Designing for System Value Sustainment using Interactive Epoch Era Analysis

Space Tug Case Study

Mike Curry and Adam Ross
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Outline

- Motivation
- Background
  - EEA
  - Prior EEA Frameworks
  - Visual Analytics
- Hypotheses
- IEEA Framework
- Space tug case study
- Summary

Motivation and Challenges

Motivation

- Development of “resilient” systems identified by DoD as a **strategic research priority**
- Desire **sustained value** delivery from systems in spite of perturbations in design, context or needs over time
- **Epoch-Era Analysis (EEA)** considers the time varying needs of stakeholders and evolving contexts in which the system operates, but challenges remain

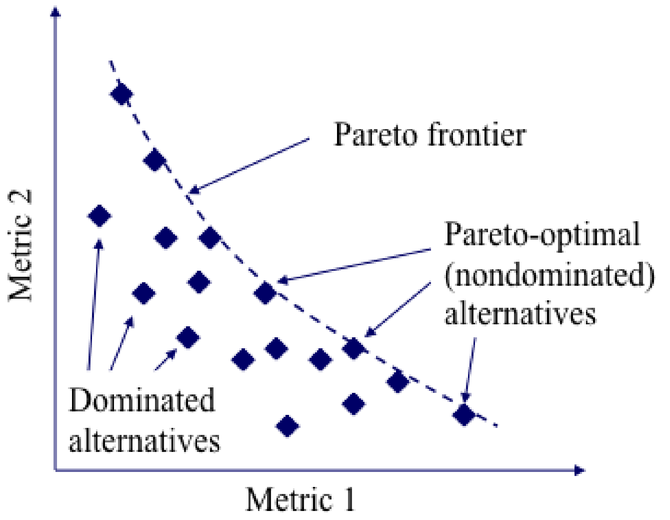
Challenges

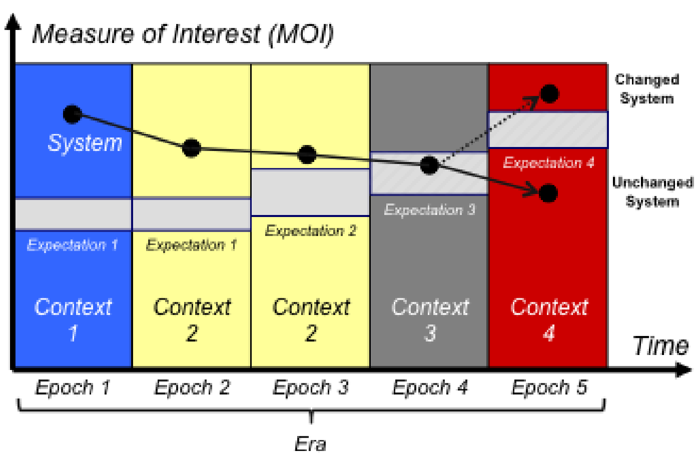
- Need framework that explicitly considers **human interaction** during EEA to comprehend and make decisions
- **Visual and analytic methods** for making sense of high-dimensional multivariate data
- **Methods and metrics** for assessment of path-dependent drivers of value in dynamic environments that allow the identification of long-term strategies

Background (EEA)

- Tradespace exploration tends to focus on analysis of system alternatives within a static context and needs [20]

- EEA conceptualizes the effects of time and changing context on a system [4,5]
  - Epochs: periods of fixed context and needs (short run)
  - Eras: sequences of epochs simulating a potential future experienced by the system (long run)





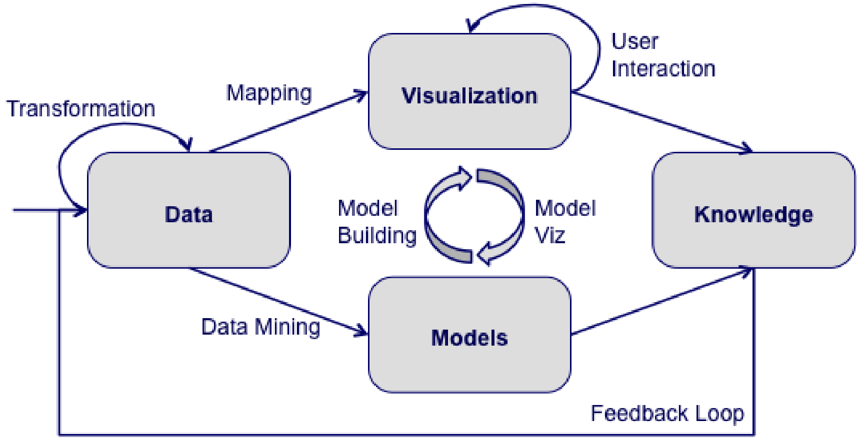
Background (EEA Frameworks)

- RSC is a method for applying EEA developed to study system value sustainment through changeability **[6,7]**
- RMACS expanded RSC processes and explored the application of multi-attribute expense (MAE) to more effectively capture all resources expenditures required to realize a given system **[8]**
- Key challenges:
  - **Volume and complexity of data** when conducting analysis across a potentially large number of epochs and eras
  - **Sense-making** when attempting to extract useful and actionable information from the analyses

Background (Visual Analytics)

- Research in the field of visual analytics has demonstrated advantages/insights that can be gained by allowing humans to interact with and visualize data

- Enhance analysts ability to understand and communicate data through interactive visualization and analysis applications



Visual analytics combines **automated analysis** with **interactive visualizations** for effective understanding, reasoning and decision making on the basis of a very large and complex dataset **[Keim, 2010]**.

Data analysis mantra: "Overview first, zoom/filter, details on demand" **[Shneiderman, 1996]**

Visual analysis mantra: "Analyze first, show the important, zoom/filter, analyze further, details on demands" **[Keim, 2006]**

Hypotheses

Incorporating research from the field of visual analytics to extend EEA can better address the challenges of ERS

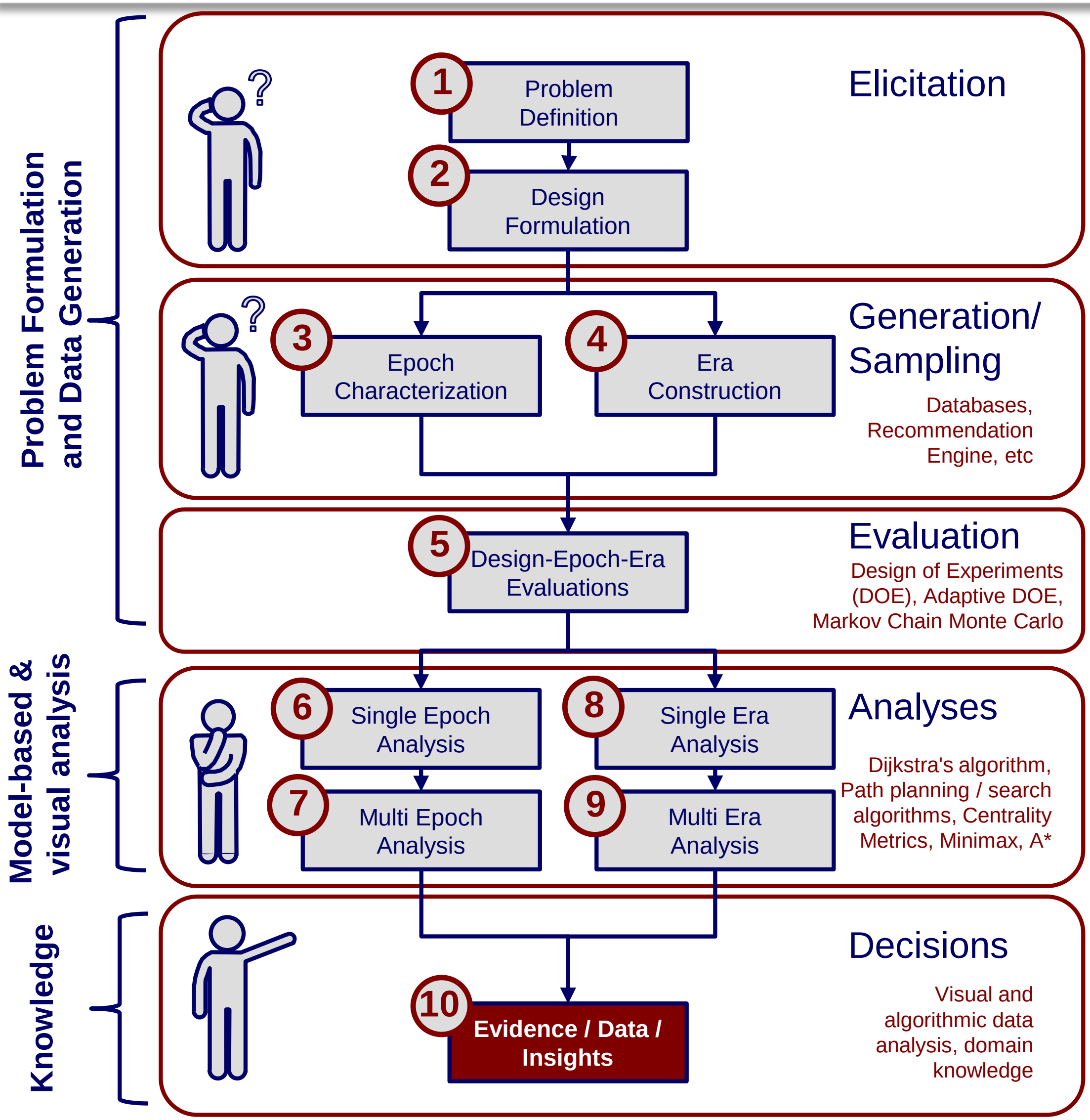
Framework with explicit consideration for human interaction

- A new design framework for EEA that incorporates research from the field of visual analytics should consider both algorithmic and visual data analysis to enable effective decision making

Interactive Visualization

- Direct interaction through a visual interface will allow decision-makers to better analyze and explore EEA data
- Interaction enables understanding, reasoning and decision making on the basis of a very large and complex EEA data

IEEA Framework



- Inspired by visual analytics process and extends processes of RSC and RMACS
- Prescriptive framework for applying EEA to gain insights includes:
  - Data generation (1-5)
  - Algorithmic and visual data analysis (6-9)

Space tug case study

- Scenario: A space tug rental company needs to provide the services of the system to customers with varying missions and preferences

Design Variable	Levels
Capability	Low, Med, High, Extreme
Propulsion Type	BiProp, Cryo, Electric, Nuclear
Fuel Mass	30, 100, 300, 600, 1200, 3000, 10000, 30000, 50000
DFC Level	0, 1, 2

384 Design Alternatives

- Goals: Provide value to customers, regardless of changing mission requirements, for as long as possible

Performance Attribute	Range
Cost	[96.9, 3952.8]
Payload	[300, 5000]
Isp	[300, 3000]
Mass fraction	[0.12, 0.30]
Speed	[0, 1]
Delta V	[24.4, 41604]
Base mass	[0, 1000]
Dry mass	[604, 22830]
Wet Mass	[634, 69800]

Decision-maker is attempting to satisfy sets of preferences corresponding to different missions

Epoch-space Characterization

- Each of the 8 missions has different performance requirements for payload, speed and ΔV
- Single context variable to describe current technology level
  - Affects the transition costs of the change mechanisms
  - Affects fuel efficiencies and mass fractions of different propulsion systems

Missions
Baseline mission
Technology demonstration
GEO satellite rescue
Satellite deployment assistance
In-orbit refueling and maintenance
Garbage collection
All-purpose military mission
Satellite saboteur

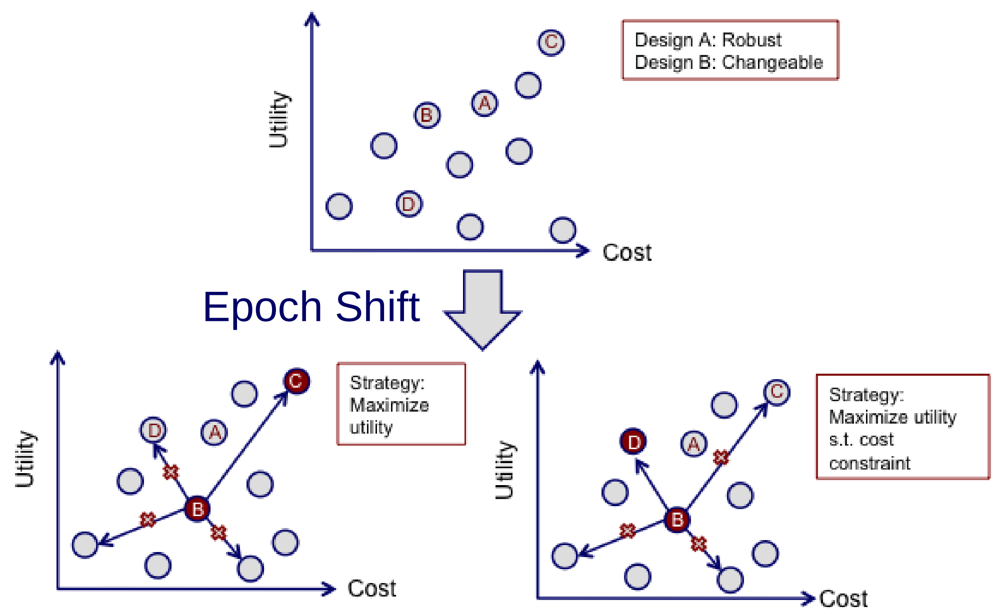
Epoch Variable	Levels
Mission	1 - 8
Technology Level	Present or Future

8 Preference Sets *
2 Contexts
= 16 Epochs

Design Changeability

- Desire systems that can maintain value delivery across different missions or changing contexts
  - Passively robust
  - Changeable (e.g. adaptable, resilient)
- Change options can allow sustained value at additional cost
  - Must be coupled with a defined strategy or policy for how they will be used

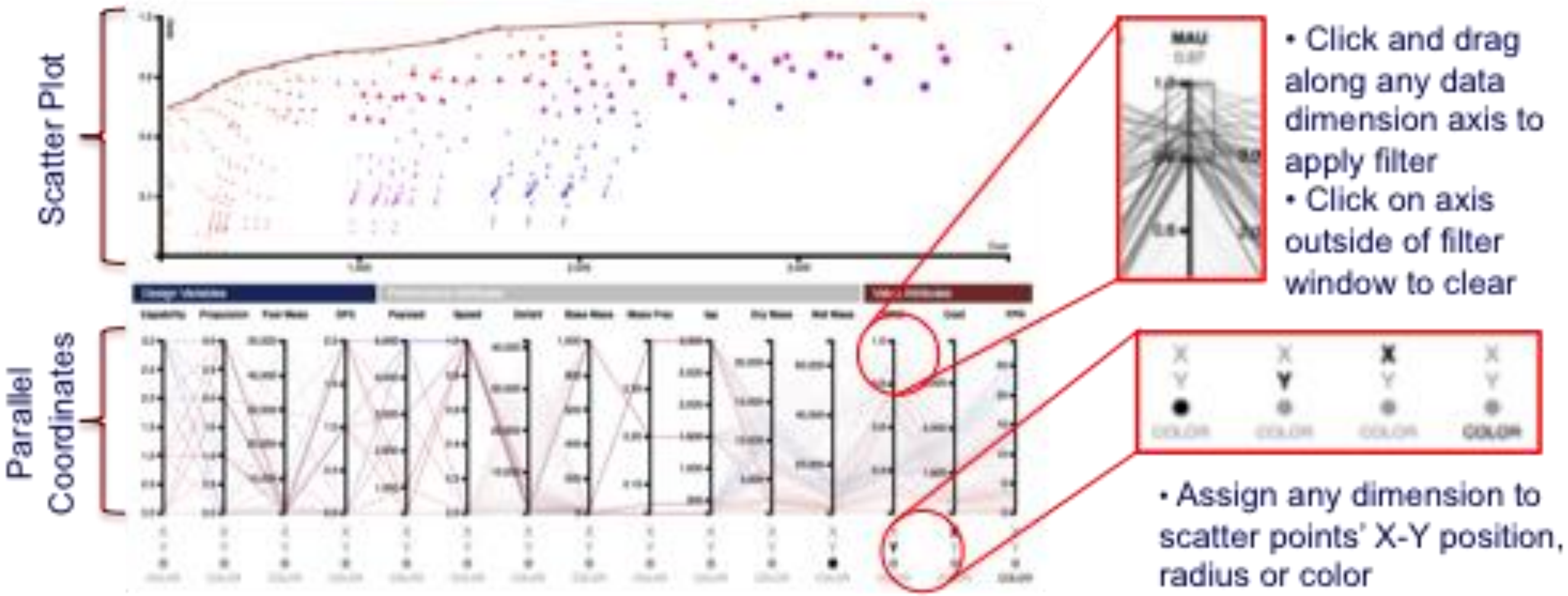
No.	Change Mechanism	Effect	DFC level
1	Engine Swap	Biprop/Cryo swap	0
2	Fuel Tank Swap	Change fuel mass	0
3	Engine Swap (reduced cost)	Biprop/Cryo swap	1 or 2
4	Fuel Tank Swap (reduced cost)	Change fuel mass	1 or 2
5	Change Capability	Change Capability	1 or 2
6	Refuel in Orbit	Change fuel mass (no redesign)	2



Single Epoch Analysis

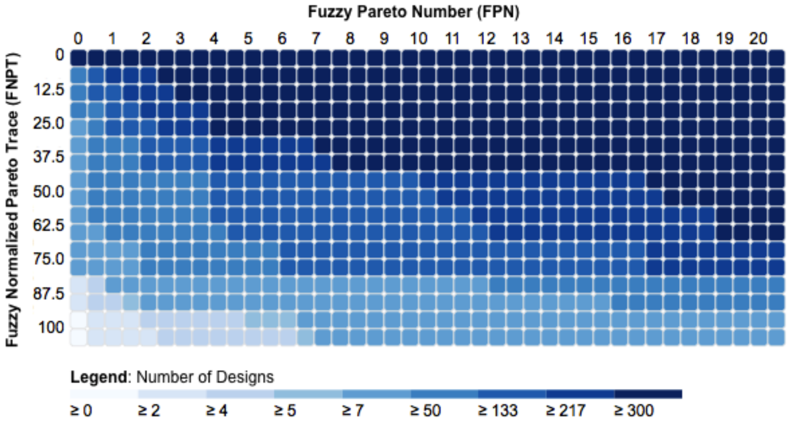
- Large numbers of design candidates generated by enumerating combinations of design variables and evaluating using system performance models

- Goal is equivalent to traditional tradespace exploration: identify Pareto efficient solutions



Multi Epoch Analysis

- Goal of multi epoch analysis analogous to that of robust design
  - Identify designs that remain close to the Pareto front across many epochs through passive robustness or changeability
- Internal mental representation of all data not strictly necessary
- Even with clever visual encoding, visualizations that show all data could incur additional cognitive load for the user rather than reduce it



3 Designs within 0% (FPN) of Pareto optimal in 87.5% of enumerated epochs

Design#	Cost ($M)	Capability	Engine Type	Propellant Mass (kg)	DFC Level
63	900	Medium	Nuclear	10000	0
95	1540	High	Nuclear	10000	0
128	3020	Extreme	Nuclear	30000	0

3 Designs within 1% (FPN) of Pareto optimal in 100% of enumerated epochs

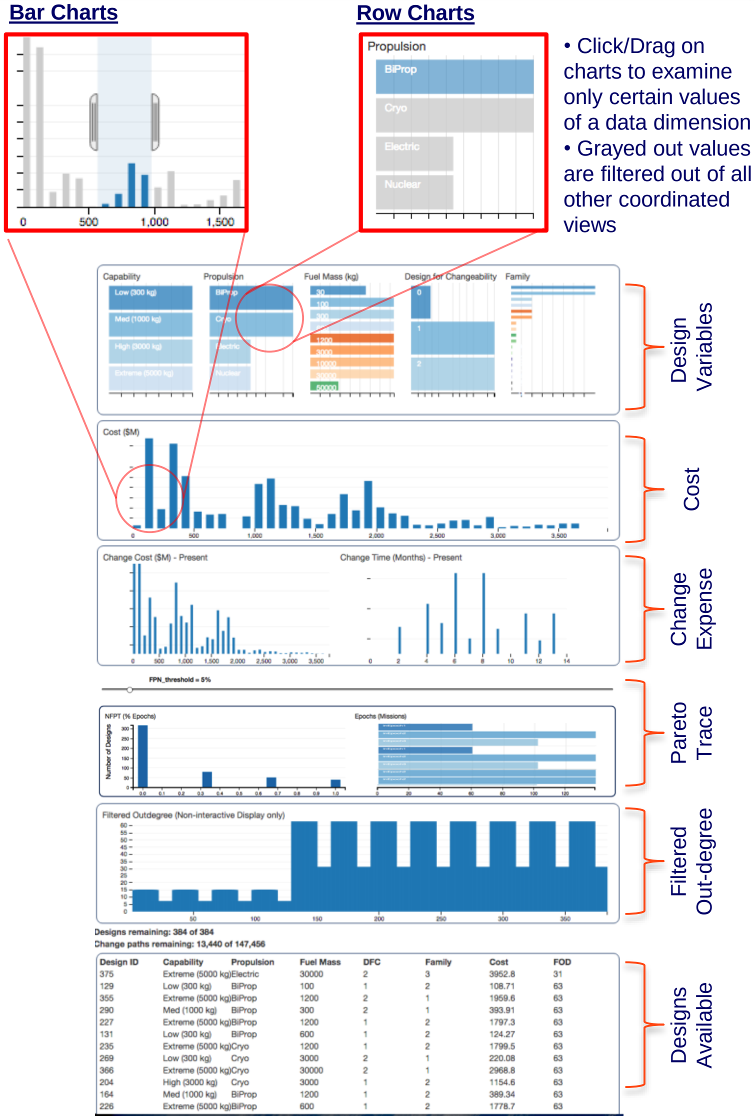
Design#	Cost ($M)	Capability	Engine Type	Propellant Mass (kg)	DFC Level
63	900	Medium	Nuclear	10000	0
128	3020	Extreme	Nuclear	30000	0
191	980	Medium	Nuclear	10000	1

5 Designs within 1% (FPN) of Pareto optimal in 87.5% of enumerated epochs

Design#	Cost ($M)	Capability	Engine Type	Propellant Mass (kg)	DFC Level
30	382	Low	Nuclear	3000	0
63	900	Medium	Nuclear	10000	0
95	1540	High	Nuclear	10000	0
128	3020	Extreme	Nuclear	30000	0
191	980	Medium	Nuclear	10000	1

Multi Epoch Analysis

- Multi epoch analysis on a broader range of data dimensions possible
- Combination of online analytical processing (OLAP) and binned aggregation techniques used for more sophisticated interactive applications

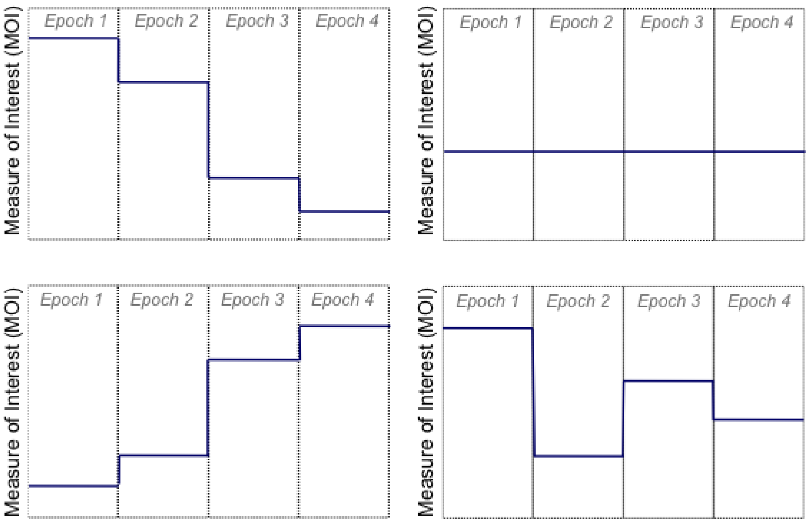


Value sustainment over time

- Long-run value is a measure of performance for a design-strategy pair over a time period (era)

- Long-term strategies
  - Maximize utility (U)
  - Minimize lifecycle cost (Acquisition, M&S)
  - Maximize efficiency (FPN)

- Metrics of interest (MOI) may be defined on any criteria of interest for the stakeholder
  - Performance attribute
  - Utility or value
  - Efficiency
  - Cost

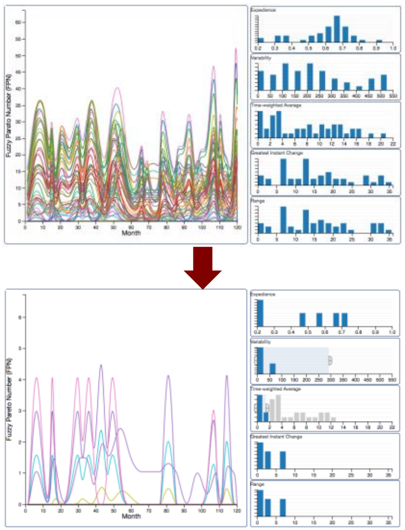


- Era-level metrics defined to capture the time-dependent nature of value
  - Time-weighted average
  - Variability
  - Expedience
  - Greatest rise / fall
  - Range

Single Era Analysis

- Goal is to evaluate value of design-strategy pairs for a single sequence of future epochs
- Coordinated visualization for interactive filtering based on 5 era-level metrics that evaluate temporal aspects of value delivery
- Interactive chord diagram for visualizing change option usage and transition behavior within design families

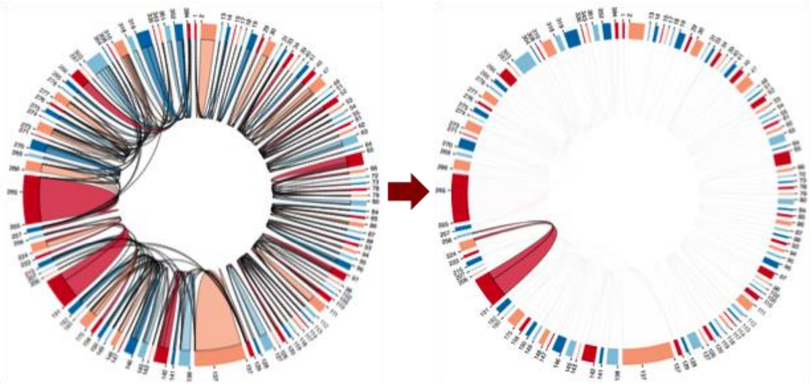
Single-Era Interactive Filtering



Era metrics:
1. Expedience
2. Variability
3. Average
4. Greatest Δ
5. Range

Filtered subset of designs based on era performance

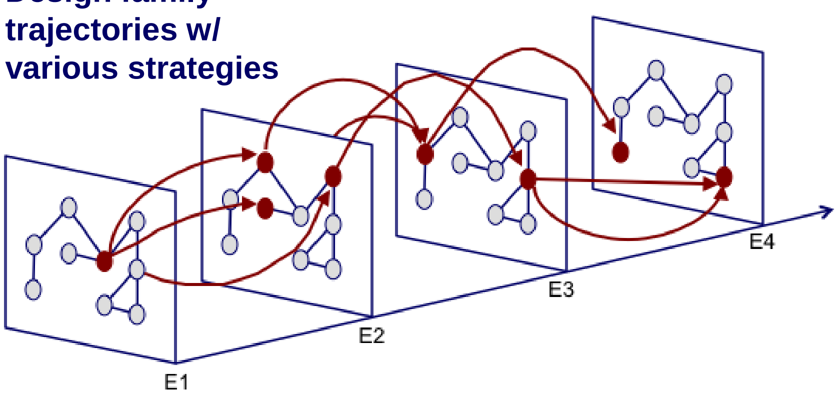
Change Path Dependency Analysis



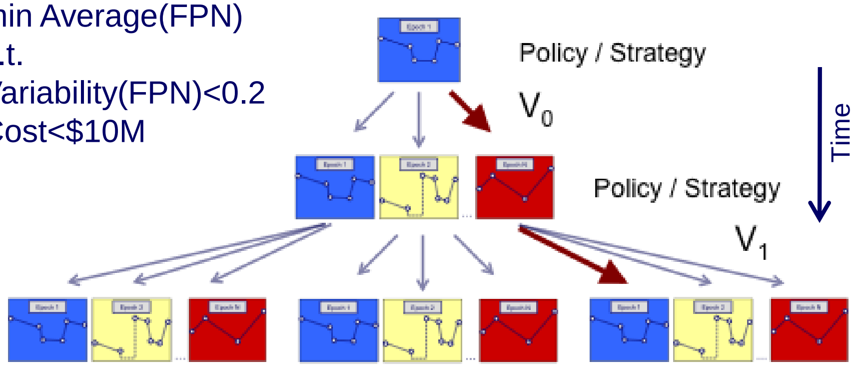
Multi-era analysis

- Goal for MERA is to identify relevant path dependencies that stem from:
  - Perturbations, disturbances and epoch shifts
  - Changes to a design as it progresses through lifecycle
- Complete exploration of the uncertainty space intractable for most problems
- Analogous to strategic games with imperfect information

Design family trajectories w/ various strategies



Example Policy/Strategy:
min Average(FPN)
s.t.
Variability(FPN)<0.2
Cost<$10M



Summary

- Demonstration of new prescriptive framework for EEA that explicitly considers human interaction inspired by the visual analytics process
- Prototype interactive visualizations implementing in interactive web-based applications
- IEEA incorporates both algorithmic and visual data analysis enables sense-making and effective decision making of high dimensional multivariate data associated with EEA

Questions?

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