Systems Engineering Advancement Research Initiative

Sustaining Lifecycle Value: Valuable Changeability Analysis with Era Simulation

Matthew Fitzgerald and Adam Ross

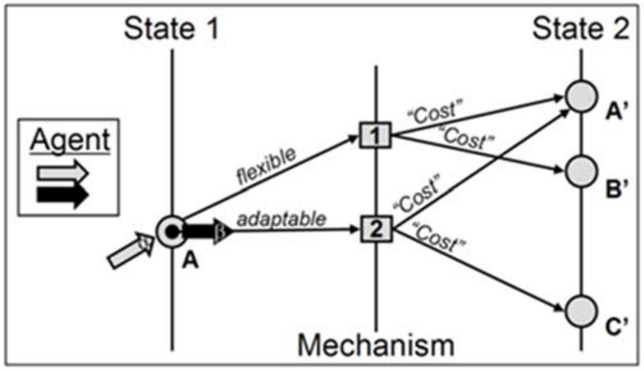
IEEE Syscon 2012

Outline

- Changeability Overview
- Epoch-Era Analysis Summary
- Changeability Usage Strategies
- Era Analysis Techniques
- Space Tug Case Study

What is Changeability?

- Changeability: *the ability of a system to change its form or behavior at some point in its lifecycle*
  - Related words: flexibility, adaptability, etc.
- Agent-Mechanism-Effect framework
  - Agent: instigator
  - Mechanism: enabler
  - Effect: ΔState



Ross et al, 2008

Why Changeability?

- Benefits
  - – Ability to avoid risk and seize opportunity as context changes over time

In the absence of changeability, exogenous disturbances / stakeholder preference modifications can compromise system value!

- Costs
  - – Development, build, execution costs both in money and time

But how do we value changeability?

Challenges arising from the nature of changeability have complicated the process of appropriately quantifying it: a necessary step to justify the costs!

Solving the Problem

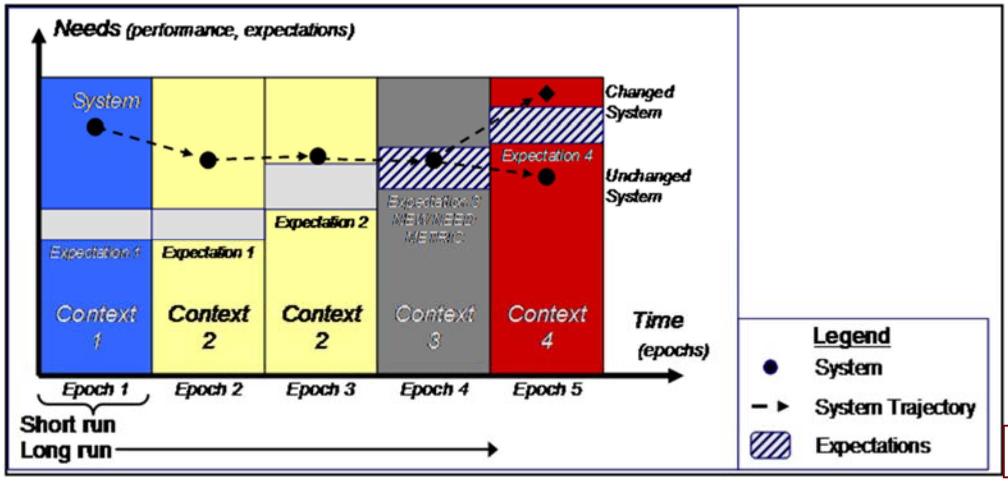
Leverage two techniques to address the biggest components of changeability analysis

- Modeling passage of time
  - Epoch-Era Analysis (EEA)
- Modeling system change
  - Changeability usage strategy

Combined, these two will allow for a fundamental modeling and understanding of changeability in design and operation

Epoch-Era Analysis (EEA)

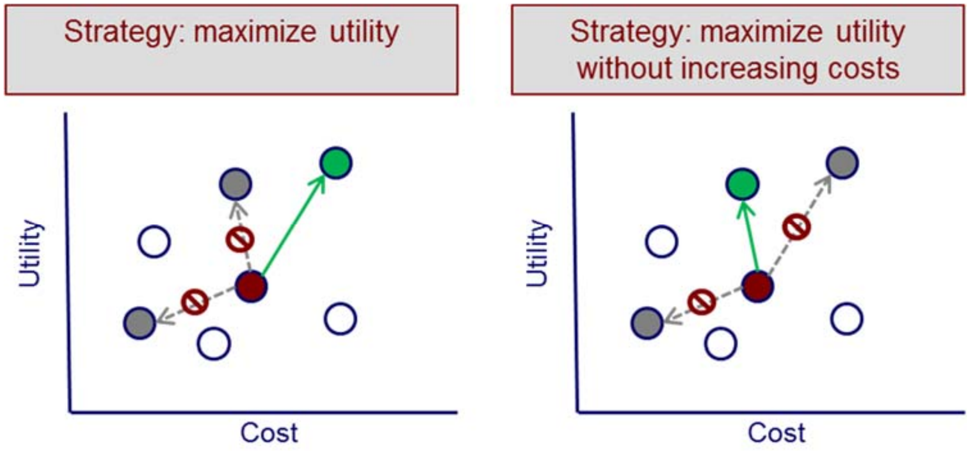
- Conceptualizes the effects of time and changing context on a system
  - Epochs: periods of fixed context (short run)
  - Eras: sequences of epochs simulating a potential future experienced by the system (long run)



Ross, Rhodes, 2008

Strategy

- ***Changeability usage strategy*** – a stakeholder or decision-maker's statement of intended use of changeability
  - Assists in valuing changeability by selecting a single change path in each epoch (as defined by the mechanism-effect framework)



Strategy statement represents logic used to select amongst available change paths

Strategies can vary in metrics used or complexity of logic depending on stakeholder desires

Era Domain Analysis Techniques (1)

- Best/Worst/Average Fuzzy Pareto Number (FPN) tracking
  - FPN = a measure of cost efficiency
  - Follow the design’s performance via this metric as it changes as epochs evolve

See our other paper for details!

- Rule usage
  - Record all change mechanism usages, can calculate likelihood of need in random lifetime
  - Can justify inclusion/exclusion

Era Domain Analysis Techniques (2)

- Changeability “Going Rate”
  - Establish initial cost vs lifecycle benefit of changeability

- Rule removal
  - Rederive strategic change decisions without access to certain mechanisms
  - Performance decrement is the *removal weakness*, quantifies dependency on those mechanisms
  - May suggest need for redundancy, if value is critically dependent

Space Tug Data Set - Intro

- Scenario: You are the owner of a space tug rental company, providing the services of your system to customers with varying preferences.
- Goals: Meet customer demands as well as possible, for as long as possible – satisfied contracts provide revenue based on duration and utility.

In this case, the system decision-maker (you) is attempting to satisfy different sets of preferences corresponding to other people.

7 designs of interest (out of 384) identified for further analysis across 4 strategies and 16 epochs, defined by 8 "mission" preferences and 2 technology levels

		Design Variables			Performance Attributes			
Design Number	**Ref**	**Prop Type**	**DFC Level**	**Fuel Mass (kg)**	**Capability (kg)**	**Fast?**	**DeltaV (m/s)**	**Base Cost ($M)**
1	A	Biprop	0	30	300	Y	143	97
29	B	Nuke	0	1200	300	Y	7381	306
47	C	Cryo	0	10000	1000	Y	6147	628
128	D	Nuke	0	30000	5000	Y	14949	3020
191	E	Nuke	1	10000	1000	Y	16150	980
328	F	Biprop	2	50000	3000	Y	4828	2804
376	G	Elec	2	30000	5000	N	27829	3952

Space Tug – DFC Level

Key design variable: Design for Changeability (DFC) level

- Levels: 0, 1, 2 where higher = more investment
- Investment modeled as both a mass and cost penalty on satellite
- Higher level → improved or new change mechanisms

#	Rule	Effect	DFC level
1	Engine Swap	Biprop←→cryo	0
2	Fuel Tank Swap	Change propellant mass	0
3	Engine Swap (reduced cost)	Biprop←→cryo	1 or 2
4	Fuel Tank Swap (reduced cost)	Change propellant mass	1 or 2
5	Change capability	Change capability	1 or 2
6	Refuel in orbit	Change propellant mass (no redesign)	2

Space Tug – Era Characteristics

Remember: **Epochs = period of fixed context**
Eras = sequences of epochs

Era simulation for Space Tug is trickier than a simple random ordering of epochs with predetermined change executions

- ***Time-ordered context variables*** – the epochs must be sampled intelligently so that the technology level starts at "present" and progresses to "future" and stays there
- ***Epoch length knowledge*** – the epochs are essentially space tug rental "contracts" from prospective customers, so unlike many exogenous variables we know how long each will last, potentially affecting decision making

Space Tug - Strategies

- Maximize Utility
  - A common first-order strategy (make system as good at its job as possible)
- Maximize Efficiency
  - Similar to above, but with a desire to be as cost efficient as possible while fielding a good system
- Survive
  - Change is executed only if system is invalid (including running out of fuel)
- Maximize Profit (short-run)
  - You think that you have a good idea how much money you can demand from your customers based on utility, and develop a revenue model, using design changes to maximize revenues less costs in each epoch
  - Enabled by knowledge of epoch length!

Space Tug – Era Characteristics

As mentioned, we implement a basic revenue model:

$$\underset{\textit{Per-epoch}}{\mathbf{Rev}} = \begin{cases} \mathbf{\$200M + \$1000M * Utility * MonthsServed} & \textit{If viable} \\ \mathbf{0} & \textit{If inviable} \end{cases}$$

Designs are rewarded for viability/utility and availability

The Max Profit strategy will weigh the monetary cost AND downtime associated with executing a change against the benefits of higher utility

For each design and strategy, the following simulation was performed:

- 5000 eras of 10 years
- Future technology arrives at a random time after 5 years
- Each potential contract (epoch) has a random duration from 1 to 12 months

Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3
	SURVIVE			MAX PROFIT		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10^4\$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	🟥 3.3	1.7	1.6	2.4	🟩 0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	🟩 6.9	4.6	2.3	🟩 7.9	3.6	🟩 4.3 D
E	6.6	🟥 5.7	🟥 0.9	6.7	🟥 3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	🟩 0.4	🟩 6.1 G	🟥 2.2	0.9	🟥 1.3

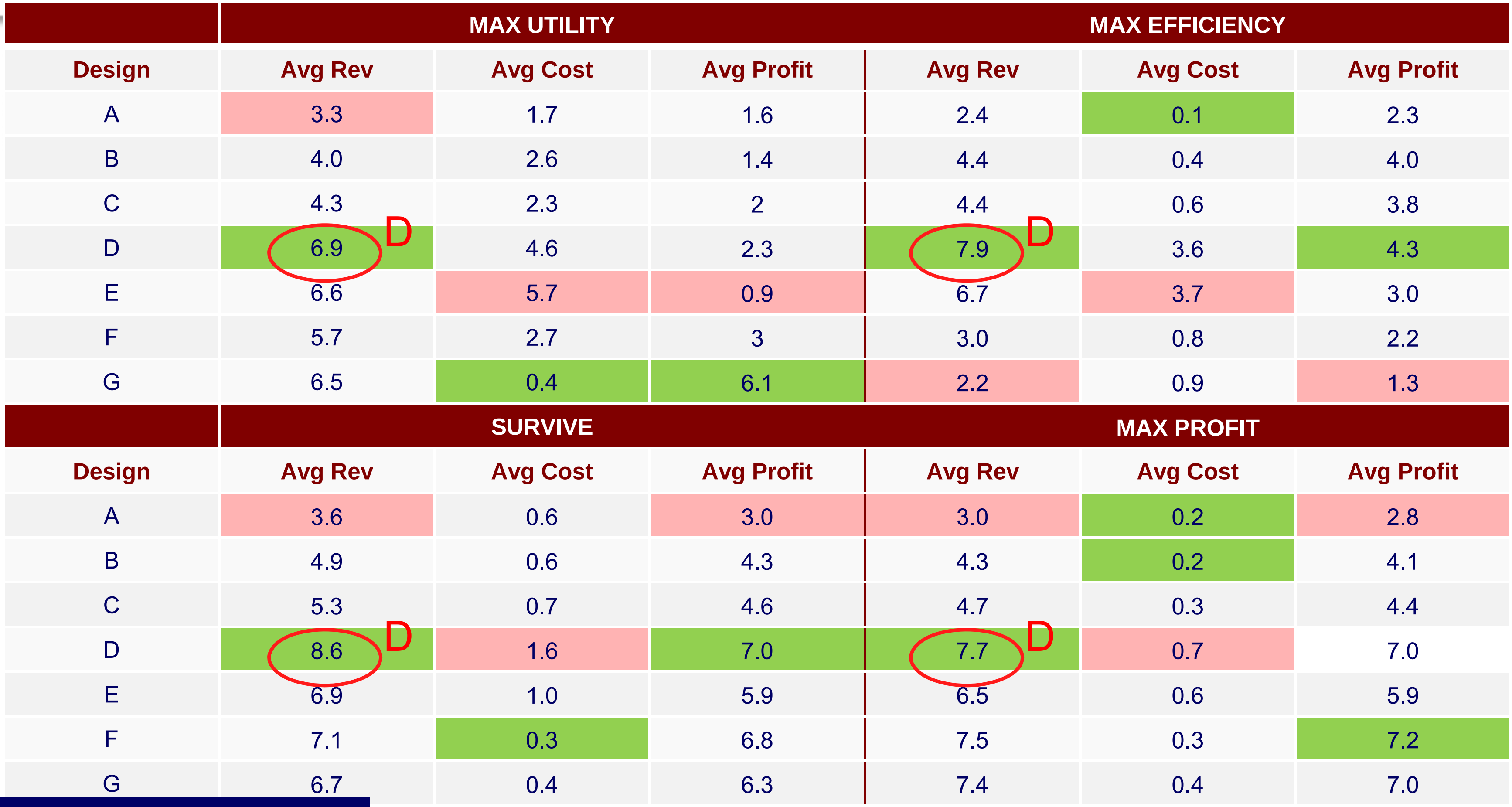
	SURVIVE			MAX PROFIT		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	🟥 3.6	0.6	🟥 3.0	🟥 3.0	🟩 0.2	🟥 2.8
B	4.9	0.6	4.3	4.3	🟩 0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	🟩 8.6	🟥 1.6	🟩 7.0 D	🟩 7.7	🟥 0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	🟩 0.3	6.8	7.5	0.3	🟩 7.2 F
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10^4\$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #1: 3 different designs have highest profits for the 4 strategies

Space Tug – Era-level Profit



Design	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10^4\$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #2: Design D has highest revenues for each

Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

#'s
1,2,3,5

	SURVIVE			MAX PROFIT		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x10^4\$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #3: Cheap DFC0 designs dominate the Max Efficiency strategy (but not the others)

Space Tug – Era-level Profit

	MAX UTILITY			MAX EFFICIENCY		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	🟥 3.3	1.7	1.6	2.4	🟩 0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	🟩 6.9	4.6	2.3	🟩 7.9	3.6	🟩 4.3
E	6.6	🟥 5.7	🟥 0.9	6.7	🟥 3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	🟩 0.4	🟩 6.1	🟥 2.2	0.9	🟥 1.3

	SURVIVE			MAX PROFIT		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	🟥 3.6	0.6	🟥 3.0	🟥 3.0	🟩 0.2	🟥 2.8
B	4.9	0.6	4.3	4.3	🟩 0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	🟩 8.6	🟥 1.6	🟩 7.0	🟩 7.7	🟥 0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	🟩 0.3	6.8	7.5	0.3	🟩 7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

Higher

Tie

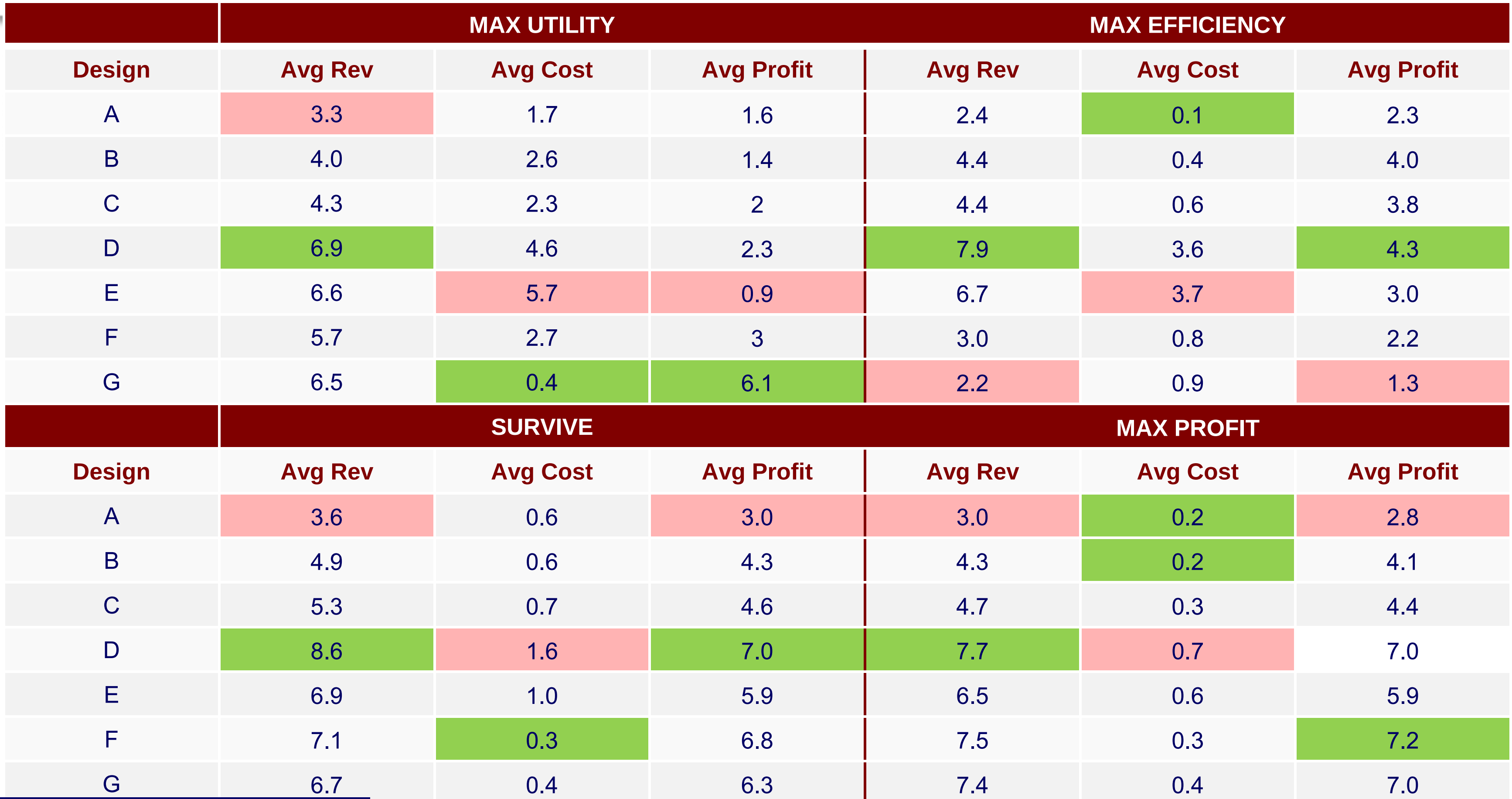
DFC2

All numbers are x10^4\$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #4: Survive strategy has higher projected long-term profits for non-DFC2 designs than the short-term profit maximization strategy

Space Tug – Era-level Profit



	MAX UTILITY			MAX EFFICIENCY		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

	SURVIVE			MAX PROFIT		
Design	**Avg Rev**	**Avg Cost**	**Avg Profit**	**Avg Rev**	**Avg Cost**	**Avg Profit**
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

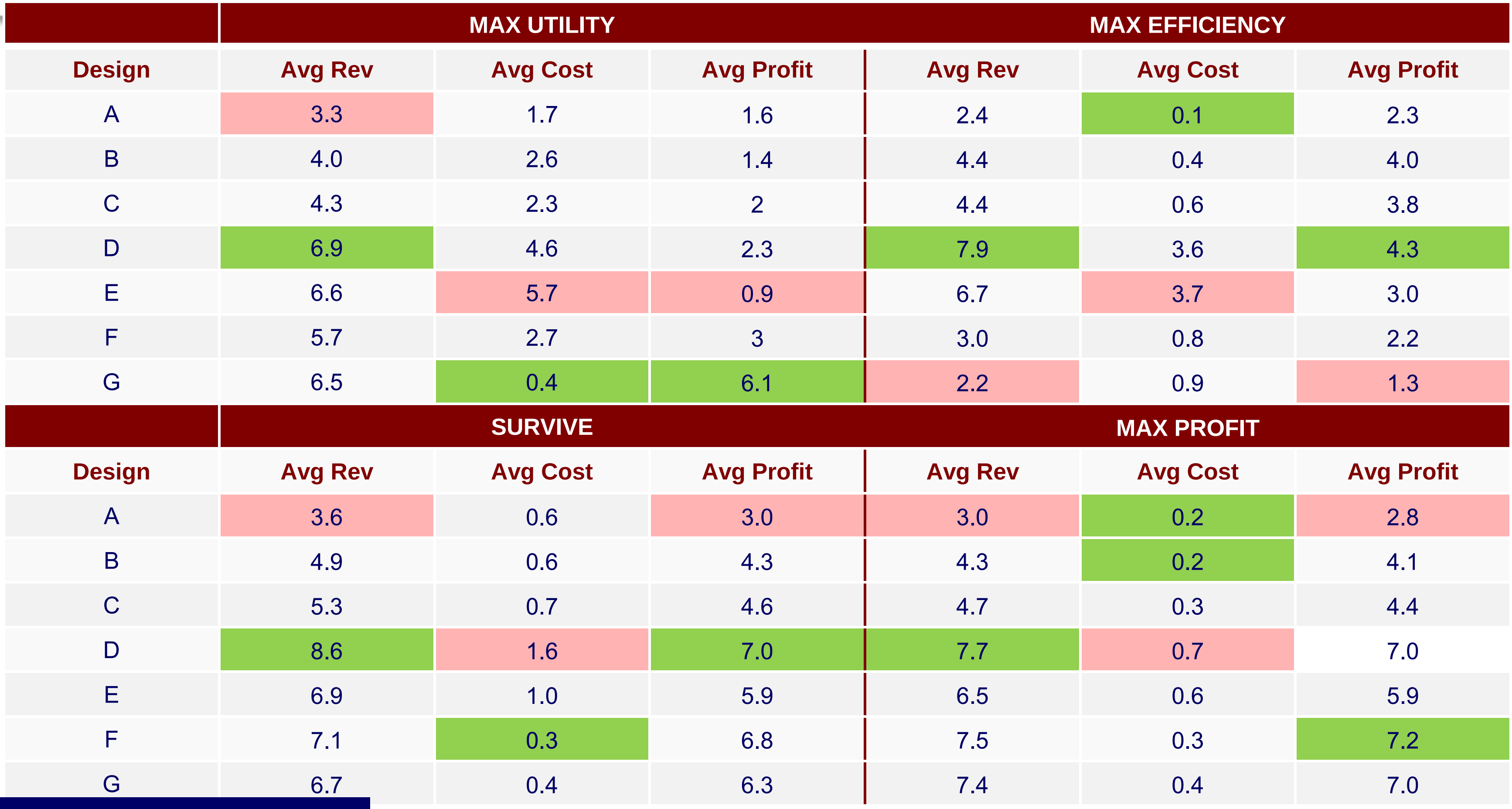
All numbers are x10^4\$M

Backgrounds are for BEST and WORST designs in that category for that strategy

Insight #5: Designs D and F have best average performance

D: rank 3,1,1,2
F: rank 2,6,2,1

Space Tug – Era-level Profit



	MAX UTILITY			MAX EFFICIENCY		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.3	1.7	1.6	2.4	0.1	2.3
B	4.0	2.6	1.4	4.4	0.4	4.0
C	4.3	2.3	2	4.4	0.6	3.8
D	6.9	4.6	2.3	7.9	3.6	4.3
E	6.6	5.7	0.9	6.7	3.7	3.0
F	5.7	2.7	3	3.0	0.8	2.2
G	6.5	0.4	6.1	2.2	0.9	1.3

	SURVIVE			MAX PROFIT		
Design	Avg Rev	Avg Cost	Avg Profit	Avg Rev	Avg Cost	Avg Profit
A	3.6	0.6	3.0	3.0	0.2	2.8
B	4.9	0.6	4.3	4.3	0.2	4.1
C	5.3	0.7	4.6	4.7	0.3	4.4
D	8.6	1.6	7.0	7.7	0.7	7.0
E	6.9	1.0	5.9	6.5	0.6	5.9
F	7.1	0.3	6.8	7.5	0.3	7.2
G	6.7	0.4	6.3	7.4	0.4	7.0

All numbers are x$10^4$$M

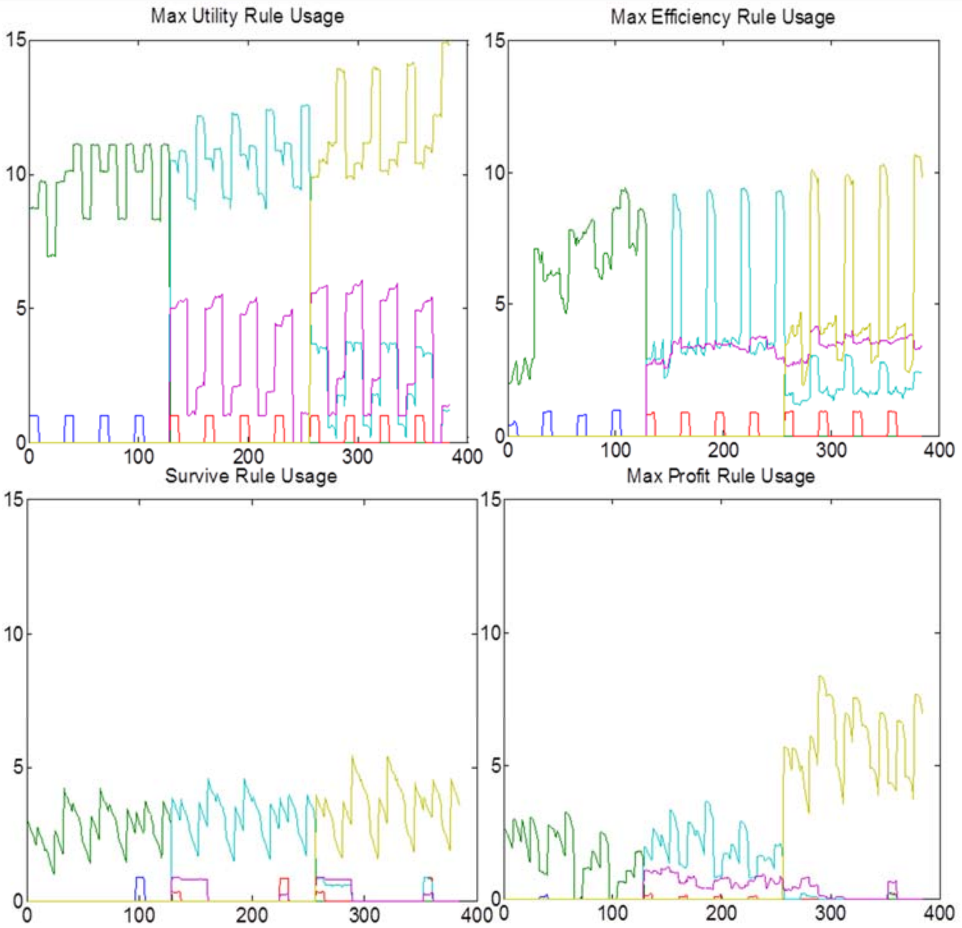
Backgrounds are for BEST and WORST designs in that category for that strategy

But overall:

Strategy selection has a large effect on performance for every design!

Space Tug – Rule Usage

X axis == design number
Y axis == average rule executions per era



- 🟦 Rule 1 – Cryo/Biprop switch
- 🟩 Rule 2 – Fuel tank resize
- 🟥 Rule 3 – Cryo/Biprop switch 2
- 🟦 Rule 4 – Fuel tank resize 2
- 🟪 Rule 5 – Change capability
- 🟨 Rule 6 – Refuel in orbit

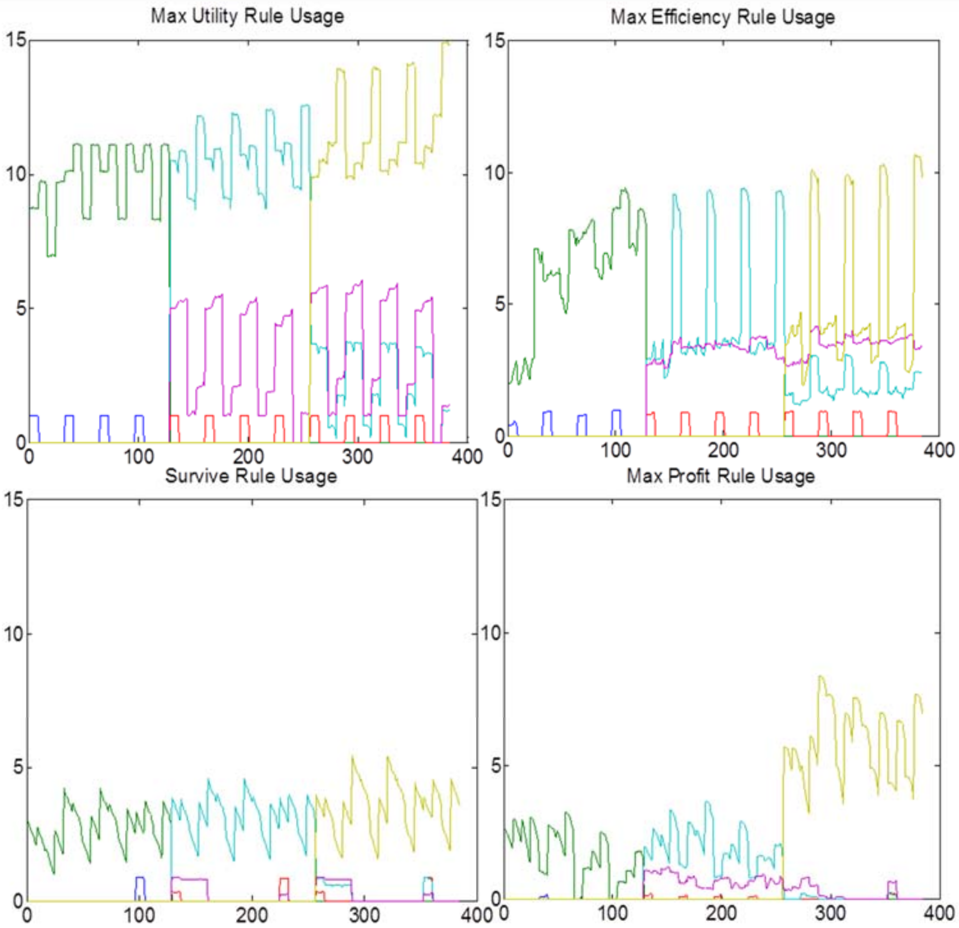
We count the number of executions for each change mechanism (transition “rule”) in an *average era*: revealing their relative frequency of use

Space Tug – Rule Usage

~10 total for DFC0,
~15 for others

X axis == design number
Y axis == average rule executions per era

- 🟦 Rule 1 – Cryo/Biprop switch
- 🟩 Rule 2 – Fuel tank resize
- 🟥 Rule 3 – Cryo/Biprop switch 2
- 🟦 Rule 4 – Fuel tank resize 2
- 🟪 Rule 5 – Change capability
- 🟨 Rule 6 – Refuel in orbit



~10 total for all

<5 total for all

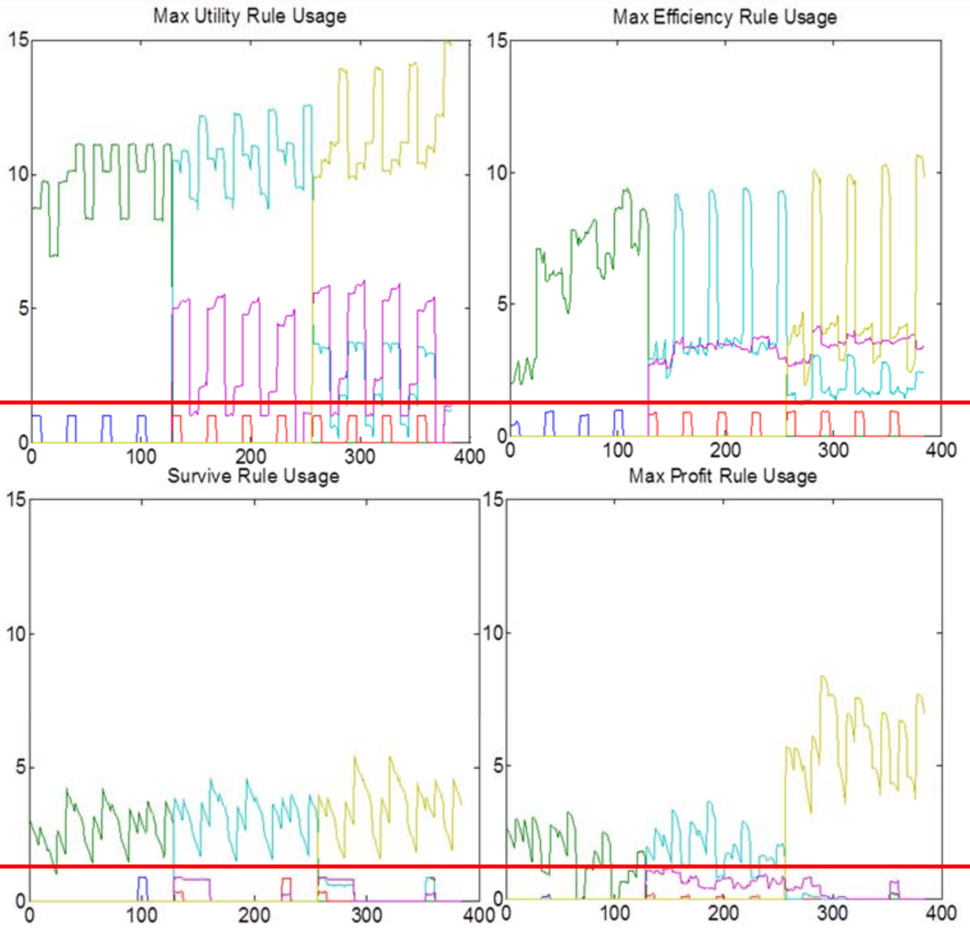
~5 total for DFC2,
<5 for others

Insight #1: Max Utility and Max Efficiency strategies have significantly more transitions than the others

Space Tug – Rule Usage

Rule removal could also be performed here to investigate the performance effects of eliminating those few transitions

X axis == design number
Y axis == average rule executions per era



- 🟦 Rule 1 – Cryo/Biprop switch
- 🟩 Rule 2 – Fuel tank resize
- 🟥 Rule 3 – Cryo/Biprop switch 2
- 🟦 Rule 4 – Fuel tank resize 2
- 🟪 Rule 5 – Change capability
- 🟨 Rule 6 – Refuel in orbit

Never averages more than once per era

Insight #2: Rules 1,3 are rarely used, could possibly save money by choosing not to invest in development **(also true of Rule 5 under Survive/Profit strategies)**

Space Tug – FPN Tracking

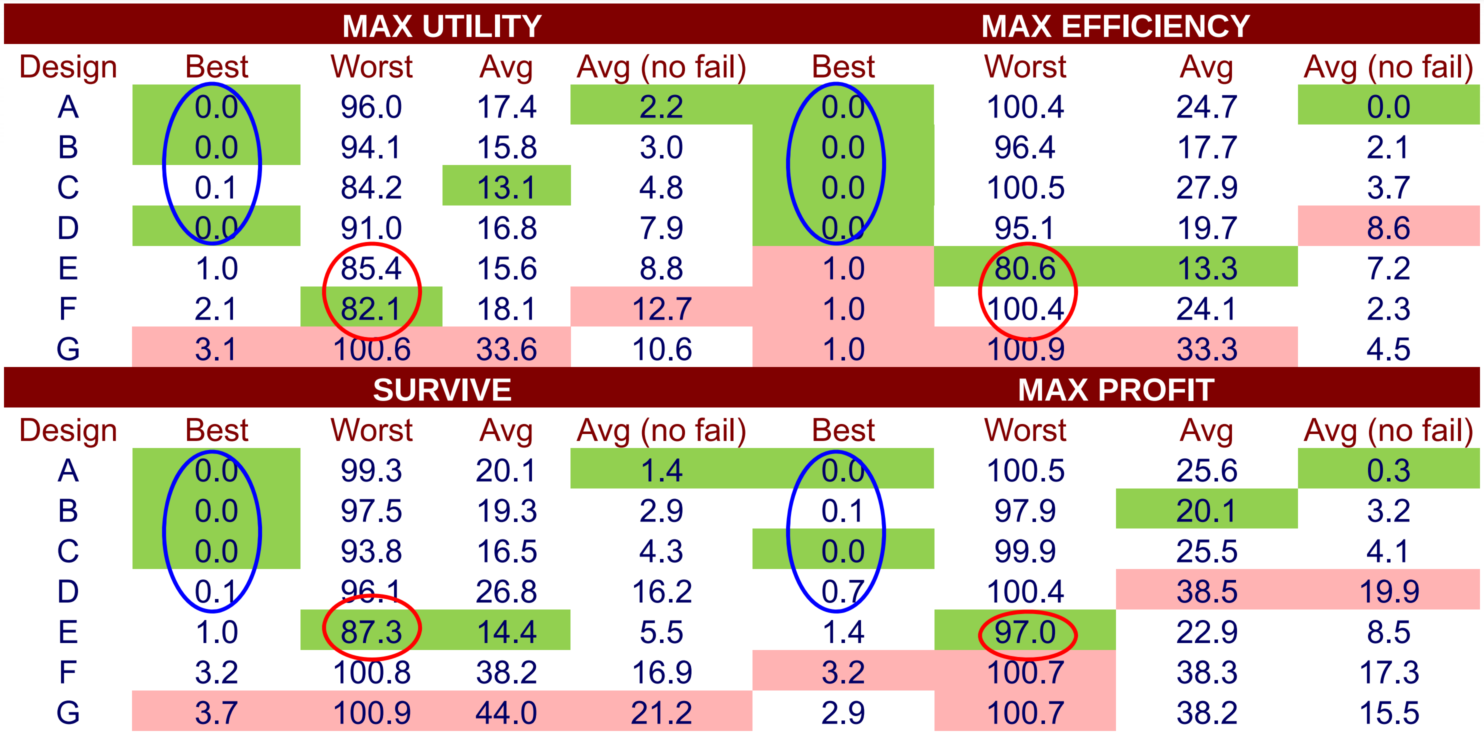
	MAX UTILITY				MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

	SURVIVE				MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

Remember that FPN is a pseudo-distance from the Pareto Front, so lower is better!

We can also track the designs' Fuzzy Pareto Number over the eras to get a sense of their continuing efficiency as they use fuel and execute design transitions

Space Tug – FPN Tracking



	MAX UTILITY				MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

	SURVIVE				MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

DFC0 designs tend to have better *best* FPNs
but higher DFCs have better *worst* FPNs

Insight #1: Changeability is avoiding worst case scenarios more than switching between optima

Space Tug – FPN Tracking

	MAX UTILITY				MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

	SURVIVE				MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

no-fail = A

with-fail = not A

Insight #2: Design A always has the best average when not considering inviable epochs, but is inviable too often to have the best overall average

Space Tug – FPN Tracking

	MAX UTILITY				MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

	SURVIVE				MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

When G is ranked last

Insight #3: Design **G** is regularly among the worst due to its high failure rate and high cost exceeding its marginal utility gains

Space Tug – FPN Tracking

	MAX UTILITY				MAX EFFICIENCY			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	96.0	17.4	2.2	0.0	100.4	24.7	0.0
B	0.0	94.1	15.8	3.0	0.0	96.4	17.7	2.1
C	0.1	84.2	13.1	4.8	0.0	100.5	27.9	3.7
D	0.0	91.0	16.8	7.9	0.0	95.1	19.7	8.6
E	1.0	85.4	15.6	8.8	1.0	80.6	13.3	7.2
F	2.1	82.1	18.1	12.7	1.0	100.4	24.1	2.3
G	3.1	100.6	33.6	10.6	1.0	100.9	33.3	4.5

	SURVIVE				MAX PROFIT			
Design	Best	Worst	Avg	Avg (no fail)	Best	Worst	Avg	Avg (no fail)
A	0.0	99.3	20.1	1.4	0.0	100.5	25.6	0.3
B	0.0	97.5	19.3	2.9	0.1	97.9	20.1	3.2
C	0.0	93.8	16.5	4.3	0.0	99.9	25.5	4.1
D	0.1	96.1	26.8	16.2	0.7	100.4	38.5	19.9
E	1.0	87.3	14.4	5.5	1.4	97.0	22.9	8.5
F	3.2	100.8	38.2	16.9	3.2	100.7	38.3	17.3
G	3.7	100.9	44.0	21.2	2.9	100.7	38.2	15.5

Ranks 3,1,1,1 in “worst” FPN
Ranks 2,1,1,2 in “avg” FPN

→

Robust in efficiency of changeability

Insight #4: Design E appears to be the best compromise between the strategies (potentially valuable if strategy will change over time)

Space Tug – Cost/Benefit

D is not changeable… what if we added changeability?

DFC1 counterpart: Design 256
DFC2 counterpart: Design 384

→ Let's investigate these briefly

Assume for now that Profit is our biggest goal in design selection, we want to decide what the cost/benefits to profit of increasing changeability are under the Maximize Profit strategy

Maximize Profit
Avg 10-year Era

Design	Revenue (10^4 \$M)	Cost (10^4 \$M)	Profit (10^4 \$M)
D	7.7	0.7	7
256	7.4	0.8	6.6
384	10.7	0.3	10.4

So maybe we are interested in Design 384, but that changeability comes at an increased Base Cost, which could present a challenge if funds are limited

Base Cost D → 384 = 3020 → 3564 = +544 $M

Thus the decision is between $544M up front and $34B over ten years

This "going rate" between changeability and some goal can be calculated for any design with any metric deemed critically important: perhaps Met Contracts or Avg FPN

Space Tug – "Going Rates"

-DFC tradeoff	**Design**	**+DFC tradeoff**
N/A	**D**	+$544M initial cost, +$34B profit over 10 years
-$80M initial cost, -$4B profit over 10 years	**E**	+$80M initial cost, +$21B profit over 10 years
-$384M initial cost, -$20B profit over 10 years	**F**	N/A

- Thus, the final decision will be made with a small set of designs of interest, selected for varying abilities to be valuable (rarely inviable, high utility across many epochs, very changeable, etc)
- Robust vs changeable designs should be identified, with "going rates" for changeability established to consider small variations which may prove valuable

Conclusions

- Multi-Epoch Analysis offers some different insights
  - Often performed first due to lower costs/assumptions
  - Slightly lower fidelity

- no randomization / simulation
- no time-ordering effects or direct passive/active comparison

If interested: see our next presentation!

Above that, Era Analysis offers:

- – Direct value comparison of passively robust and changeable designs
- – Establishment of “going rate” cost/benefit of changeability
- – Quantification of full lifecycle performance, exploration of how changeability is utilized

Thank you!

Questions?

References

[1] A.M. Ross, D.H. Rhodes, and D.E. Hastings, "Defining Changeability : Reconciling Flexibility , Adaptability , Scalability , Modifiability , and Robustness for Maintaining System Lifecycle Value," *Systems Engineering, vol. 11, 2008, pp. 246-262.*

[2] A.M. Ross and D.E. Hastings, "Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration," *AIAA Space 2006, 2006, pp. 1-18.*

[3] A.M. Ross, H.L. McManus, D.H. Rhodes, and D.E. Hastings, "Responsive Systems Comparison Method : Dynamic Insights into Designing a Satellite Radar System," *AIAA Space 2009, 2009, pp. 1-25.*

[4] L. Viscito and A.M. Ross, "Quantifying Flexibility in Tradespace Exploration : Value Weighted Filtered Outdegree," *AIAA Space 2009, 2009, pp. 1-9.*

[5] S. Mathews and V. Datar, "A Practical Method for Valuing Real Options: The Boeing Approach," *Journal of Applied Corporate Finance, vol. 19, 2007, pp. 95-104.*

[6] R.D. Neufville, S. Scholtes, and T. Wang, "Real Options by Spreadsheet: Parking Garage Case Example," *Journal of Infrastructure Systems, vol. 12, 2006, p. 107.*

[7] A.M. Ross and D.H. Rhodes, "Using Natural Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," *INCOSE 2008, 2008.*

[8] R.M. Smaling, "System Architecture Analysis and Selection Under Uncertainty," MIT PhD thesis, Engineering Systems Division, 2005.

More about VASC

M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "A Method Using Epoch-Era Analysis to Identify Valuable Changeability in System Design," *CSER 2011, 2011.*

Forthcoming

M.E. Fitzgerald and A.M. Ross, "Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain," *IEEE Syscon 2012, 2012.*

M.E. Fitzgerald and A.M. Ross, "Sustaining Lifecycle Value: Valuable Changeability Analysis with Era Simulation," *IEEE Syscon 2012, 2012.*

M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "Assessing Uncertain Benefits: a Valuation Approach for Strategic Changeability (VASC)," *INCOSE International Symposium 2012, 2012.*

M.E. Fitzgerald, A.M. Ross, and D.H. Rhodes, "Quantifying the Effect of Changeability on Value, Cost, and Schedule for a Satellite Radar System," *AIAA Space 2012, 2012.*

Other related work

M.G. Richards, A.M. Ross, N.B. Shah, and D.E. Hastings, "Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration," *Journal of Spacecraft and Rockets, vol. 46, Sep. 2009, pp. 1049-1064.*

S.C. Myers, "Finance Theory and Financial Strategy," *Interfaces, vol. 14, Jan. 1984, pp. 126-137.*

J. Saleh, G. Mark, and N. Jordan, "Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems," *Journal of Engineering Design, vol. 20, Jun. 2009, pp. 307-323.*

E. Fricke and A.P. Schulz, "Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle," *Systems Engineering, vol. 8, 2005, pp. 342-359.*

J. Mun and T. Housel, *A Primer on Applying Monte Carlo Simulation , Real Options Analysis , Knowledge Value Added , Forecasting , and Portfolio Optimization Acquisitions White Paper A Primer on Decision and Risk Analysis, Monterey, CA: 2010.*

M.R. Silver and O.L. de Weck, "Time-expanded decision networks: A framework for designing evolvable complex systems," *Systems Engineering, vol. 10, 2007, pp. 167-188.*