SEA RI

Systems Engineering Advancement Research Initiative

"Evaluating System Change Options and Timing Using the Epoch Syncopation Framework"

Daniel O. Fulcoly, Adam M. Ross, and Donna H. Rhodes
Massachusetts Institute of Technology

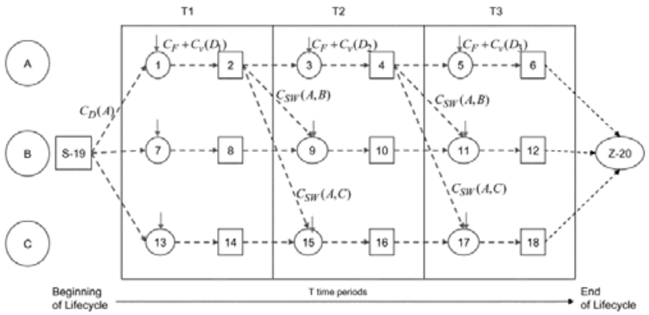
CSER 2012
St. Louis, 19-22 March 2012

Definitions

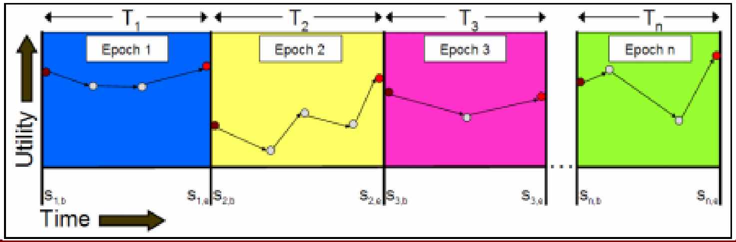
- Epoch: a set of fixed contexts and needs that a system operates in
- Era: a time-ordered sequence of epochs
- Evolvability: the ability of a design to change its architecture between generations with inheritance
- Epoch Syncopation Framework (ESF): a method for evaluating designs, change mechanisms, and change strategies through Monte Carlo analysis of eras

Motivation

- Decisions early in the design process have far-reaching implications
- Simulating the entire lifecycle of a system provides unique insights
- Evolvable changes become more important as cost and complexity increase
- Existing methods
  - Time-Expanded Decision Networks[1]



  - Epoch-Era Analysis[2]

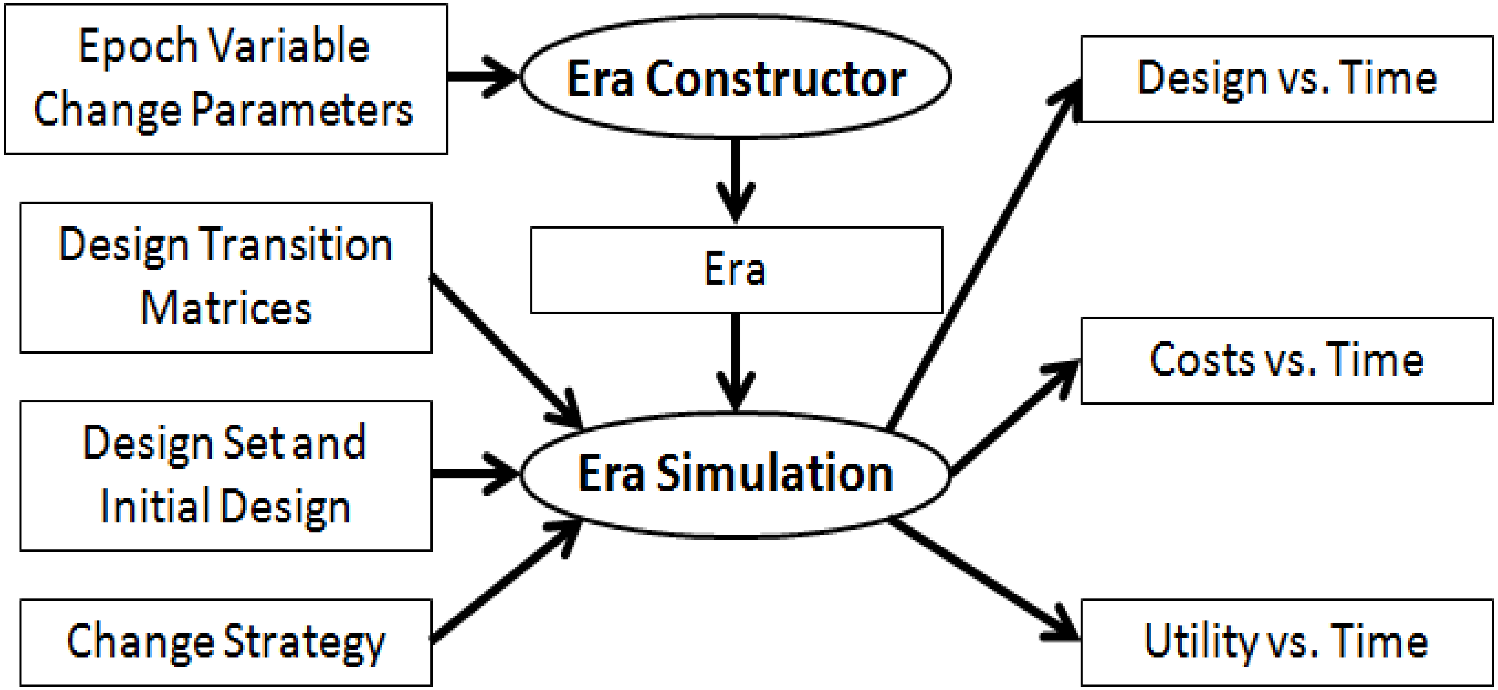


Examining the way a design will propagate through possible eras can provide valuable insights

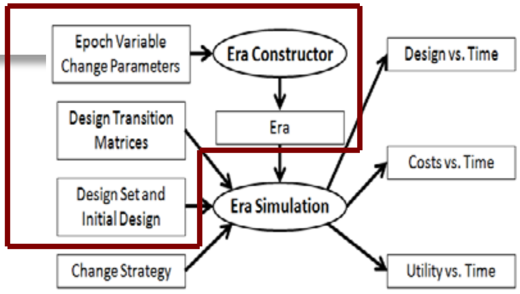
1. M. Silver, O. de Weck, "Time-expanded decision networks: a framework for designing evolvable complex systems," Systems Engineering, vol. 10(2), 2007.
2. Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008

ESF Overview

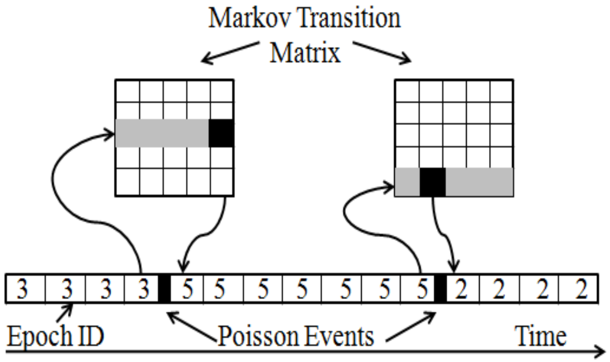
- Perform tradespace exploration of a design set given allowed transitions and predicted changes in context
- Given expected contexts, identify valuable:
  - Initial designs, path enablers, and change strategies



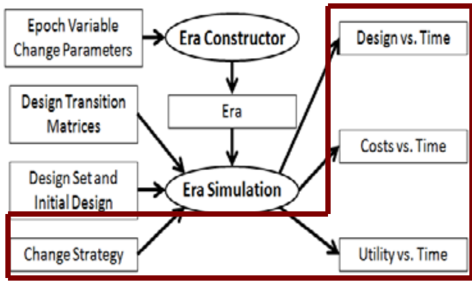
Inputs to ESF



- Design set and initial design
  - Includes initial cost and schedule
  - Performance model maps design variables to attributes
  - Path enablers included in initial cost and schedule
- Transition Matrices
  - Contains transition costs and schedules
  - A transition cost can be a function of current state, desired state, current epoch, or past uses of a transition
- Markov Probability Era Constructor
  - Creates input era for ESF based on change parameters of epoch variables
  - Treats shifts in epoch variables as Poisson events
  - When shifts occur, Markov transition matrix is to determine new state



Change Strategies and Outputs



- Change strategies determine when and how a system changes as well as to what design
  - Strategy 1: "Always seek highest utility"
  - Strategy 2: "Always stay above threshold"
  - Strategy 3: "Stay above threshold at set generation lengths"
- Outputs for each era simulation
  - Lifecycle cost versus time vector
  - Design number versus time vector
  - Utility versus time vector
- Metrics applied to outputs
  - Lifecycle cost (initial design cost and cost of all executed transitions)
  - Time below threshold (number of steps where utility was below a predetermined value)
  - Time-weighted average utility (mean value of system utility over entire era)

APPLICATION TO SPACE TUG[3]

3. McManus, H. and Schuman, T. “Understanding the Orbital Transfer Vehicle Trade Space,” proceedings of AIAA Space 2003, Long Beach, CA, Sept. 2003.

Space Tug Epoch Variables

- 2 variables: mission (preference set) and technology level
- Technology is either "present" or "future"
  - Mean time between shifts: 8 years
  - Can only transition from present to future

Technology	To Present	To Future
From Present	0	1
From Future	0	1

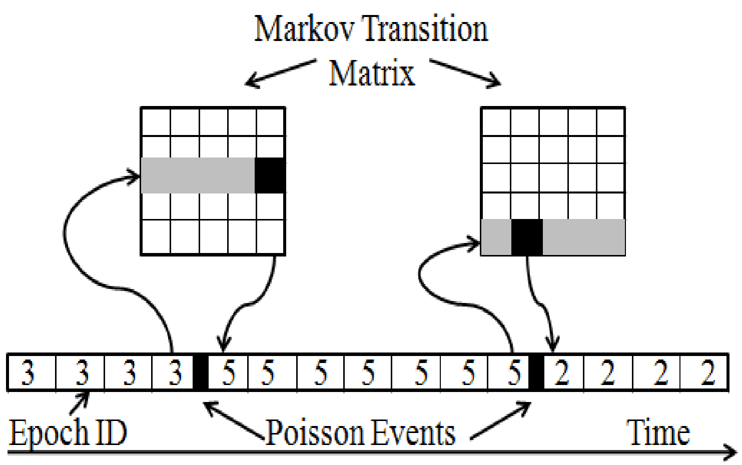
- 8 Missions: (1) baseline, (2) technology demonstration, (3) GEO rescue, (4) deployment assistance, (5) refueling and maintenance, (6) garbage collector, (7) all-purpose military, and (8) satellite saboteur
  - Average mission duration: 4 years
  - Treated as contracts

Mission	To 1	To 2	To 3	To 4	To 5	To 6	To 7	To 8
From 1	0.300	0.400	0.050	0.050	0.050	0.050	0.050	0.050
From 2	0.050	0.150	0.133	0.133	0.133	0.133	0.133	0.133
From 3	0.150	0.050	0.500	0.060	0.060	0.060	0.060	0.060
From 4	0.150	0.050	0.060	0.500	0.060	0.060	0.060	0.060
From 5	0.150	0.050	0.060	0.060	0.500	0.060	0.060	0.060
From 6	0.150	0.050	0.060	0.060	0.060	0.500	0.060	0.060
From 7	0.150	0.050	0.038	0.038	0.038	0.038	0.500	0.150
From 8	0.150	0.050	0.038	0.038	0.038	0.038	0.150	0.500

Space Tug Epoch Variables

- 2 variables: mission (preference set) and technology level
- Technology is either "present" or "future"
  - Mean time be
  - Can only tran
- 8 Missions: (1) b ... ation, (3) GEO rescue, (4) depl ... nd maintenance, (6 ... e military, and (8) satellite sabo
  - Average miss
  - Treated as co

Technology	To Present	To Future
From Present	0	1
[illegible]e	0	1



These transition matrices and duration parameters will be used to construct the eras

Mission	To 1	To 2	To 3	To 4	To 5	To 6	To 7	To 8
From 1	0.300	0.4[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.050	0.050
From 2	0.050	0.1[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.133	0.133
From 3	0.150	0.0[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.060	0.060
From 4	0.150	0.05[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.060	0.060
From 5	0.150	0.050	0.060	0.060	0.500	0.060	0.060	0.060
From 6	0.150	0.050	0.060	0.060	0.060	0.500	0.060	0.060
From 7	0.150	0.050	0.038	0.038	0.038	0.038	0.500	0.150
From 8	0.150	0.050	0.038	0.038	0.038	0.038	0.150	0.500

Space Tug Design Set[3]

- 4 Design Variables
- "DfE" represents inclusion of evolvability design principles (modularity, margin, etc.) with cost/schedule penalties

Design Variables	Levels
Manipulator Mass (kg)	[300, 1000, 3000, 5000]
Propulsion System	Storable BiPropellant, Cryogenic, Electric, Nuclear
Fuel Mass (kg)	[30, 100, 300, 600, 1200, 3000, 10000, 30000]
DfE (% Mass Penalty)	[0, 20]

- Propulsion type and DfE determine architecture for this simulation
- Schedule calculated based on architecture

Propulsion System	Isp (sec)	Base Mass (kg)	Mass Fract.	Fast?	Baseline Schedule (months)
Storable BiProp	300	0	0.12	Y	8
Cryo	450/550	0	0.13	Y	9
Electric	3000	25	0.25/.3	N	10
Nuclear	1500	1000/600	0.20	Y	12

- Where 2 values are given: (Present Tech/Future Tech)
- 2 month penalty added to initial schedule if DfE included

3. McManus, H. and Schuman, T. "Understanding the Orbital Transfer Vehicle Trade Space," proceedings of AIAA Space 2003, Long Beach, CA, Sept. 2003.

DfE Transitions

- Single transition mechanism: “redesign with inheritance”
- If current design does not include DfE, redesign cost is just the cost of the new design
- If current design includes DfE, mass of continuing components reduced by “reuse advantage”
  - Mass maps to cost in space tug
  - Redesign advantage = 50% in this simulation
- Redesign schedule is the same as initial schedule if DfE is not included in current design
- If current design has DfE, initial schedule is reduced by evolvability advantage to get redesign schedule
  - Evolvability advantage = 3 months
  - No penalty or advantage for discontinuing DfE

“Redesign with inheritance” is used to illustrate the way a transition rule would be implemented, not a proposed model

Example Data

- Gave the same era and starting design to each strategy
  - Chart below shows the initial epoch and 4 subsequent epoch shifts

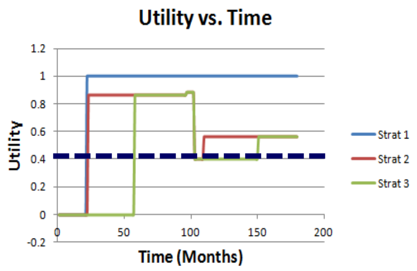
Month	1	12	78	96	102
Mission	1	3	3	8	4
Tech	Present	Present	Future	Future	Future
Epoch ID	1	3	11	16	12

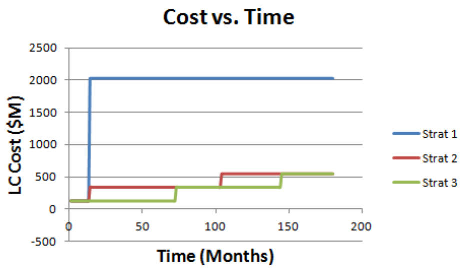
- Starting design was 155
  - 300 kg manipulator, electric propulsion, 300 kg fuel, includes DfE
- 40th percentile used for strategies 2 and 3
- 4 year generation length used for strategy 3
- Aggregate data shown here:
- Strategy 1 has better performance, but at 4 times the cost

Strategy	LC Cost ($M)	Time Below (Months)	TWAU
Strat 1	2,030	21	0.8833
Strat 2 (40)	549	22	0.6195
Strat 3 (40/4 yrs)	549	57	0.4157

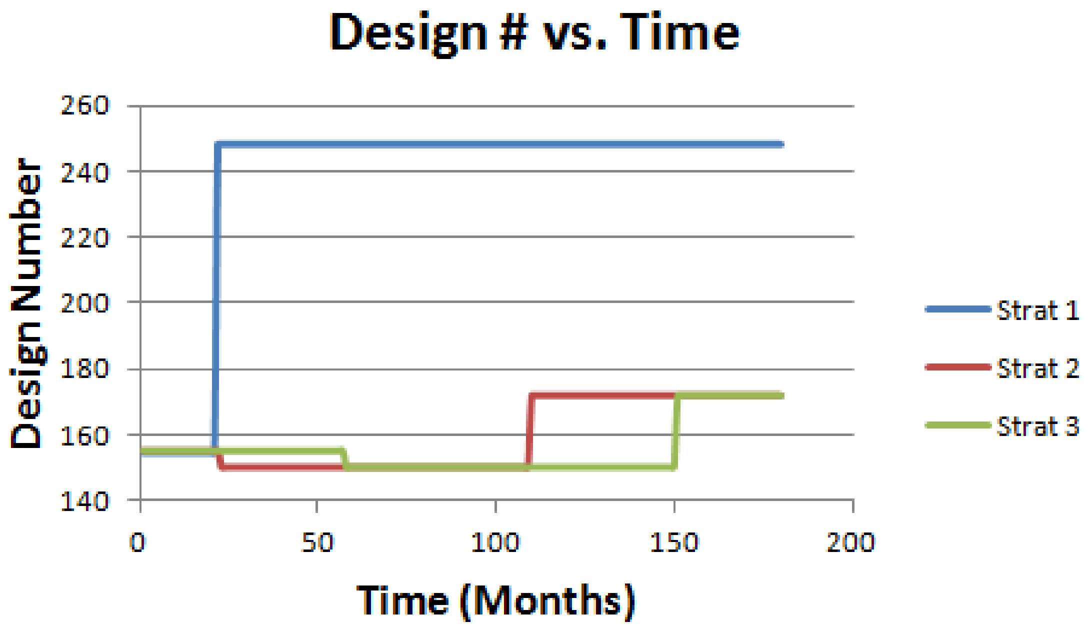
These results capture overall performance, but give us little information about what happened during the era.

Example Trajectories



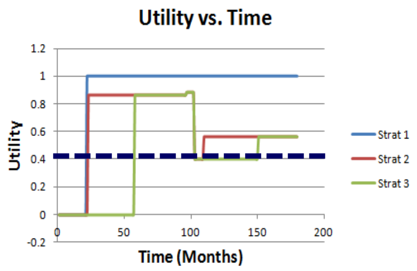


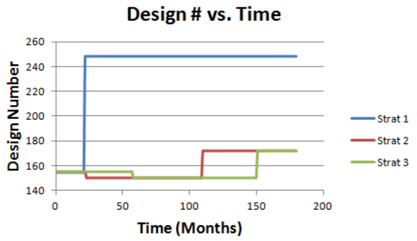
Strategy 1: "Always seek highest utility"
Strategy 2: "Always stay above threshold"
Strategy 3: "Stay above threshold at set generation lengths"

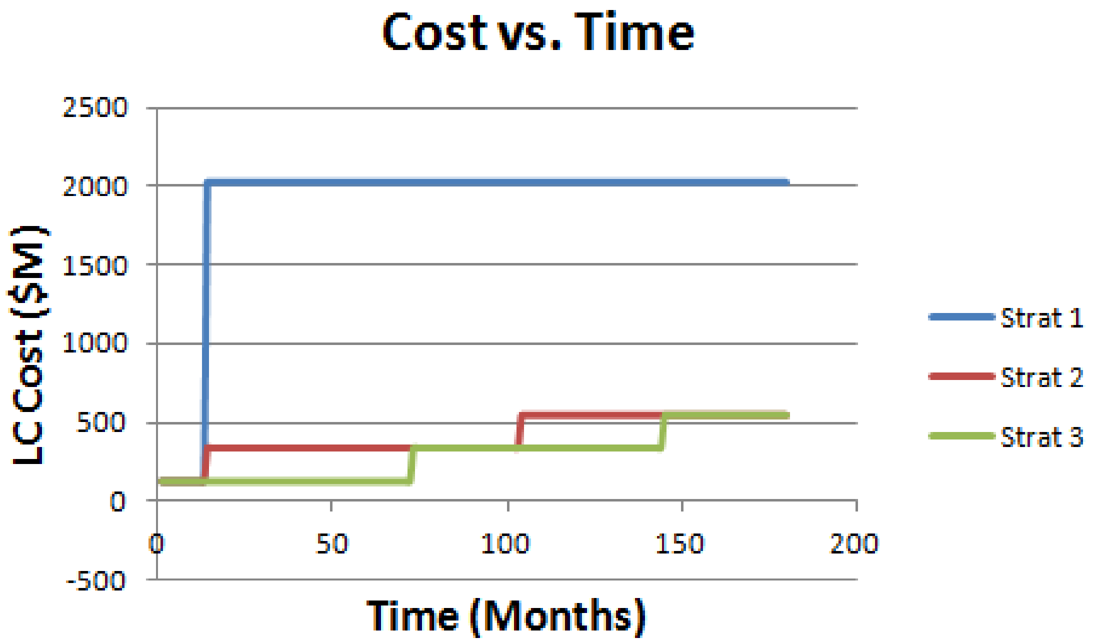


Example Trajectories

Strategy 1: "Always seek highest utility"
Strategy 2: "Always stay above threshold"
Strategy 3: "Stay above threshold at set generation lengths"

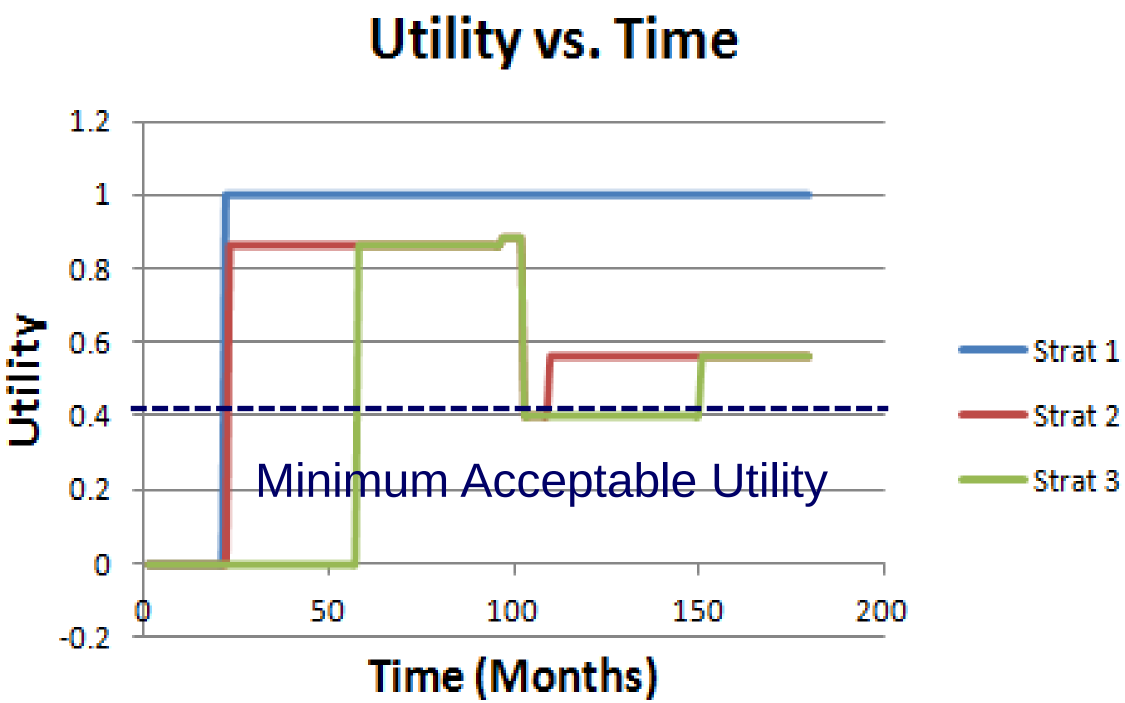


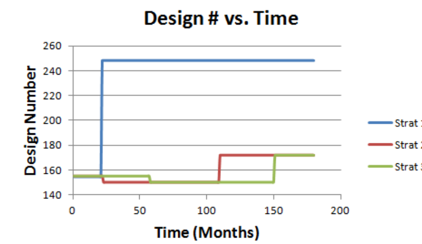


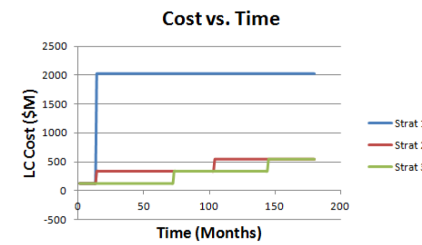


Example Trajectories

Strategy 1: “Always seek highest utility”
Strategy 2: “Always stay above threshold”
Strategy 3: “Stay above threshold at set generation lengths”

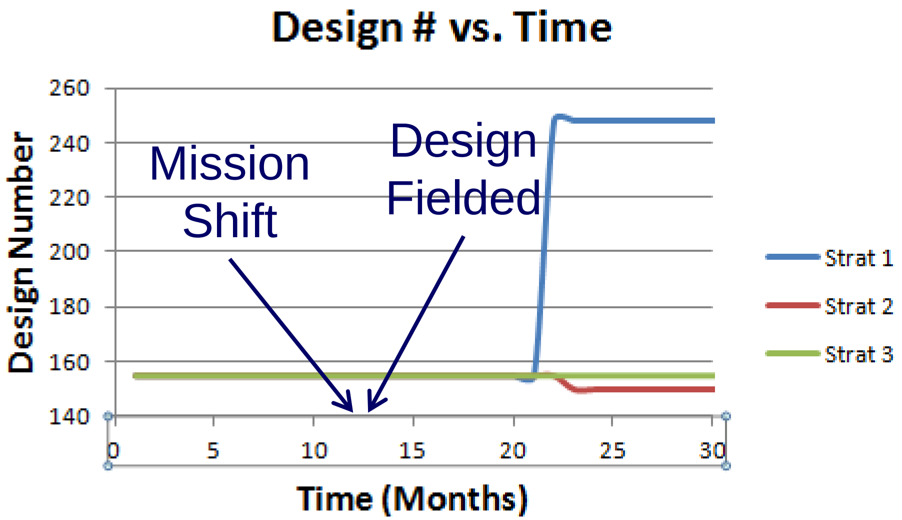






Example Data Discussion

- When Design 155 was fielded in month 13, the mission had just changed from 1 to 3 (month 12)
  - Mission 1 Utility (Design 155) = 0.65
  - Mission 3 Utility (Design 155) = 0 (slow mover)
  - Redesign immediately initiated in strategies 1 and 2
- Strategy 3 trajectories reached same values as strategy 2 trajectories, but lagged
  - Same logic applied at different points in era
- Here strategy 3 was dominated by strategy 2 in all categories
  - Not always the case, especially with volatile eras



Setting up Simulation

- 11 “trials” simulated
- Each trial has a single change strategy
- Each trial simulates 1,000 stochastically generated eras
  - Convergence verified execution
- For each era, every starting design is paired with the era for simulation
- ESF executed 256,000 times for each trial
- Era length was 15 years
- Minimum acceptable utility was 0.4

Trial	Strategy	Threshold Percentile	Years
1	1	-	-
2	2	20	-
3	2	40	-
4	2	60	-
5	2	80	-
6	3	40	2
7	3	40	4
8	3	40	6
9	3	80	2
10	3	80	4
11	3	80	6

Trial Results and Discussion

Trial	Average LC Cost ($M)	Lowest LC Cost ($M)	Average Time Below (months)	Lowest Time Below (months)	Average TWAU	Highest TWAU
1	***3501***	***2403***	***13.76***	***8.00***	***0.910***	***0.937***
2	***1282***	***324***	***52.08***	9.00	0.511	0.931
3	1491	518	34.07	9.67	0.547	0.931
4	2158	1056	20.60	9.13	0.623	0.931
5	2646	1442	18.20	9.88	0.732	0.931
6	1423	466	42.81	9.00	0.524	0.931
7	1340	395	45.23	9.00	0.500	0.931
8	1297	360	48.83	8.90	***0.482***	0.931
9	2379	1244	24.82	***10.44***	0.683	0.931
10	2056	992	31.56	10.33	0.627	0.931
11	1902	874	37.68	10.01	0.584	0.931

- Strategy 1 dominates in utility and time below threshold, but at a very high cost
  - Few transitions between most expensive designs

Trial Results and Discussion

	Trial	Average LC Cost ($M)	Lowest LC Cost ($M)	Average Time Below (months)	Lowest Time Below (months)	Average TWAU	Highest TWAU
	1	***3501***	***2403***	***13.76***	***8.00***	***0.910***	***0.937***
20	2	***1282***	***324***	***52.08***	9.00	0.511	0.931
40	3	1491	518	34.07	9.67	0.547	0.931
60	4	2158	1056	20.60	9.13	0.623	0.931
80	5	2646	1442	18.20	9.88	0.732	0.931
40	6	1423	466	42.81	9.00	0.524	0.931
40	7	1340	395	45.23	9.00	0.500	0.931
40	8	1297	360	48.83	8.90	***0.482***	0.931
80	9	2379	1244	24.82	***10.44***	0.683	0.931
80	10	2056	992	31.56	10.33	0.627	0.931
80	11	1902	874	37.68	10.01	0.584	0.931

- As utility threshold increases for strategies 2 and 3
  - LC cost increases, time below acceptability decreases, utility increases

Trial Results and Discussion

	Trial	Average LC Cost ($M)	Lowest LC Cost ($M)	Average Time Below (months)	Lowest Time Below (months)	Average TWAU	Highest TWAU
	1	***3501***	***2403***	***13.76***	***8.00***	***0.910***	***0.937***
	2	***1282***	***324***	***52.08***	9.00	0.511	0.931
	3	1491	518	34.07	9.67	0.547	0.931
	4	2158	1056	20.60	9.13	0.623	0.931
	5	2646	1442	18.20	9.88	0.732	0.931
2	6	1423	466	42.81	9.00	0.524	0.931
4	7	1340	395	45.23	9.00	0.500	0.931
6	8	1297	360	48.83	8.90	***0.482***	0.931
2	9	2379	1244	24.82	***10.44***	0.683	0.931
4	10	2056	992	31.56	10.33	0.627	0.931
6	11	1902	874	37.68	10.01	0.584	0.931

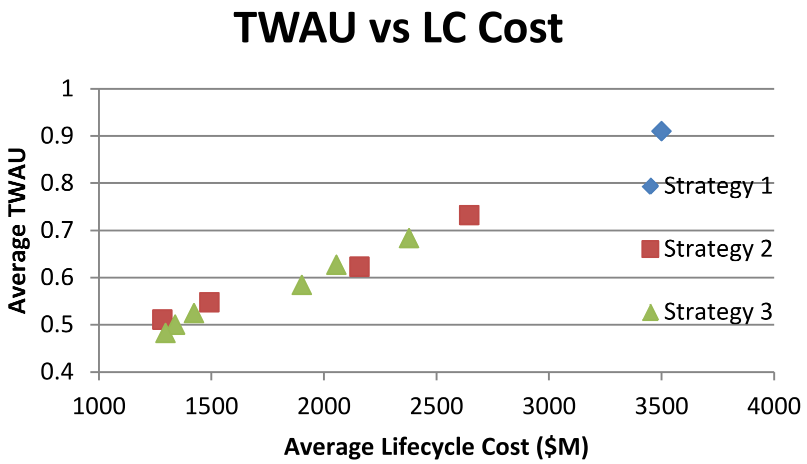
- As generation length increases for strategy 3
  - Lifecycle cost decreases, utility decreases
  - Fewer transitions means fewer chances to correct poor performance

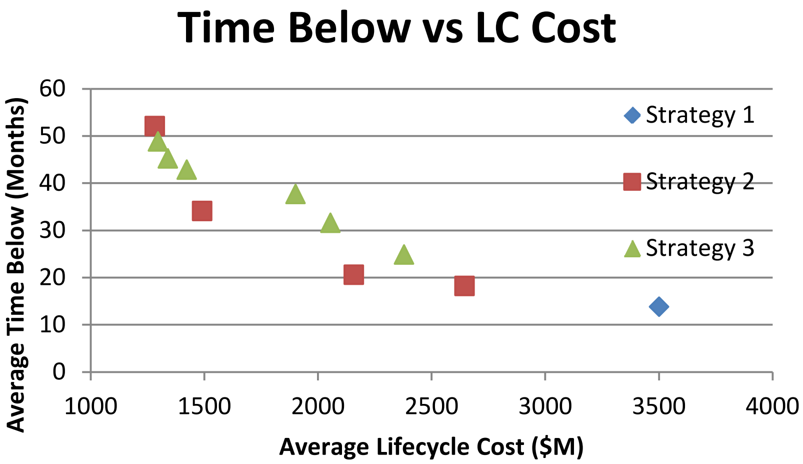
Discussion Cont'd

- The best performing designs with respect to lifecycle cost showed the following:
  - 300 kg manipulator mass, Nuclear or Electric propulsion
  - 30-300 kg of fuel, included DfE
  - Did not include expensive, potentially unnecessary options
- The best performing designs with respect to time below acceptability and TWAU showed the following:
  - 3,000-5,000 kg manipulator mass, any propulsion other than electric
  - 30,000 kg of fuel, no DfE included
  - Expensive, but high performance in most epochs
    - DfE not needed since they rarely needed to transition

Space Tug Conclusions

- Space tug case study
  - For minimizing lifecycle cost, strategy 3 was best overall, particularly with low utility thresholds and longer generations
  - Strategy 1 was best for minimizing time below acceptability and maximizing utility
- Are the utility and time benefits worth the extra cost?





Conclusions

- ESF provides insights not seen in other methods
  - The sequencing of epochs impacts performance
  - The timing impacts of executing a change mechanism impact performance

ESF Future Work

- Refine era constructor stochastic modeling
  - Have transition matrix become a function of time between shifts for certain types of epoch variables
- Develop more change strategies
- Apply to more data sets
  - More system examples
  - SoS applications

QUESTIONS?