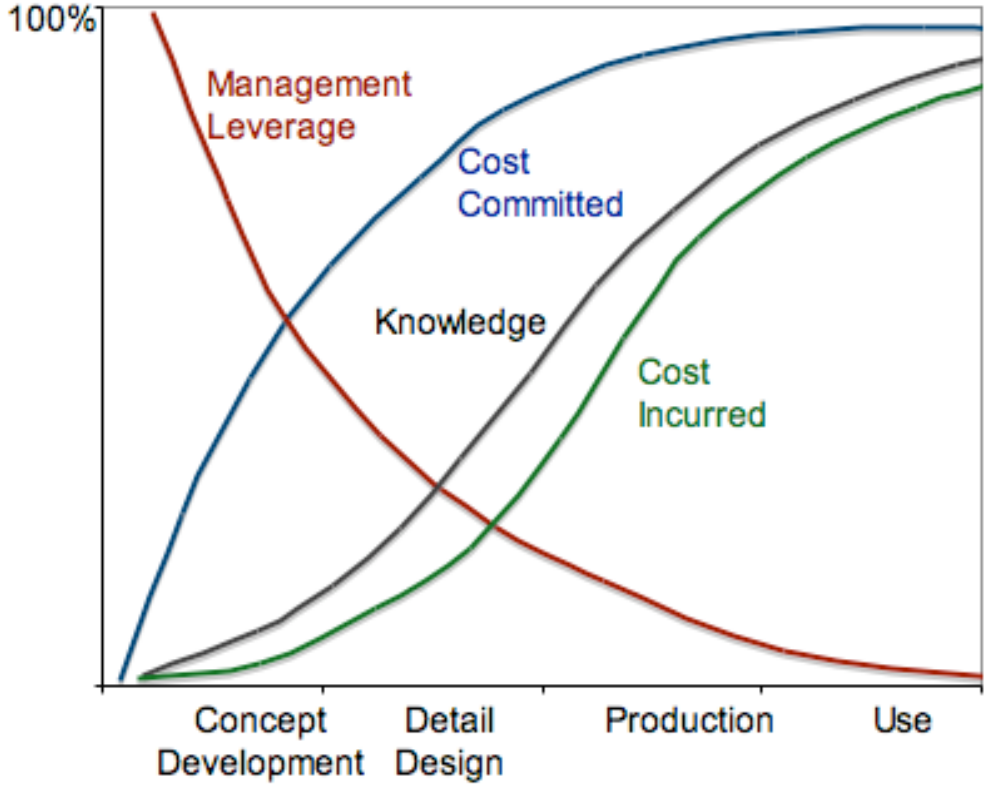
Absence of mature metrics and systematic frameworks for comprehensive affordability analysis.

The problem that this research begins to address.

The Big Picture

- The Systems Engineering Context



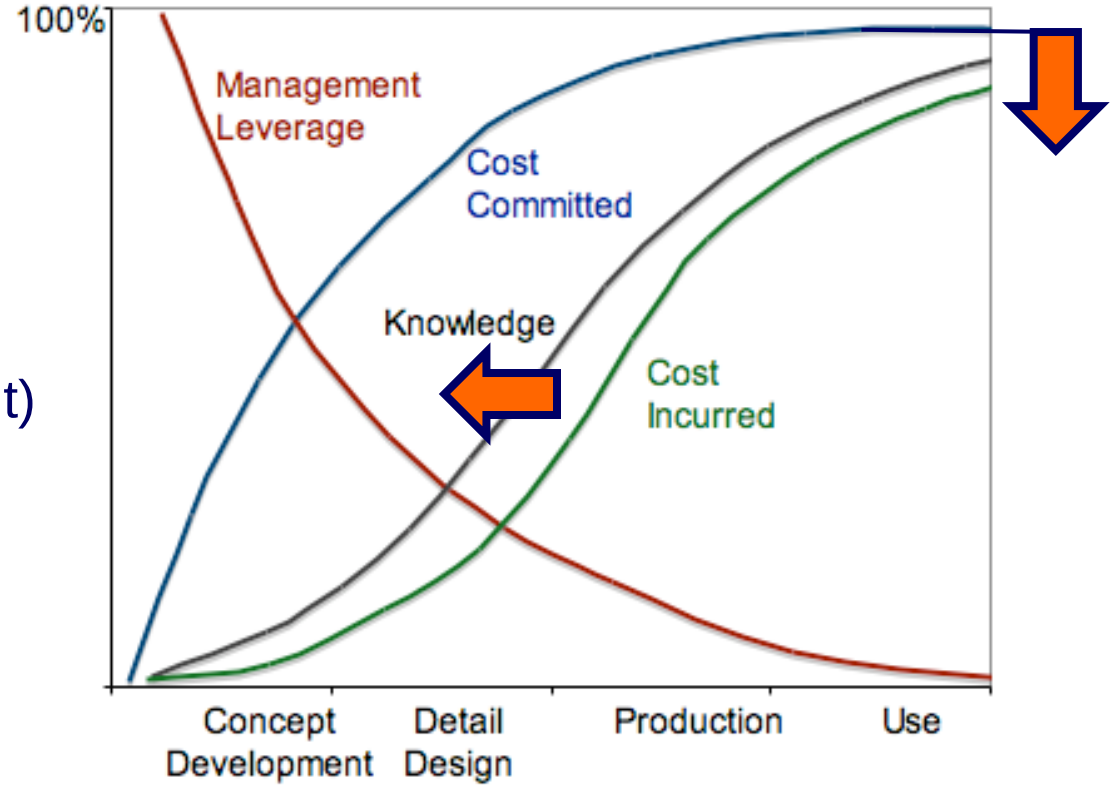
A Better Big Picture

- The Systems Engineering Context

To contribute to the design of affordable systems:

1) Bring knowledge forward to higher-leverage phase (i.e. conceptual development)

2) Reduce total amount of resources committed



Overview of the Case Application

- Design a Next-Generation Combat Ship (NGCS) that will support unmanned aircraft, smaller boats, and defense operations in littoral areas of interest.

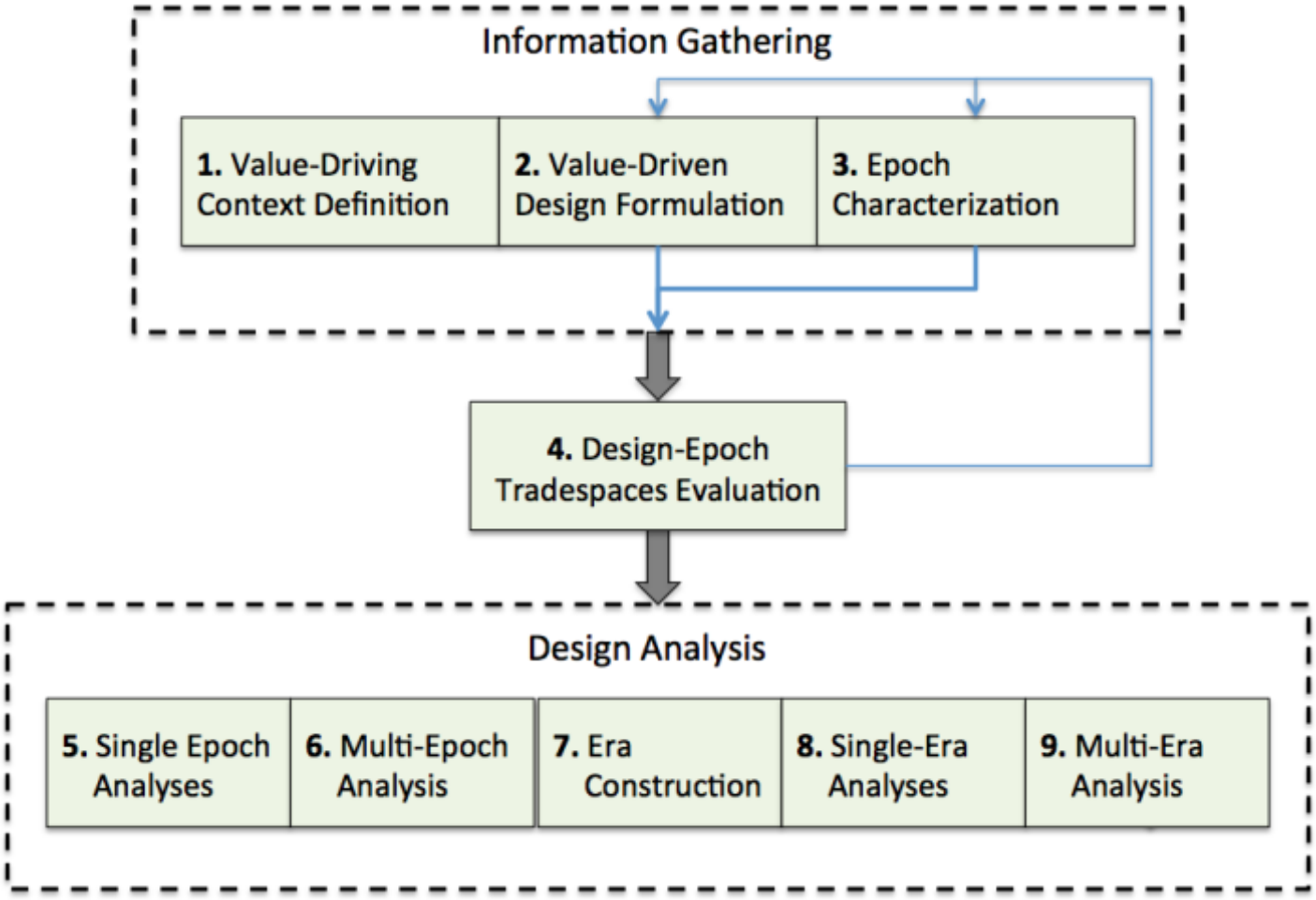
Coast Guard's
Offshore Patrol Cutter (OPC)

Navy's Littoral Combat Ship (LCS)

Overview of the Case Application

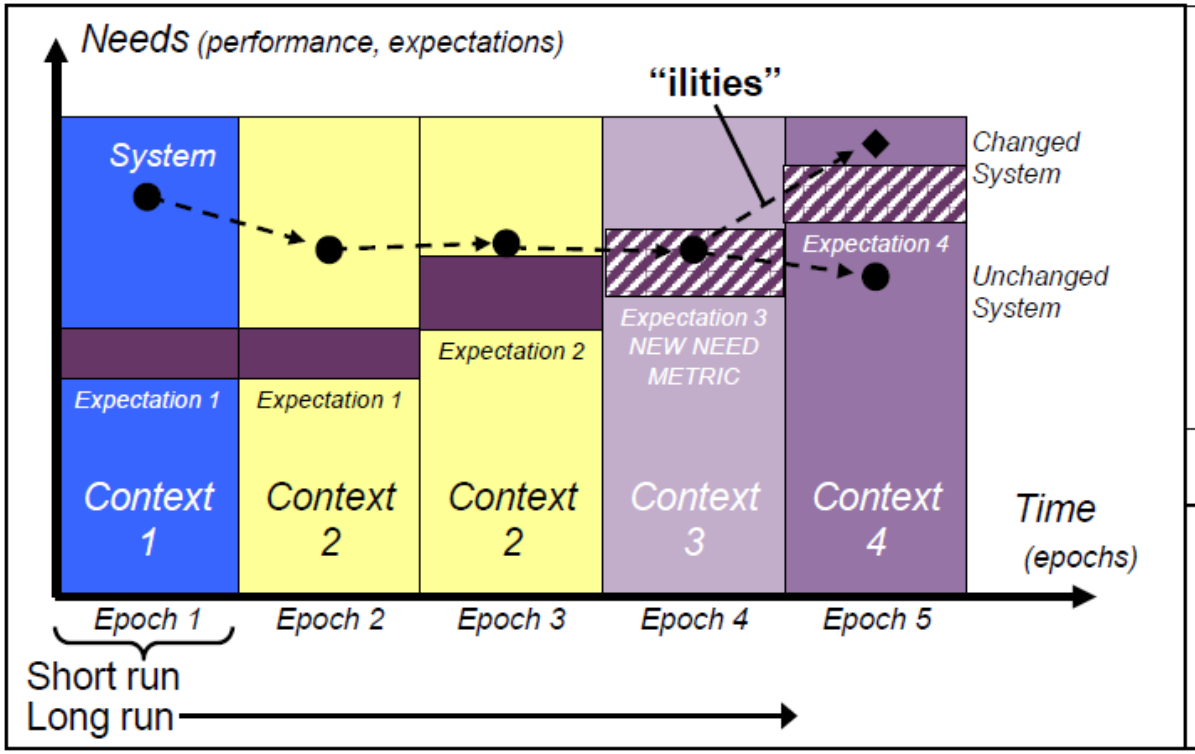
- This case derives primarily from three sources:
  - Prior application of Responsive Systems Comparison (RSC) to Coast Guard's OPC (Schofield 2010)
  - A variant of the MIT Math Model, used for Naval (LCS-like) frigate modeling and selection of feasible ship designs (http://hdl.handle.net/1721.1/44876)
  - LCDR Matthew Frye, MIT SM '10

Overview of the RSC-Based Method



Adapted from RSC originally proposed in Ross et al (2009)

Epoch & Era Constructs



Epoch:

Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated needs

Era:

Time-ordered sequence of epochs

Legend

- System
- System Trajectory
- Expectations

(Ross and Rhodes 2008)

Information Gathering:
Processes 1 through 3

For the OPC, Schofield (2010) defines 3 stakeholders, each with separate value propositions. These are combined for the NGCS into the value proposition:

Provide a new fleet of USN frigates for use in air and sea operations in open and coastal waters across the globe.

Information Gathering: Processes 1 through 3

- Value statement decomposition into expense and utility attributes

Mission Statement:	Provide new frigate fleet for the USN.			
Objective:	Provide defense, air, and sea support across the defined mission areas.			
Attribute (Acronym)	**Units**	**Range ["worst" to "best"]**		**Weight (.1 to 1)**
Acquisition Cost (Acq.)	$ million	1500	500	0.4
Lifecycle Cost (LC)	$ million	7500	3000	0.3
Initial Operating Cap. (IOC)	year	2020	2018	0.2
Crew Size (Crew)	# persons	250	200	0.1
Displacement (Disp.)	cubic ft.	11000	4000	0.2
Range	nm	4500	10000	0.2
Speed	kts	12	25	0.1
Air Capability (Air Cap)	hrs/day	2	12	0.2
Endurance (Endr)	days	30	60	0.1
Small Boat Capability (SBCap)	#ppl-hrs/day	20	100	0.2

Information Gathering: Processes 1 through 3

- Value statement decomposition into expense and utility attributes
- Map each design variable's impact on each system attribute

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Design-Value Mapping (Notional Values)

Representative Stakeholder

Expense Attributes / **Design Variables**	Length	Beam	Draft	Prop Type	Hull Material	Deckhouse Material	Defense Cabability	Helos	ASUW	AAW	**Total Impact**
Acquisition Cost	9	3	3	3	3	3	3	3	3	3	**36**
Lifecycle Cost	9	3	3	9	1	1	1	1	1	1	**30**
IOC	1	3	1	3	1	0	3	1	1	1	**15**
Crew Size	3	1	1	1	1	1	3	3	3	3	**20**
Total	**22**	**10**	**8**	**16**	**6**	**5**	**10**	**8**	**8**	**8**	
Utility Attributes											
Displacement	9	9	3	3	9	3	3	3	1	1	**44**
Range	9	3	1	9	3	1	1	3	1	1	**32**
Speed	9	3	3	9	3	1	3	1	1	1	**34**
Air Capacity	3	3	1	0	1	1	3	9	3	3	**27**
Endurance	1	3	1	3	1	1	3	3	3	3	**22**
Small Boat Cap.	3	3	1	0	1	1	3	3	3	3	**21**
Total	**34**	**24**	**10**	**24**	**18**	**8**	**16**	**22**	**12**	**12**	

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Decomposed from existing system concepts

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- Value statement decomposition into expense and utility attributes
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- Epoch variable elicitation and definition

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	Levels	
Epoch Variable	**[Range]**	**Units**
VUAV	[Small, Large]	Storage Level
Small Boat Size	[24, 35]	ft
Engine Emissions	[2, 3, 4]	(Tier)
Range Increase	[0, 10, 20]	%
Ice Region Use	[Low, Med, High]	Level

Total Impact: 36, 30, 15, 20, 44

Information Gathering: Processes 1 through 3

- Value statement decomposition into expense and utility attributes
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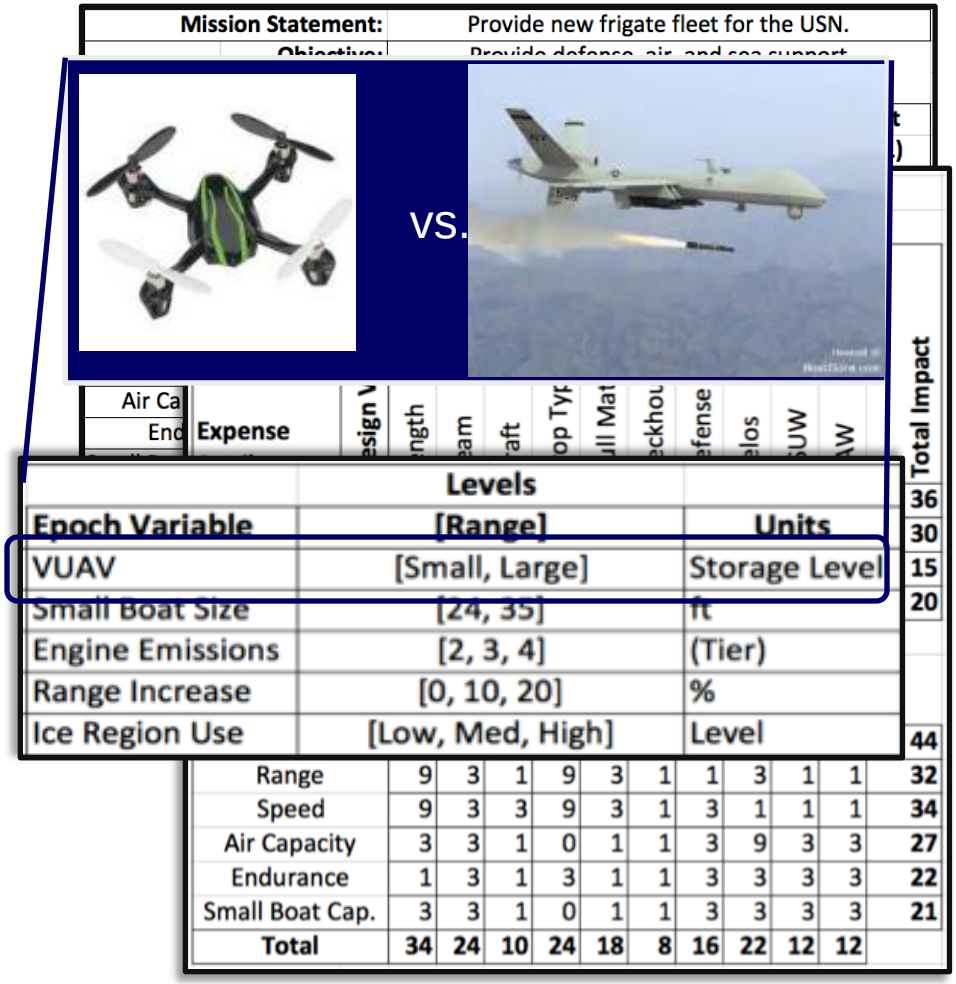
- Epoch variable elicitation and definition (e.g., VUAV = size of vertical take-off Unmanned Aerial Vehicles)



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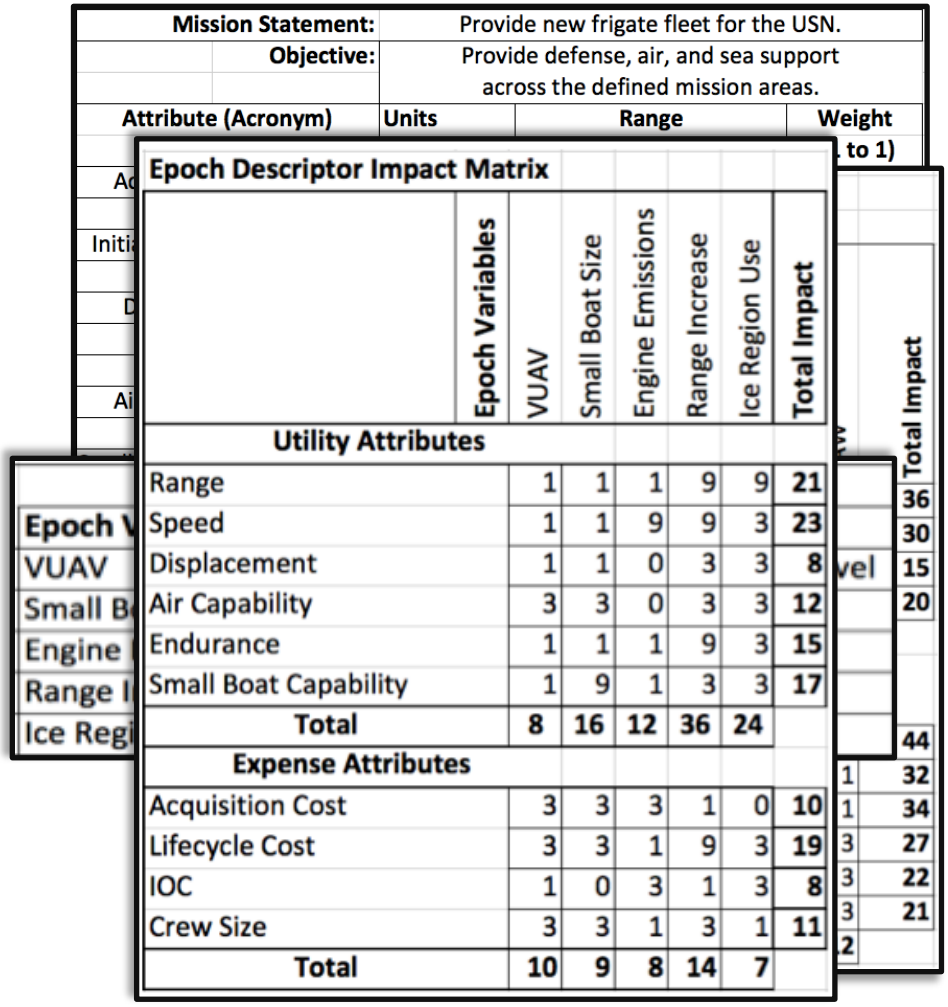

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Attribute (Acronym)	Units	Range	Weight

Epoch Descriptor Impact Matrix

Epoch Variables	VUAV	Small Boat Size	Engine Emissions	Range Increase	Ice Region Use	Total Impact
Utility Attributes						
Range	1	1	1	9	9	21
Speed	1	1	9	9	3	23
Displacement	1	1	0	3	3	8
Air Capability	3	3	0	3	3	12
Endurance	1	1	1	9	3	15
Small Boat Capability	1	9	1	3	3	17
Total	8	16	12	36	24	
Expense Attributes						
Acquisition Cost	3	3	3	1	0	10
Lifecycle Cost	3	3	1	9	3	19
IOC	1	0	3	1	3	8
Crew Size	3	3	1	3	1	11
Total	10	9	8	14	7	

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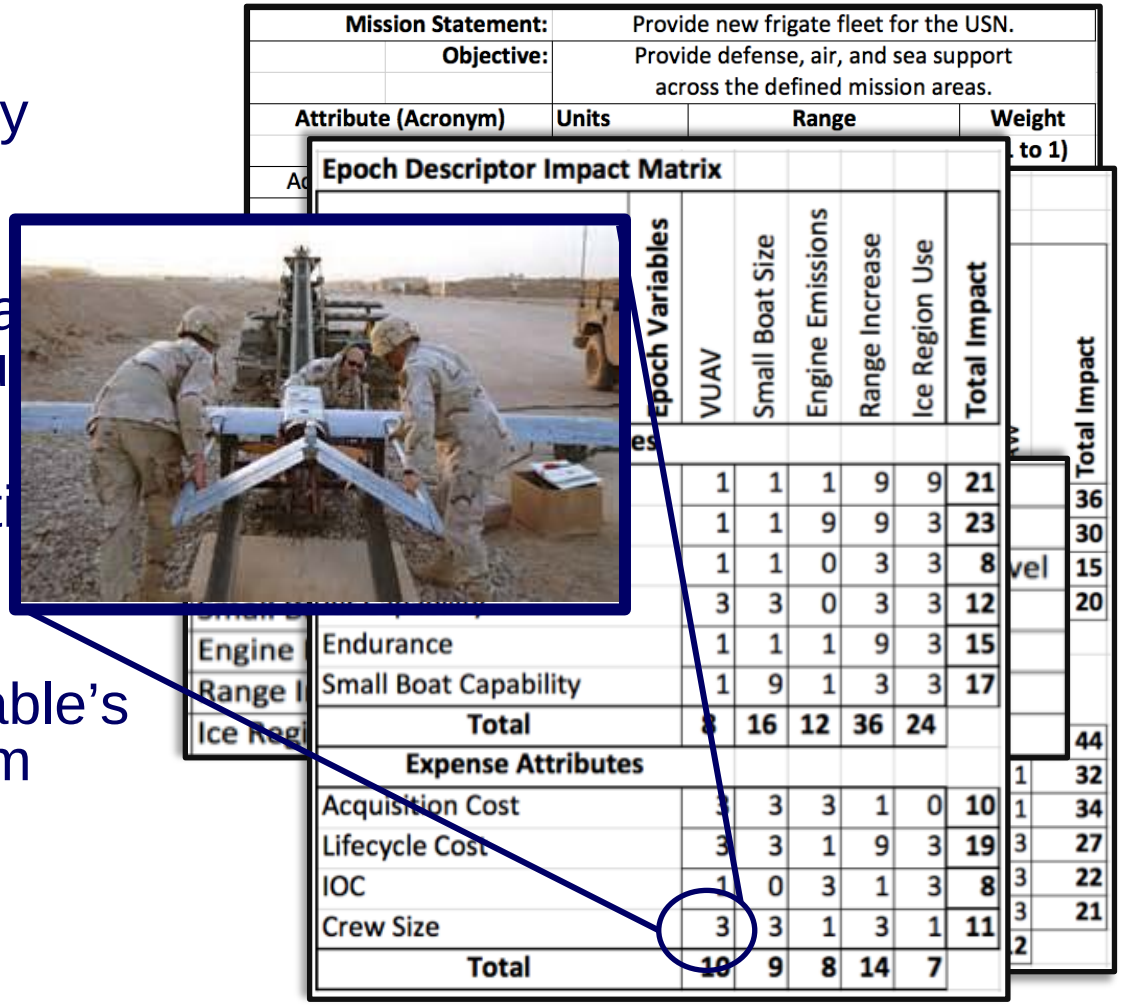

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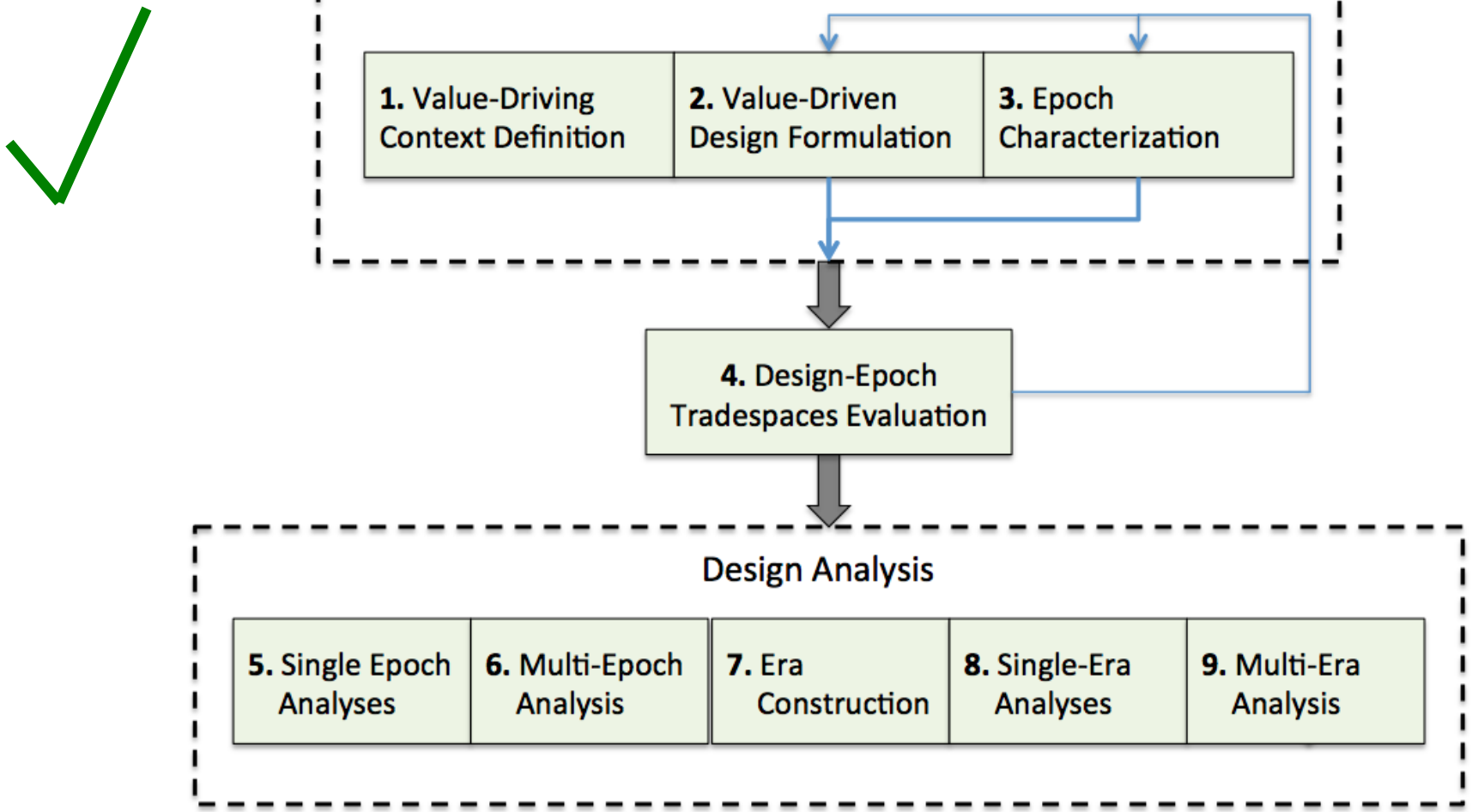

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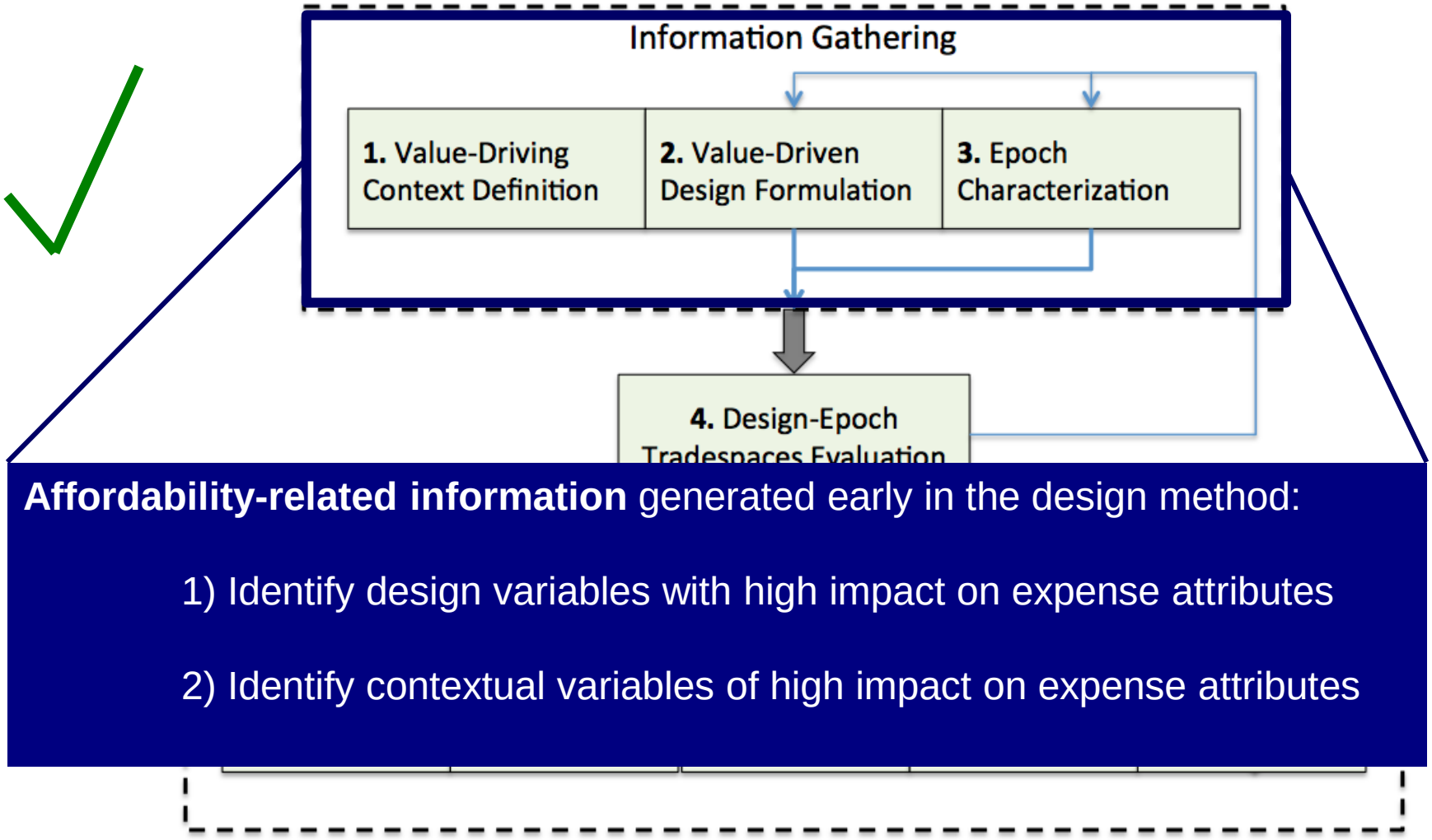

Affordability-related information generated early in the design method:

1) Identify design variables with high impact on expense attributes

2) Identify contextual variables of high impact on expense attributes

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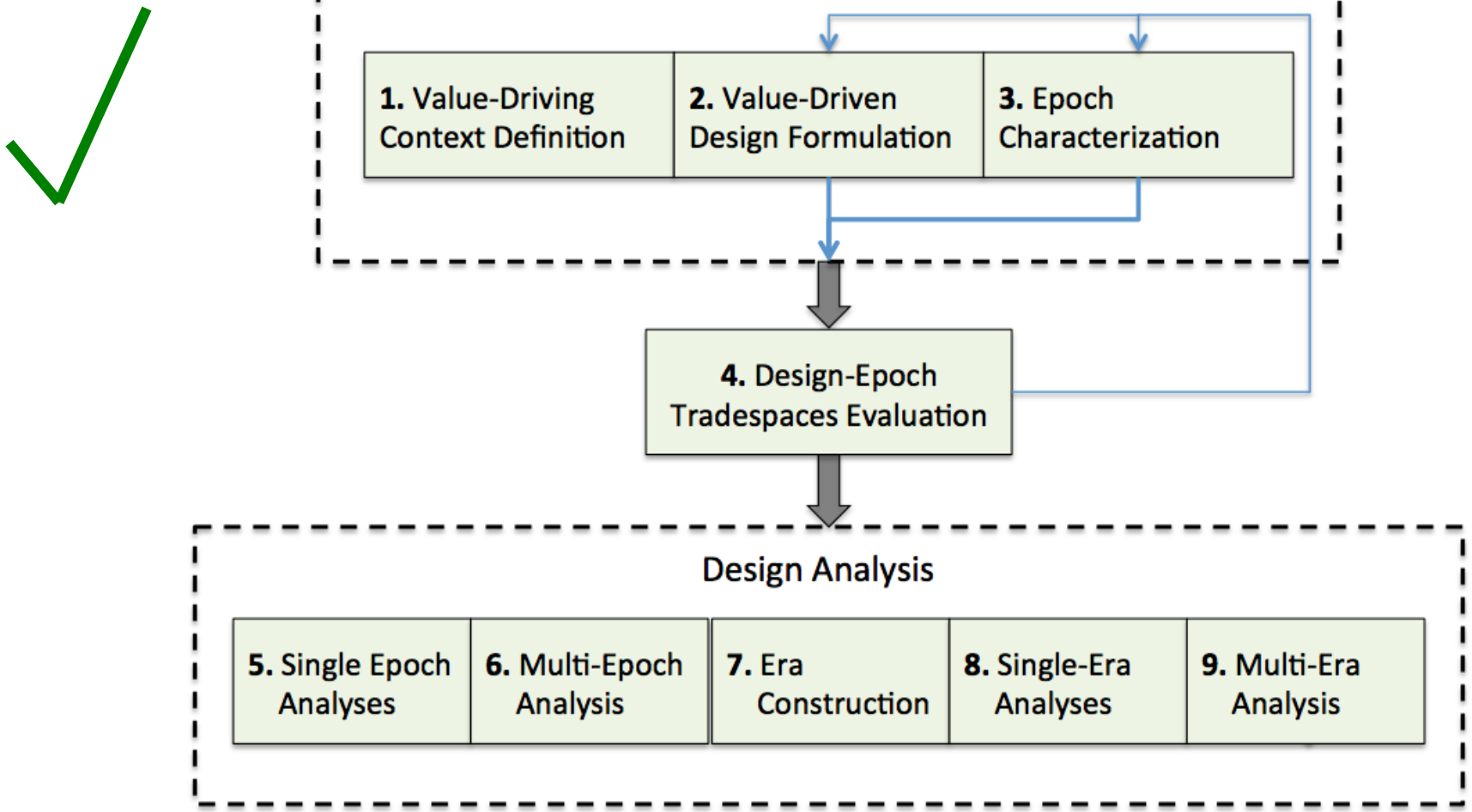

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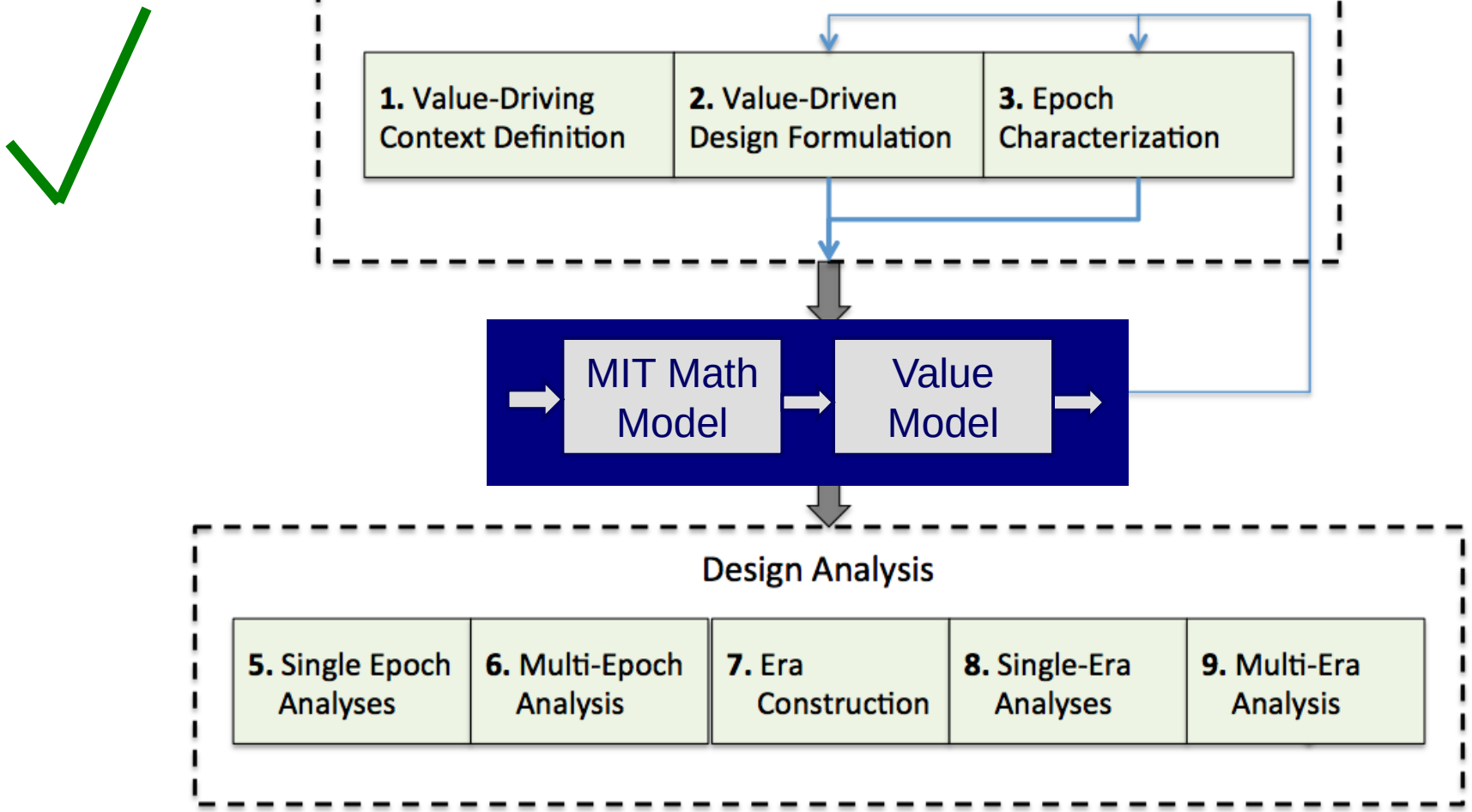
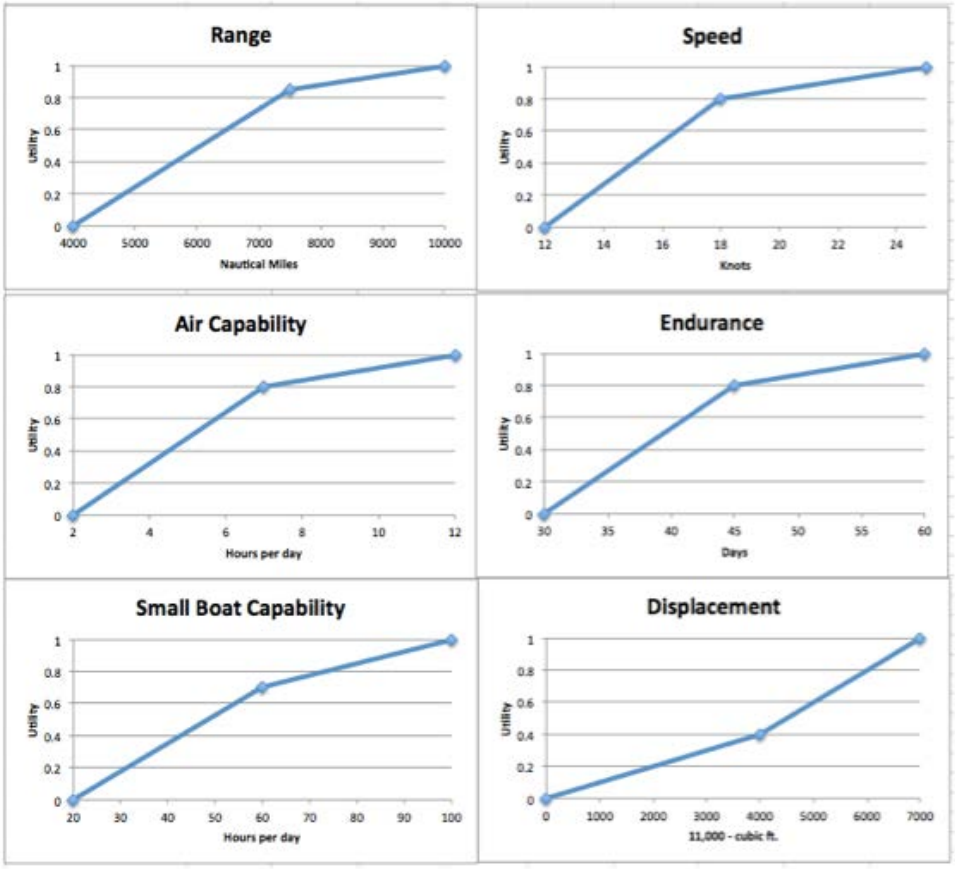


Process 4: Design-Epoch Tradespace Evaluation

Value functions in this case were constructed using utility theory:

1) for preferences over the utility attributes of the system,



*Anchoring and loss aversion explain the “bent” curves (Kahneman and Tversky 1984)

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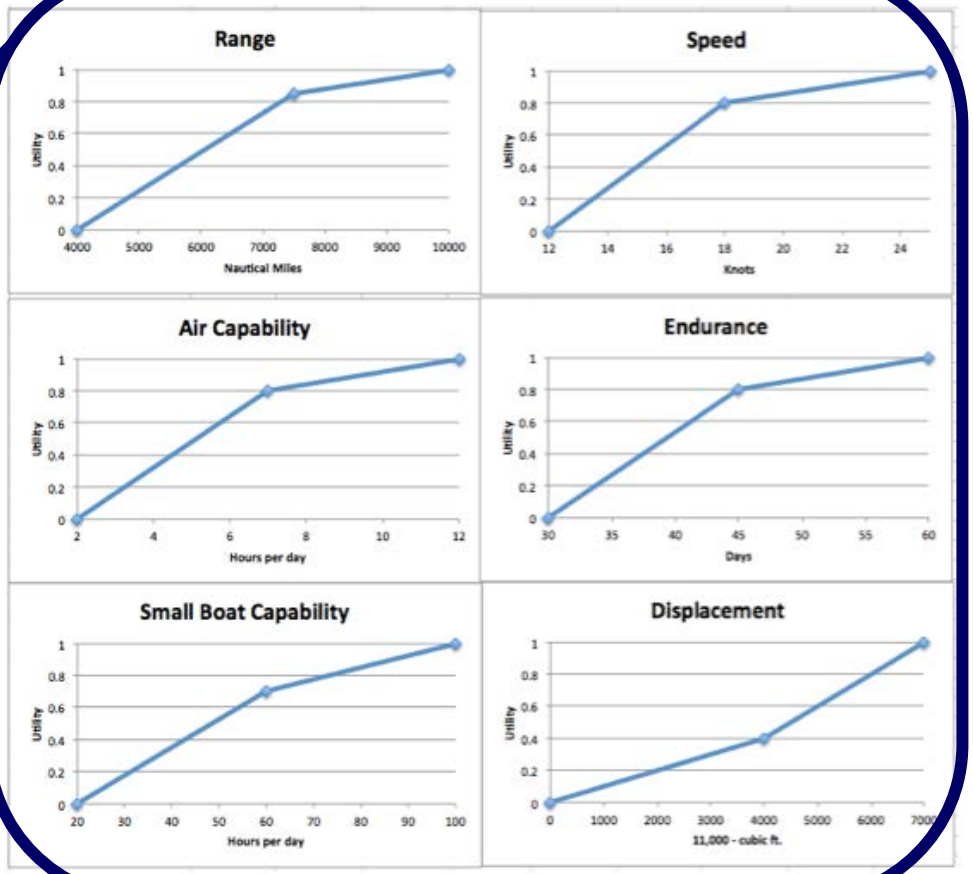

Rolled up into a single Multi-Attribute Utility (MAU) function

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Process 4: Design-Epoch Tradespace Evaluation

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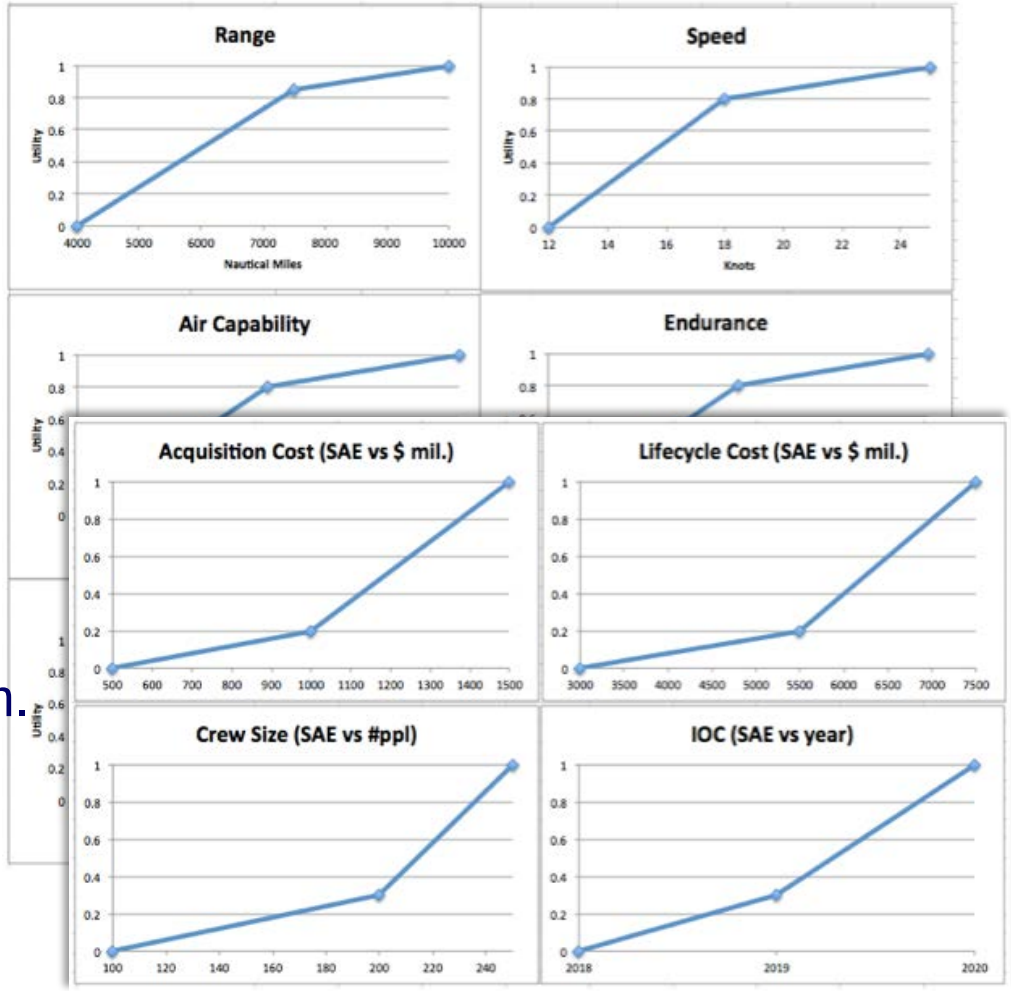

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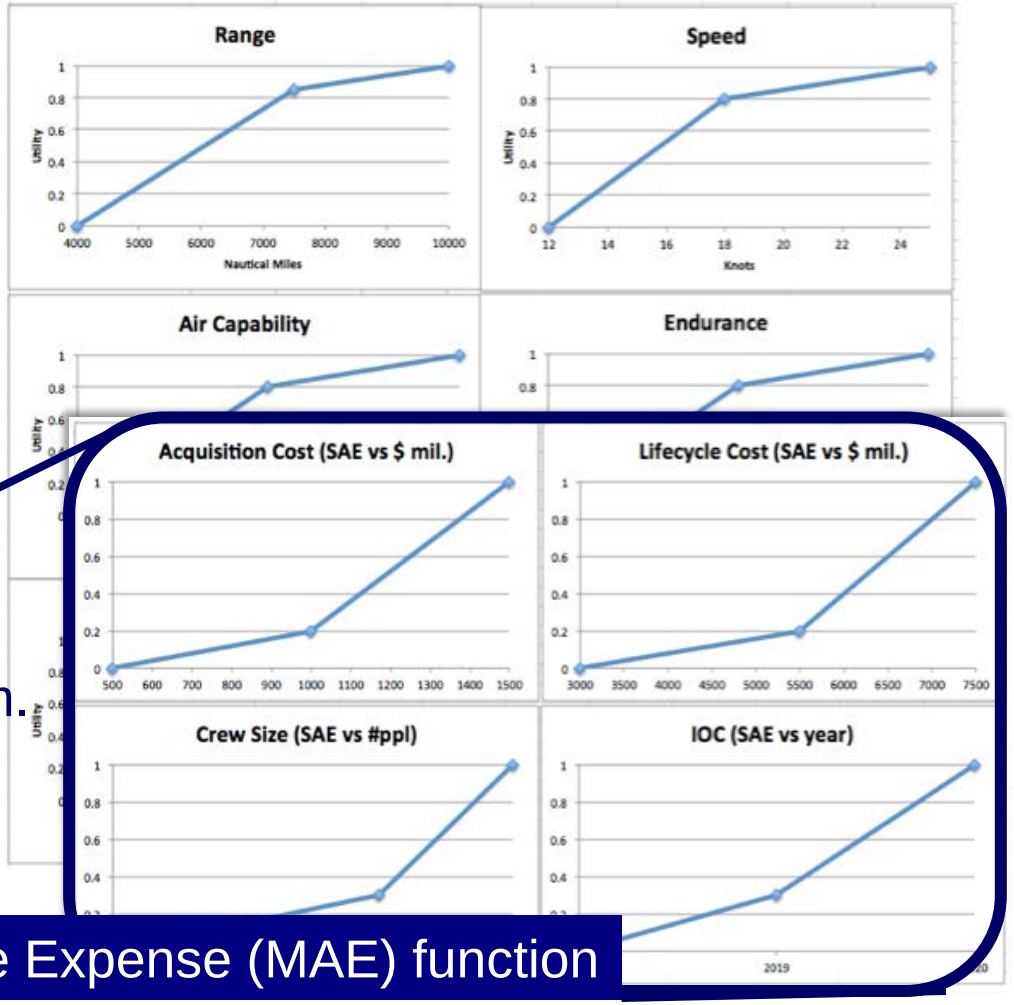

Rolled up into a single Multi-Attribute Expense (MAE) function

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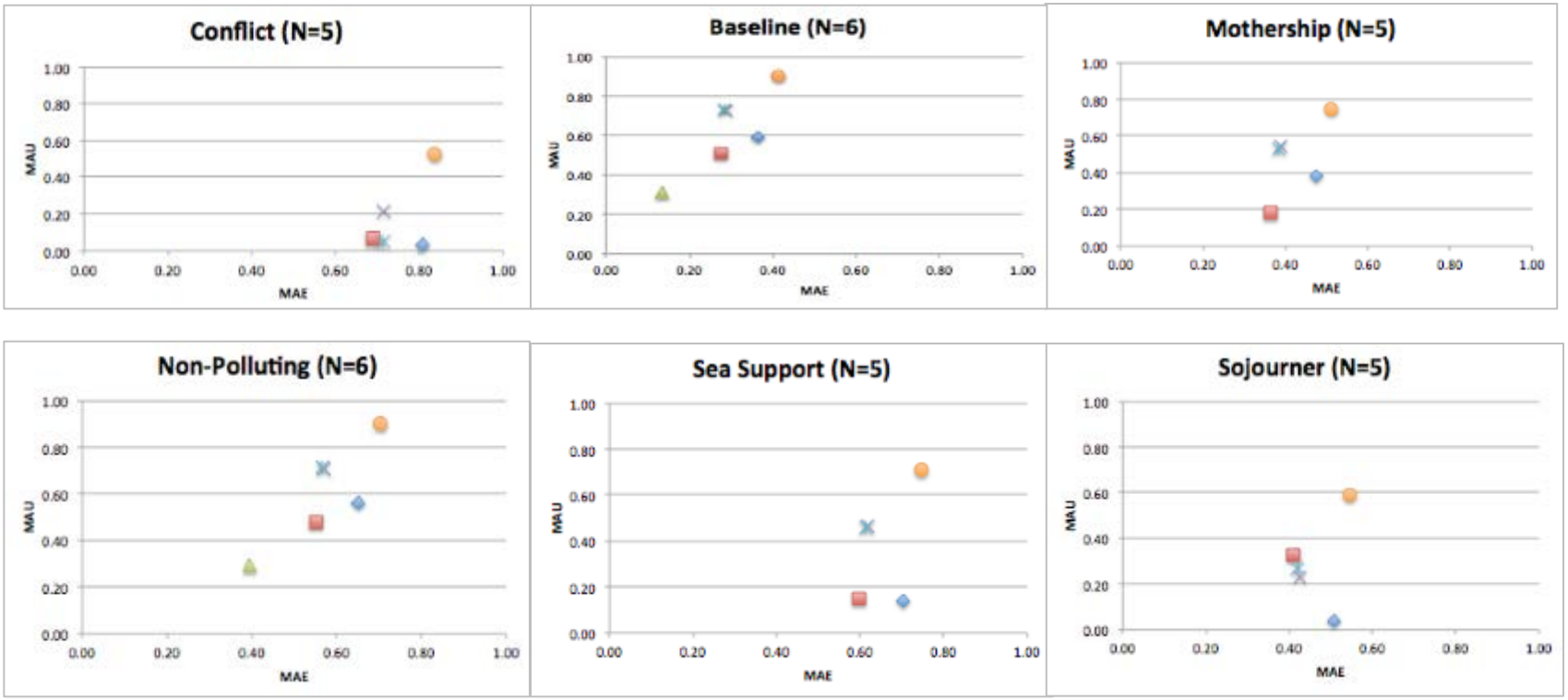
Process 4: Design-Epoch Tradespace Evaluation

Six representative designs evaluated in six epochs (of 108):



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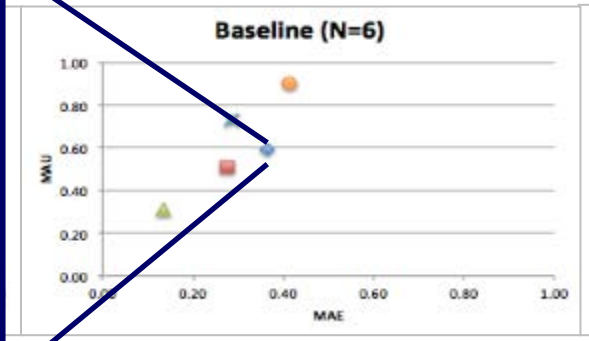

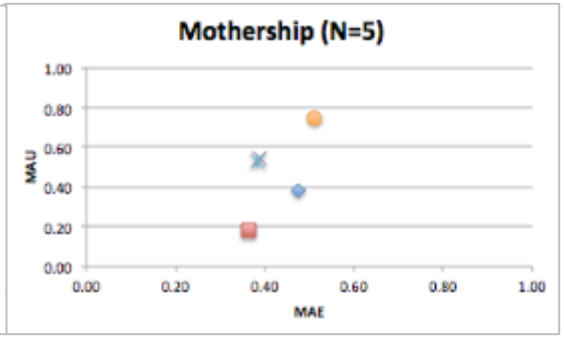

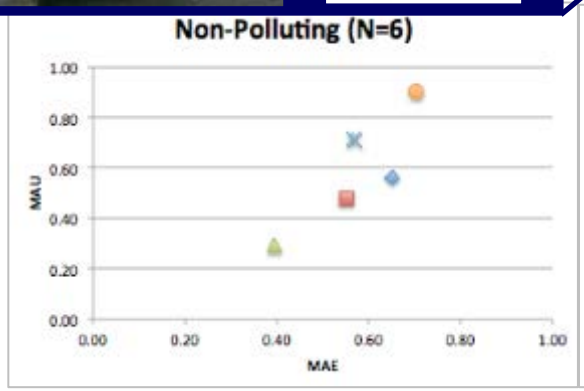

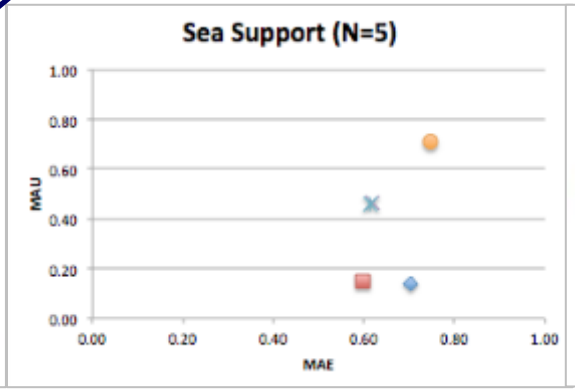

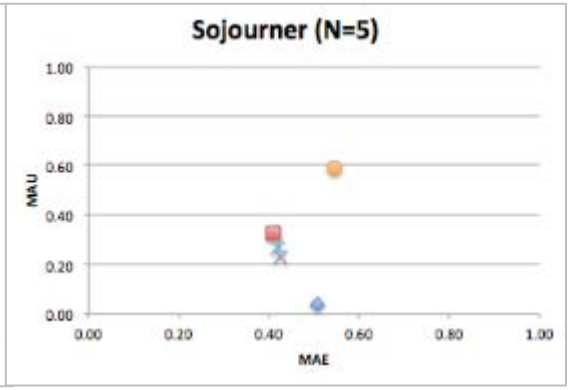

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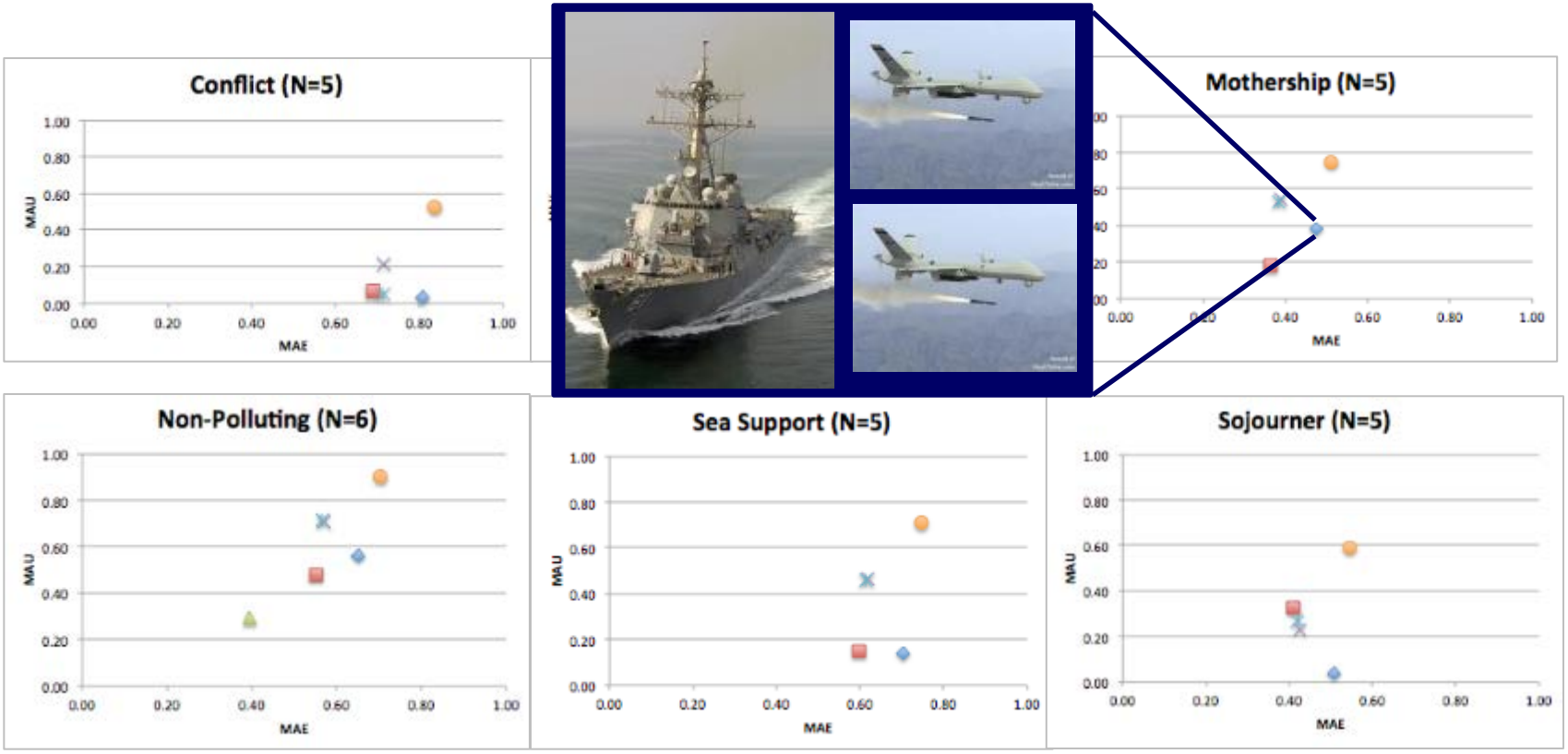

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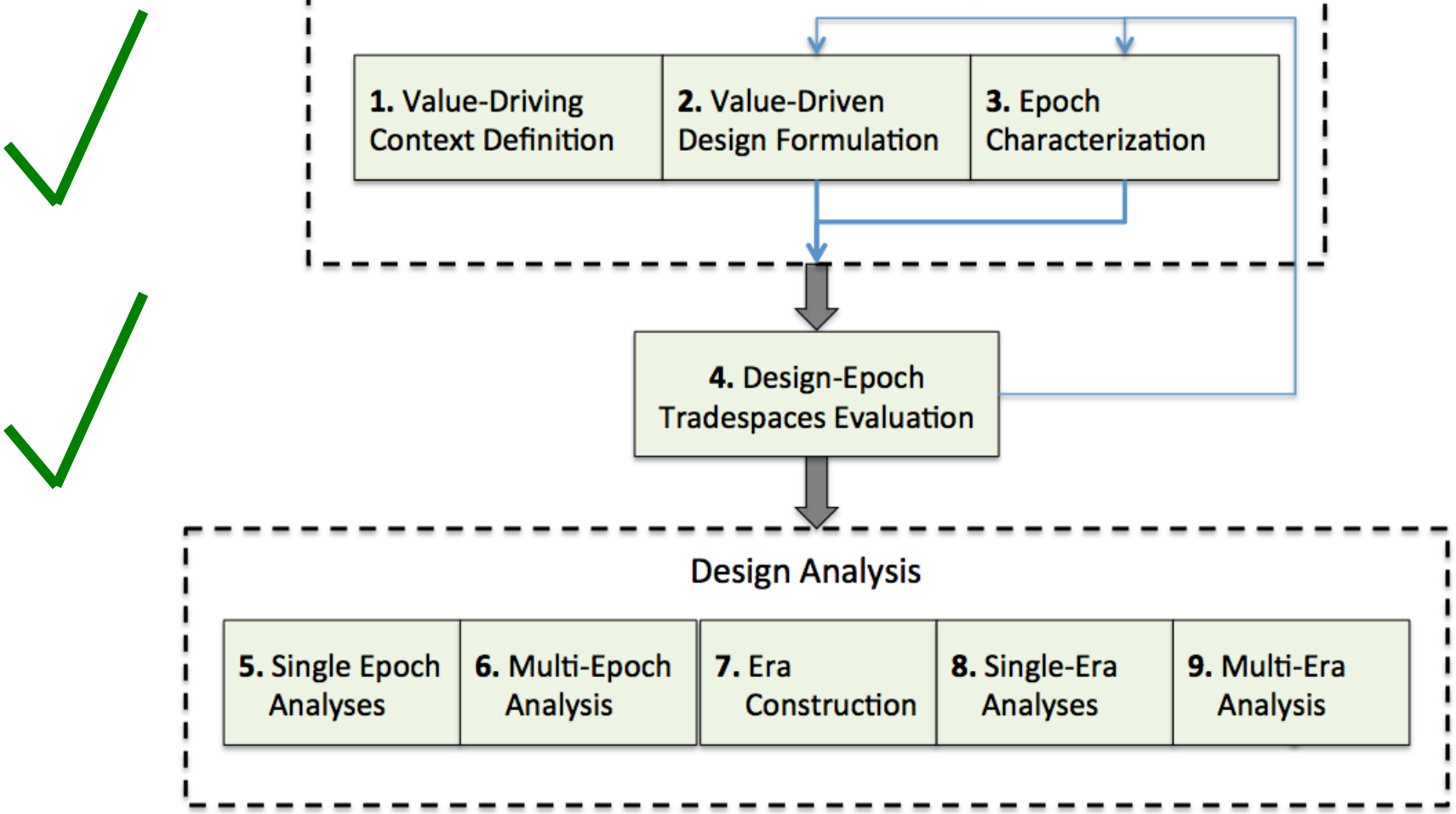

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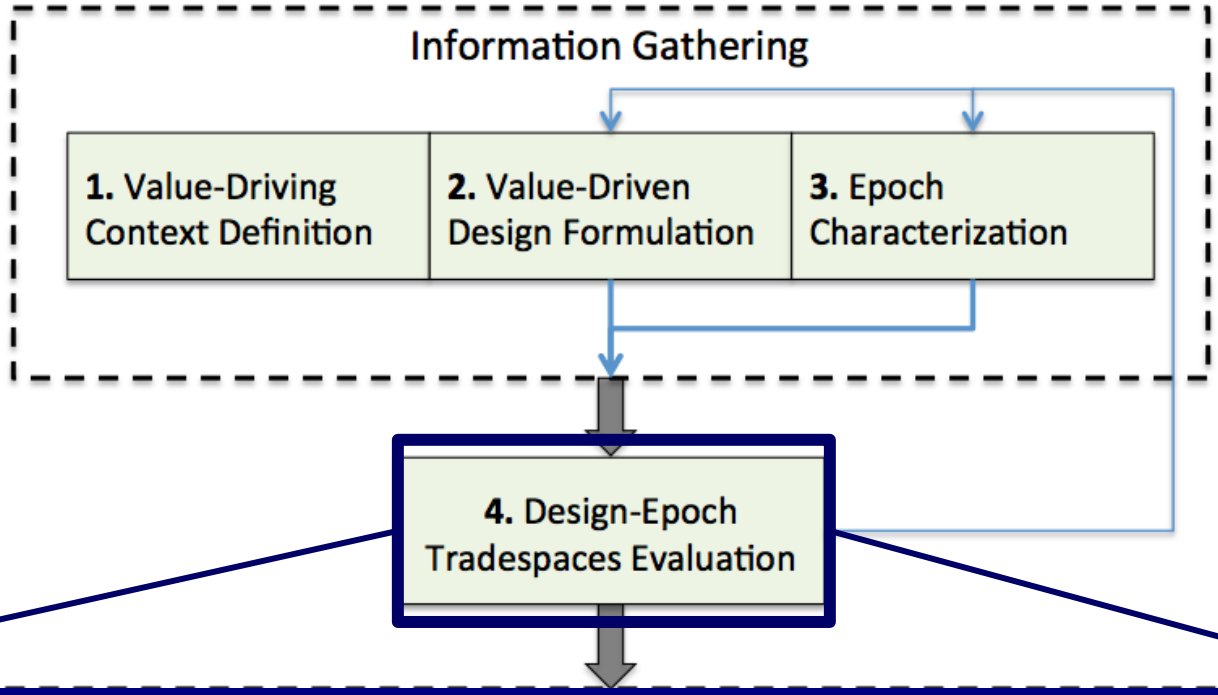
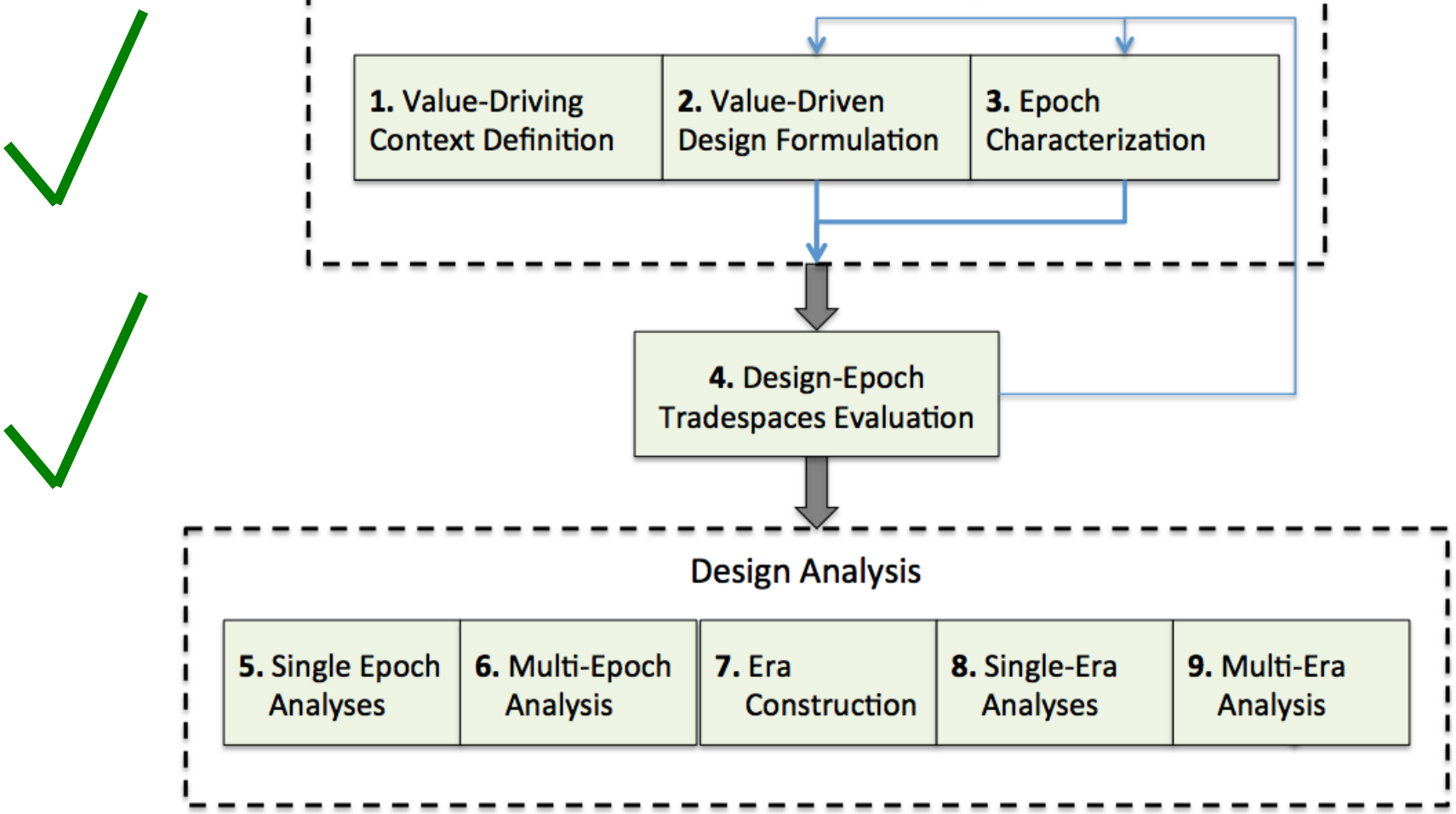


Affordability-related information generated by Process 4:

1) Stakeholder preferences captured for various types of expenses
2) Expense levels of all designs in each epoch (set of context + needs)
3) Expense levels of all designs shown alongside stakeholder preference on performance attributes (i.e., MAE vs. MAU tradespaces)

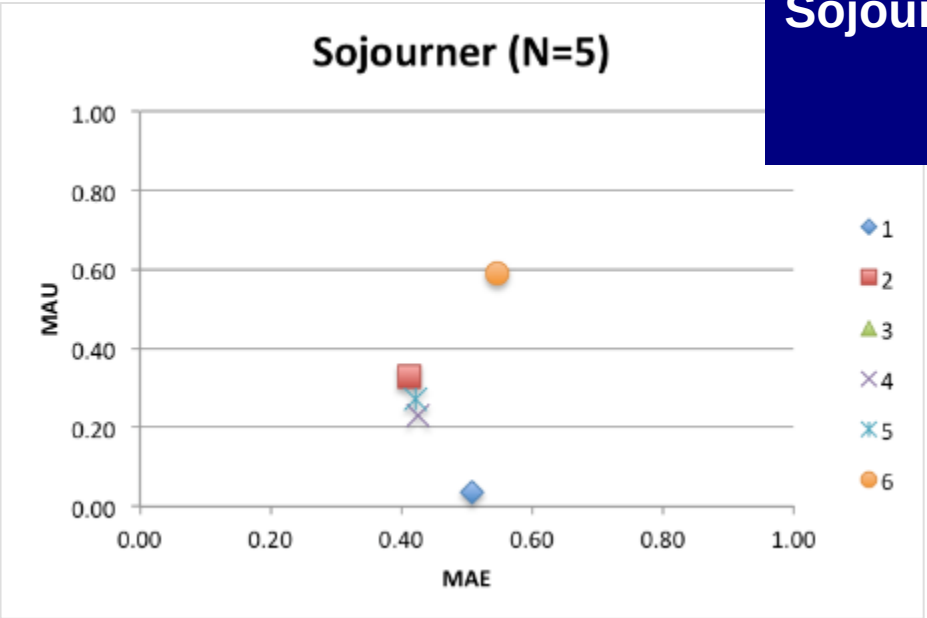
Overview of the RSC-based Method



Process 5:
Single-Epoch Analyses

Fuzzy Pareto Numbers (FPNs) in an epoch:

	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
FPN:	**23**	**0**	**Infeasible**	**4**	**3**	**0**



Sojourner epoch:
Range increase: 20%
Ice Region Use: High

FPN in epochs from Ross, Rhodes and Hastings (2009)

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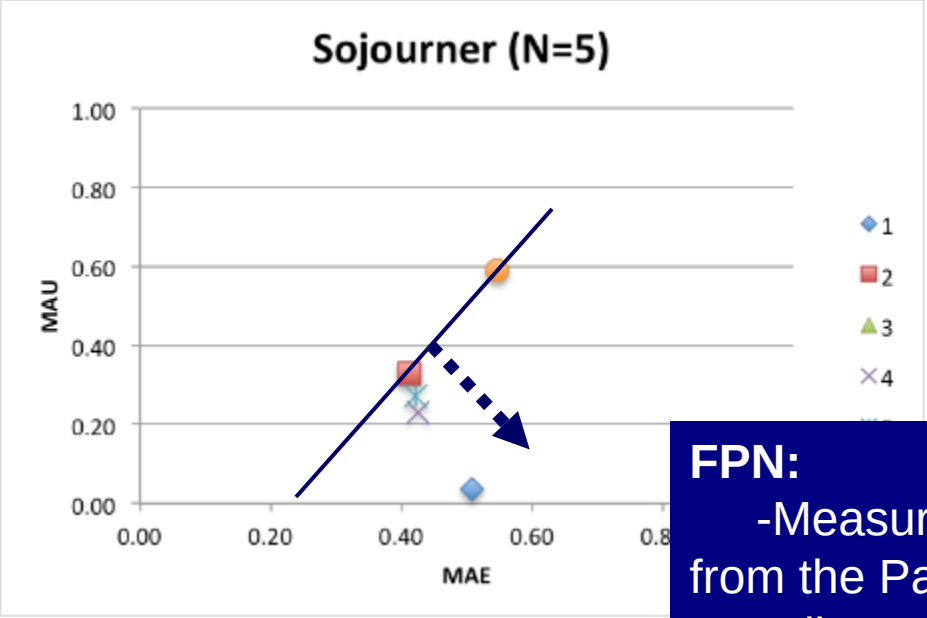
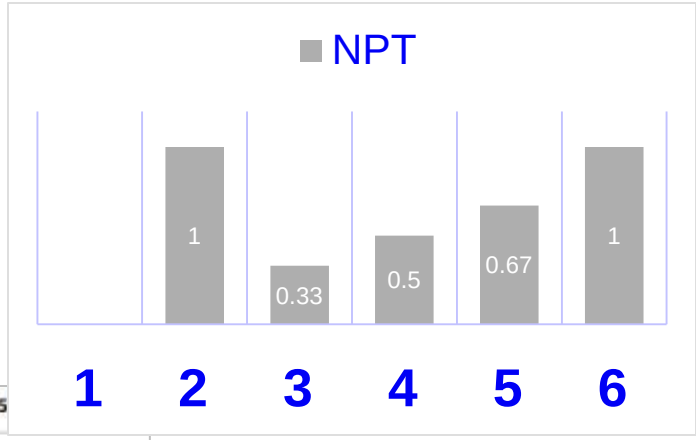


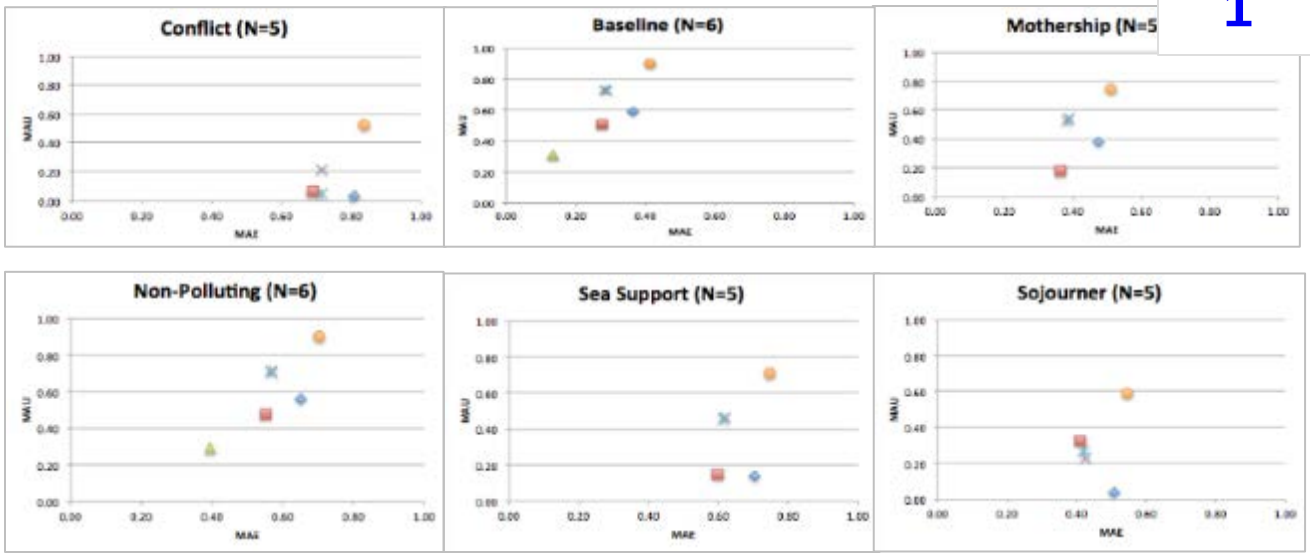
FPN:
-Measure of how far a design is from the Pareto front
-Allows comparison of efficiency

FPN i

Process 6:
Multi-Epoch Analysis

- Normalized Pareto Traces (NPTs) over all epochs
  (Ross, Rhodes and Hastings 2009)





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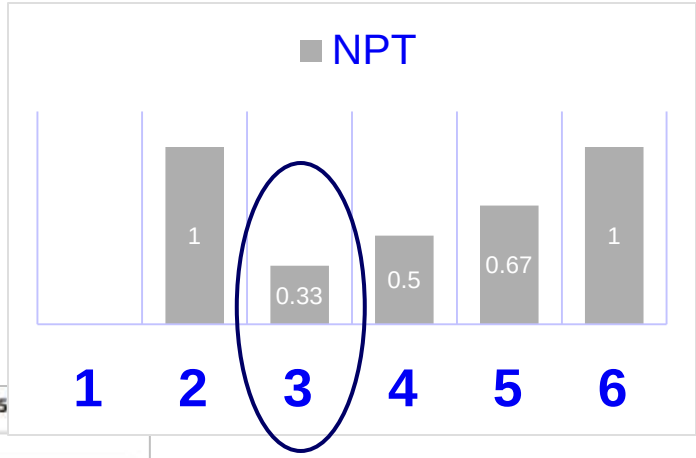
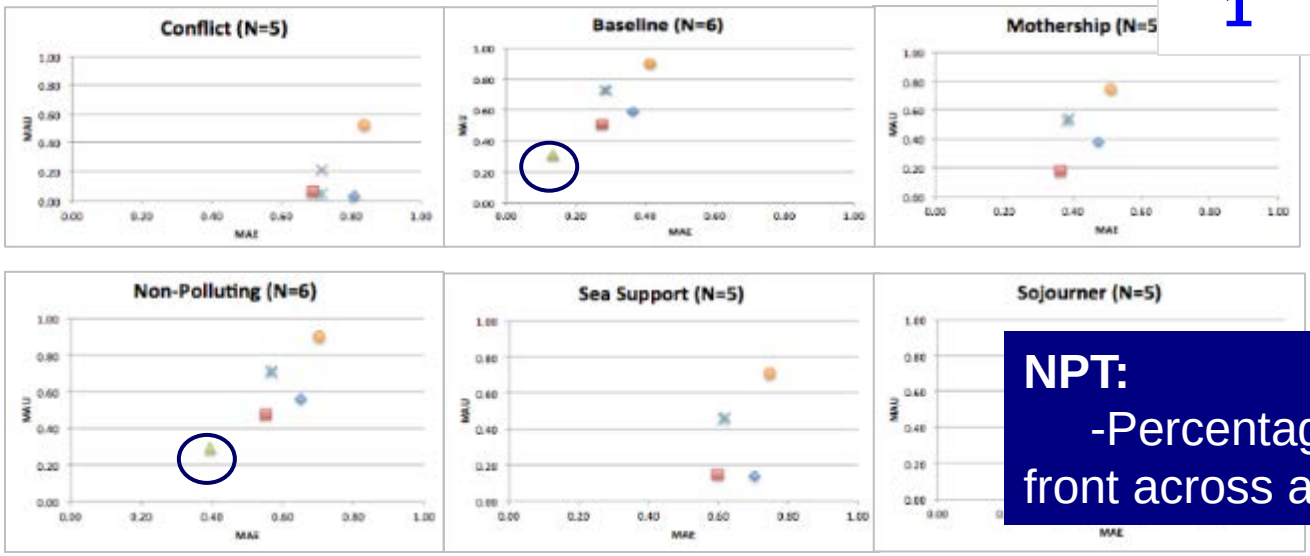


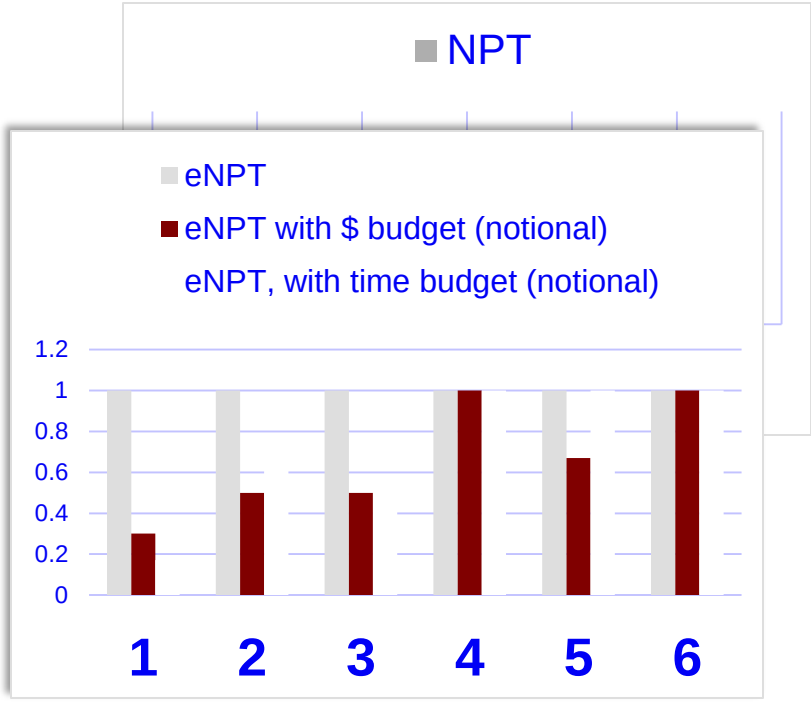


NPT:
-Percentage of time on Pareto front across all epochs considered.

Process 6:
Multi-Epoch Analysis

- Normalized Pareto Traces (NPTs) over all epochs
  (Ross, Rhodes and Hastings 2009)

- Changeability Metrics
  (Fitzgerald 2012)



Process 6:
Multi-Epoch Analysis

- Normalized Pareto Traces (NPTs) over all epochs
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- Changeability Metrics
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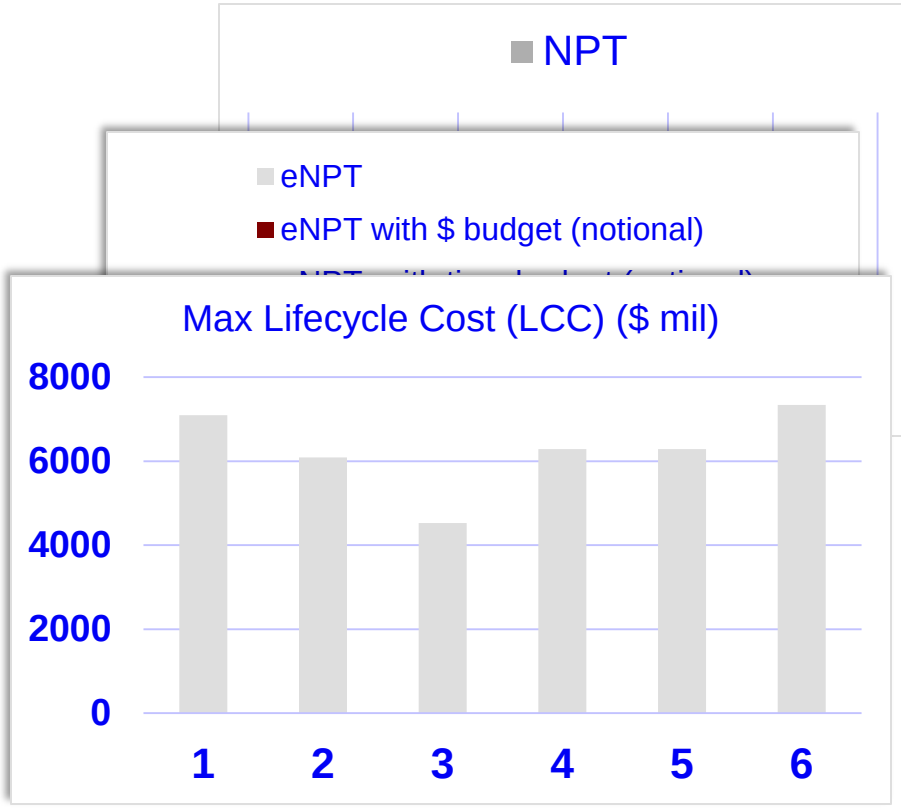
- Max Expense



Process 6:
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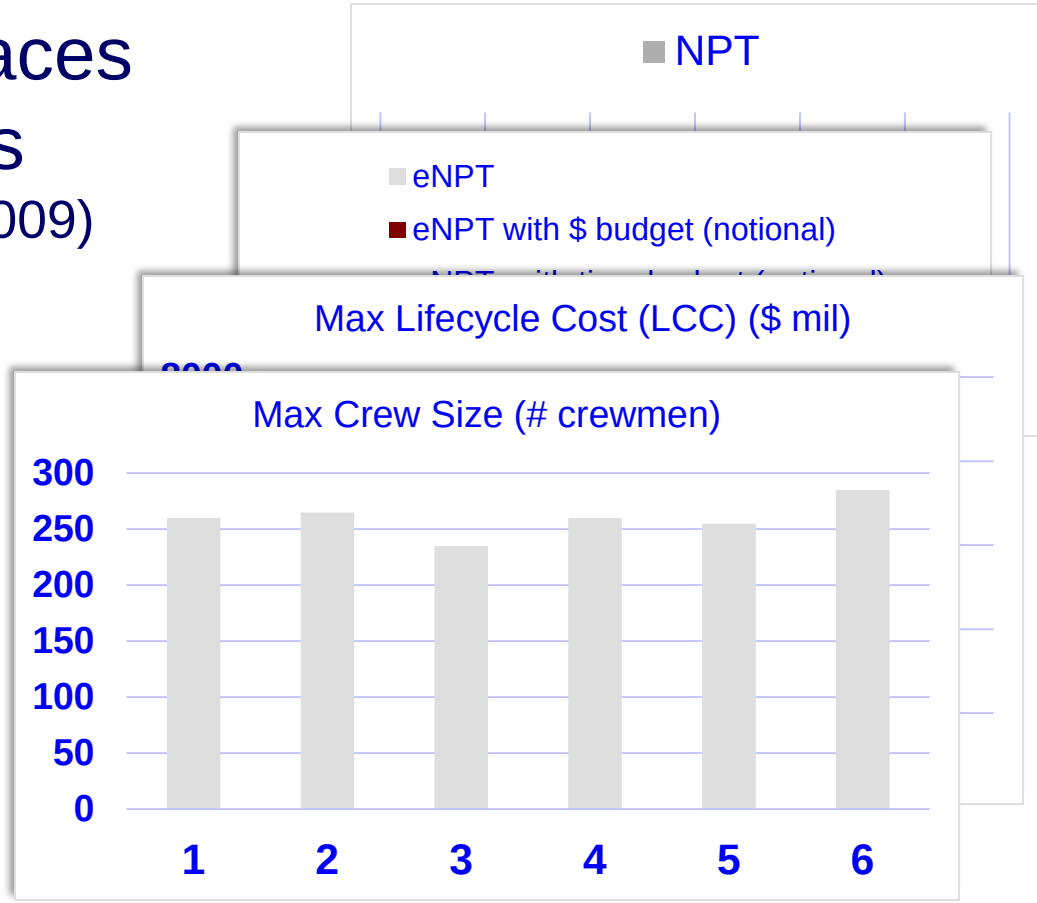

Process 6:
Multi-Epoch Analysis

- Normalized Pareto Traces (NPTs) over all epochs
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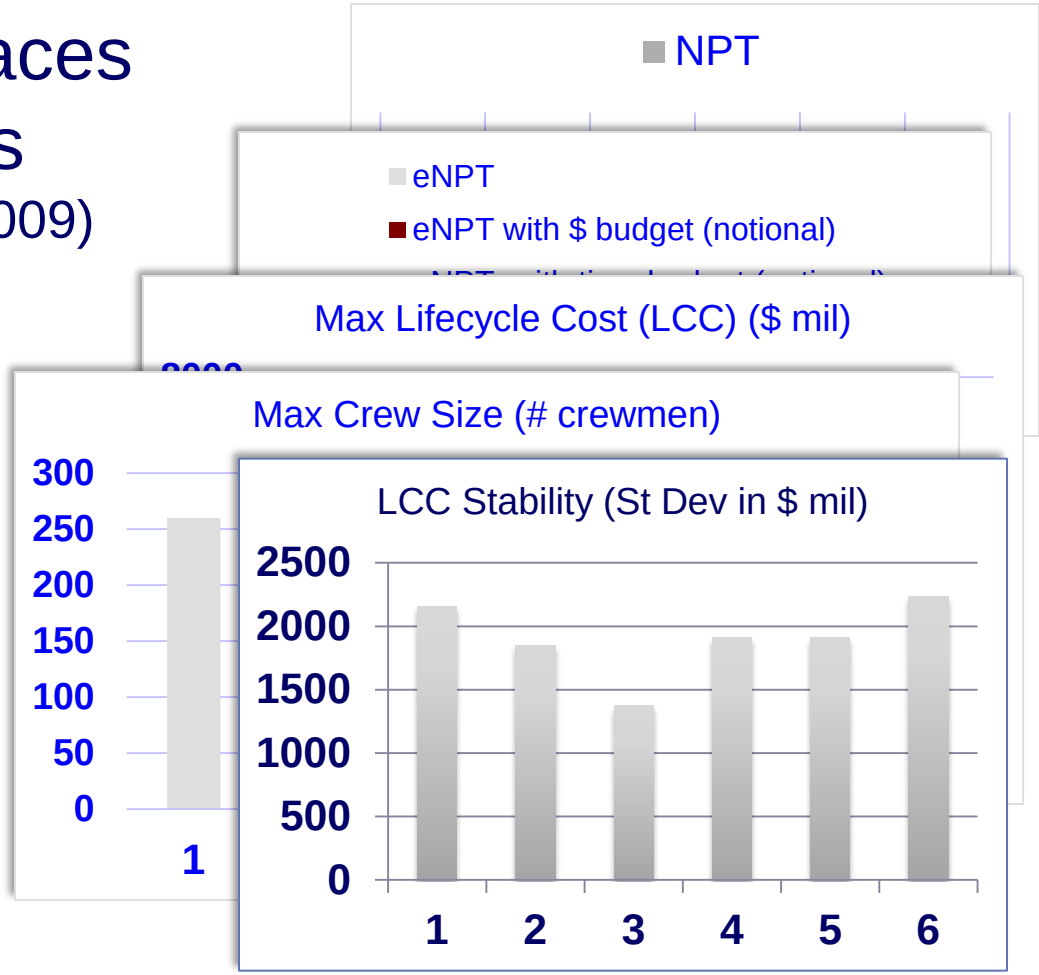
- Changeability Metrics
  (Fitzgerald 2012)
- Max Expense
- Expense Stability



Process 7:
Era Creation

- An *era* is a time-ordered sequence of epochs
- Construction of an era can involve:
  - Expert judgment on likely epochs and transitions
  - Decision maker interest in particular developments
  - Markov Chains (Epoch Syncopation Framework, Fulcoly et al., 2008)
  - Other probabilistic methods

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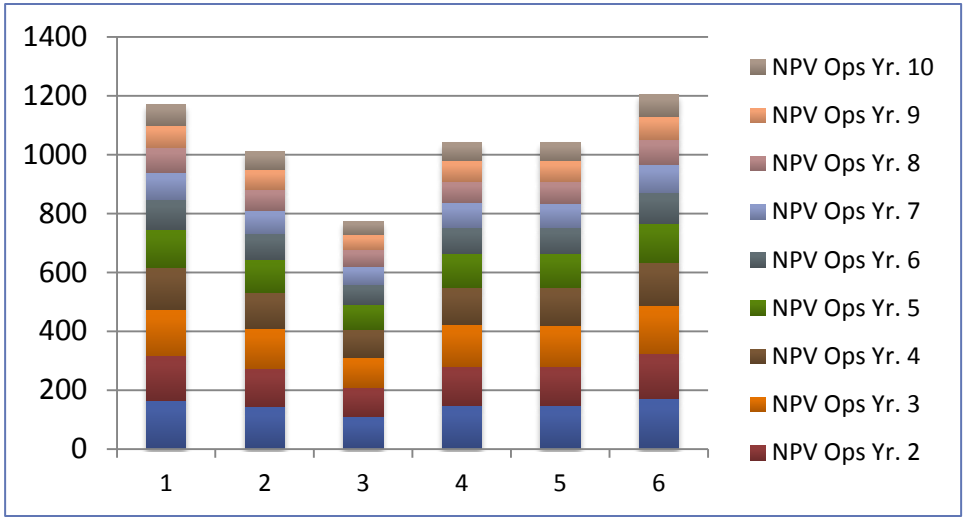
  - Other probabilistic methods

- E.g., Past Era:

(courtesy Andrew Long, 2010)

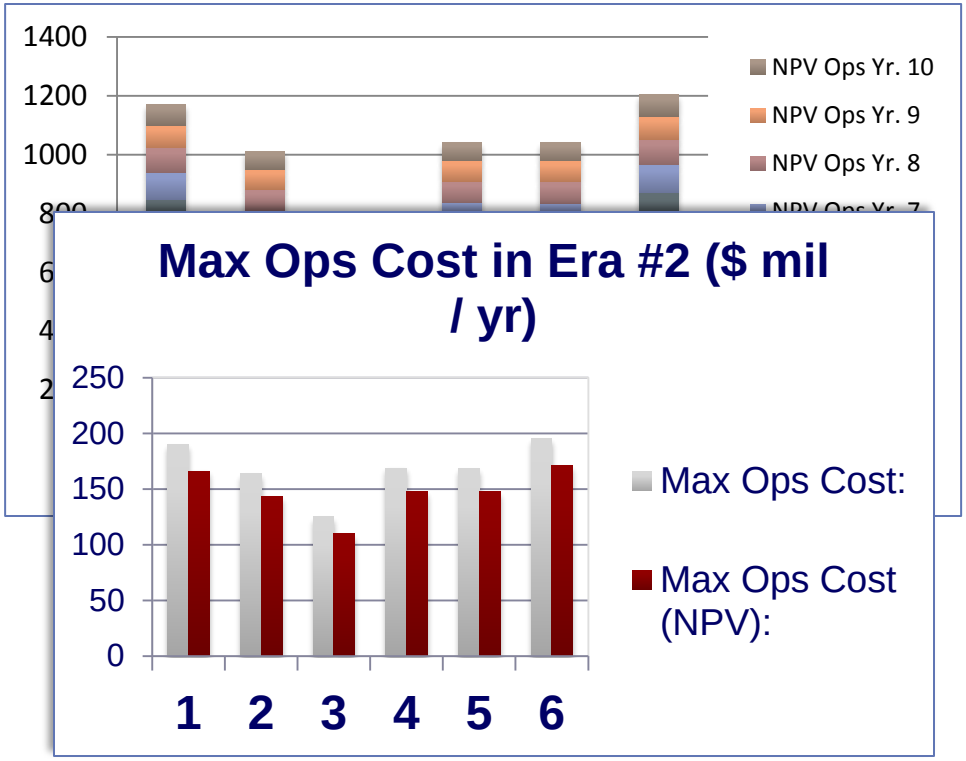
Process 8:
Single-Era Analysis

- Net Present Value (NPV) for each design
  - For monetary resources only



Process 8:
Single-Era Analysis

- Net Present Value (NPV) for each design
  - For monetary resources only
- Max Expense
  - For any resource
  - (NPV for monetary resources)



Process 8:
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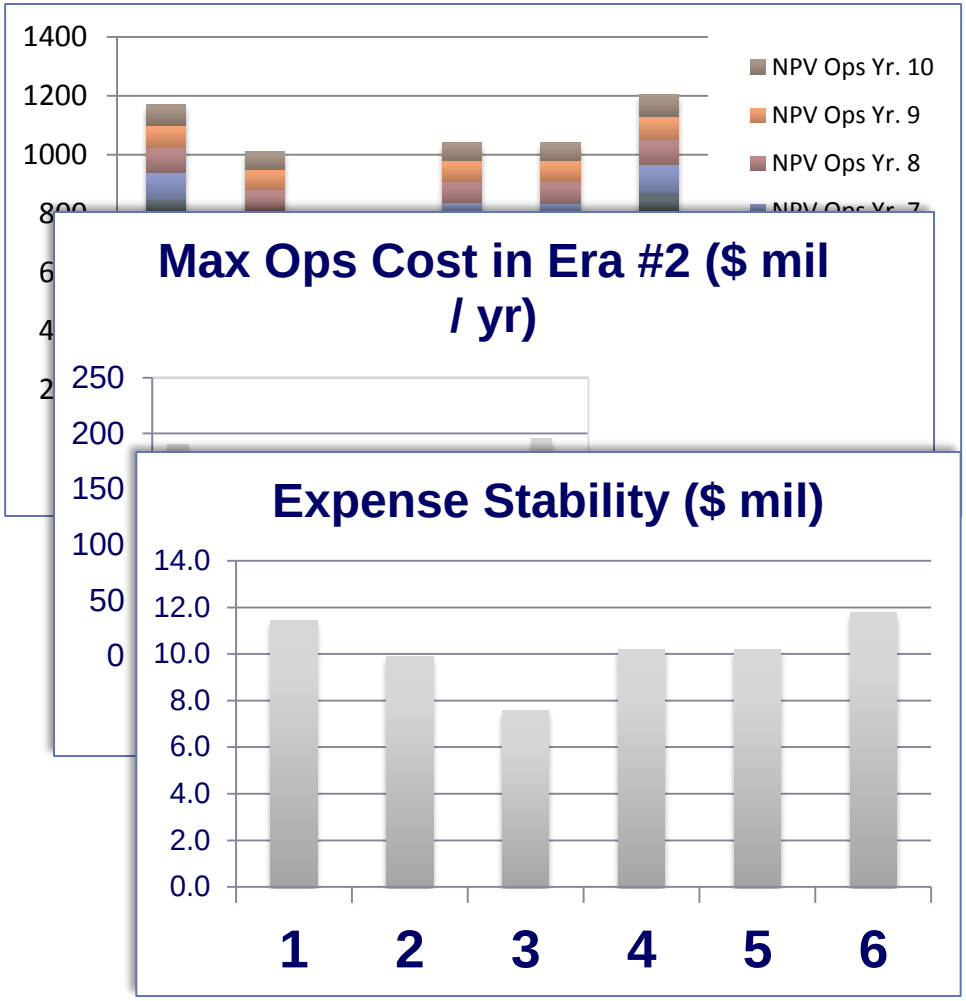
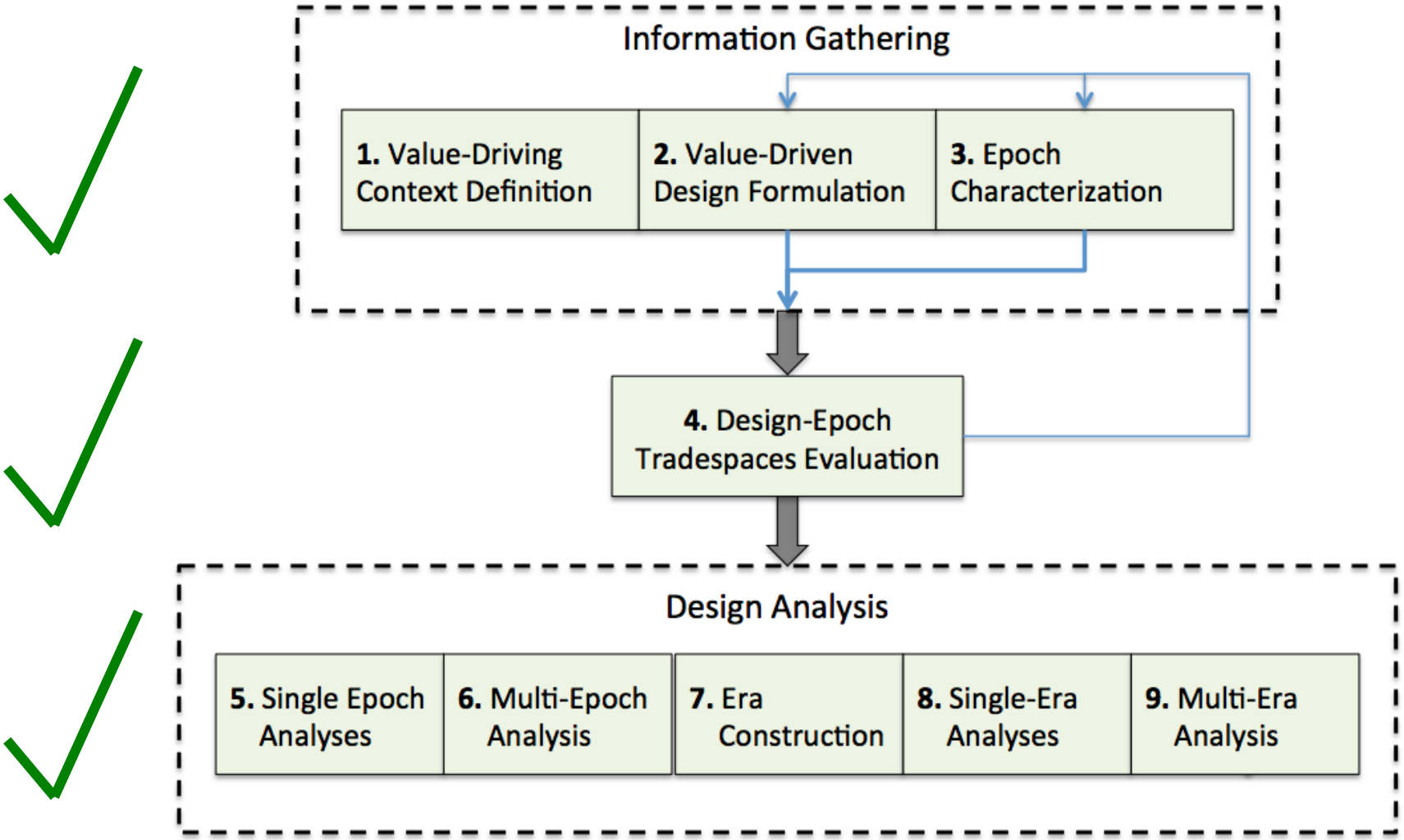


Process 9:
Multi-Era Analyses

- (Not completed for case study at this time.)
- Further/ongoing work includes:
  - Compare alternate strategies for minimizing resource usage over lifecycle
  - Establishing upper and lower bounds on resource usage throughout possible lifecycle developments
  - “Learn” heuristics for change strategies of individual designs in given epochs

Overview of the RSC-based Method

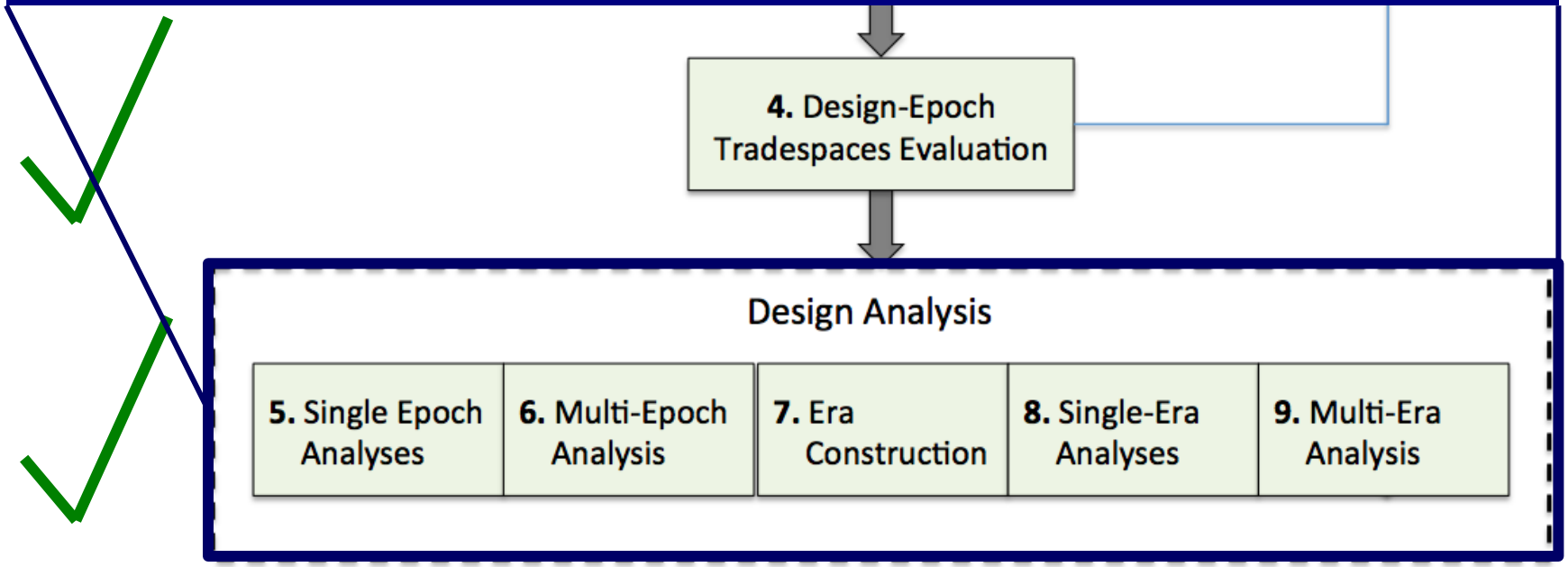


Overview of the RSC-based Method

Affordability-related information generated by Processes 5 through 9:

1) Pareto-Efficiency measures in all contexts
2) Maximum resource requirements across changing contexts
3) Resource requirement stability across changing contexts

And easily scalable to large numbers of alternatives in many contexts.



Conclusion

This research addresses:

Lack of mature metrics and systematic frameworks in the design for affordability.

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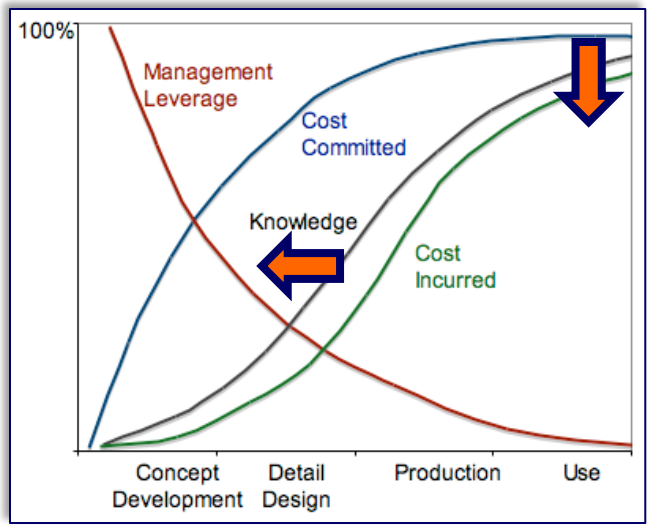


Knowledge brought forward:

-Design 3 was removed from consideration due to unaffordability (lack of feasibility in several epochs).

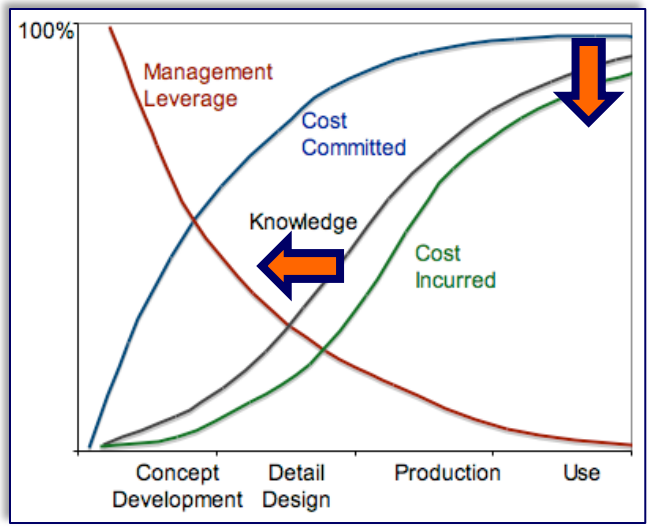
-Next-best designs in Max Expense and Expense Stability were 2, 4, and 5. Designs 2 and 4 were further investigated due to more stable value delivery.

-Affordable designs both had: 510-530 ft., Medium Weapons Packages

Conclusion

This research addresses:

Lack of mature metrics and systematic frameworks in the design for affordability.



The research provides:

An early-lifecycle design method and metrics for generating system knowledge directly related to affordability considerations while still in the conceptual development phase.

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A METHOD FOR SELECTING AFFORDABLE SYSTEM CONCEPTS

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