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Designing for System Value Sustainment using Interactive Epoch Era Analysis: A Case Study for On-orbit Servicing Vehicles

Michael Curry[a]*, Adam Ross[a]

[a]*Massachusetts Institute of Technology, Cambridge, MA*

Abstract
Epoch-Era Analysis (EEA) is a framework that supports narrative and computational scenario planning and lifecycle uncertainty analysis for both short run and long run futures. Because of the complex data that must be analyzed when extending EEA to large-scale problems, issues with cognition are introduced that may hamper decision-making. This motivates the need for extensions to EEA methods that overcome the computational and human cognition issues that may arise. The Interactive Epoch-Era Analysis (IEEA) framework, comprised of 10 processes grouped in 6 modules, is introduced as a means for analyzing lifecycle uncertainty when designing systems for sustained value delivery. IEEA is proposed as an iterative framework for concept exploration that provides a means of applying EEA constructs while controlling growth in data scale and dimensionality. Further, IEEA leverages interactive visualization because prior visual analytics research has demonstrated that when performing exploratory analysis, like early-phase system concept selection, an analyst can gain deeper understanding of data which can lead to improved decision-making. Application of IEEA to a case study for a multi-mission on-orbit servicing vehicle is provided to demonstrate key concepts and prototype interactive visualizations.

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1. Introduction

In April 2011, the Office of the Secretary of Defense (OSD) identified the development of engineered resilient systems (ERS) as a science and technology (S&T) strategic investment priority. Since that time several researchers and practitioners have begun to investigate how to define this problem and develop new methods, techniques and tools to assist designers in early-phase system concept selection activities. Several recent publications out of the ERS community of interest (COI) have provided prospective on the DoD's needs as well as attempted to identify gaps in current system design and acquisition approaches[1,2,3]. The ultimate goal of ERS can be more generally characterized as a desire to sustain value delivery from systems in spite of perturbations in design, context or needs.

The ERS COI's use of the term "resilient" causes some semantic confusion among researchers, but a close examination of the problems described reveals that they are interested in improving how they perform early-phase

* Corresponding author. Tel.: 617-258-3590
E-mail address: curry@mit.edu

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system concept trade studies (pre-Phase A) and system lifecycle analysis given uncertainty in needs, context and design. Epoch-Era Analysis (EEA), which was developed to model these types of lifecycle uncertainties, may create challenges due to the complex data that must be analyzed for the types of large-scale problems posed by the DoD. This motivates the need for extensions to EEA methods that overcome the computational and human cognition issues that may arise as a result.

Interactive Epoch-Era Analysis (IEEA) is proposed as an iterative framework for concept exploration that provides a means of applying EEA constructs while controlling growth in data scale and dimensionality. Further, IEEA will leverage interactive visualization because prior visual analytics research has demonstrated that when performing exploratory analysis, like early-phase system concept selection, an analyst can gain deeper understanding of data which can lead to improved decision-making. It is hypothesized that the extension of interactive visualization to system design problems with lifecycle uncertainty may result in improved comprehension of the nature of underlying trades and simultaneously improve a designer's ability to communicate their decision-making rationale to others.

2. Background

Epoch-Era Analysis (EEA) is designed to clarify the effects of changing contexts over time on the perceived value of a system in a structured way[4,5]. The base unit of time in EEA is the epoch, which is defined as a time period of fixed needs and context in which the system exists. Epochs are represented using a set of epoch variables, which can be continuous or discrete values. These variables can be used to represent any exogenous uncertainty that might have an effect on the usage and perceived value of the system. Weather conditions, political scenarios, financial situations, operational plans, and the availability of other technologies are all potential epoch variables. Appropriate epoch variables for an analysis include key (i.e., impactful) exogenous uncertainty factors that will affect the perceived success of the system. A large set of epochs, differentiated using different enumerated levels of these variables, can then be assembled into eras, ordered sequences of duration-labeled epochs creating a description of a potential progression of contexts and needs over time. This approach provides an intuitive basis upon which to perform analysis of value delivery over time for systems under the effects of changing circumstances and operating conditions, an important step to take when evaluating large-scale engineering systems with long lifecycles.

Encapsulating potential short run uncertainty (i.e., what epoch will my system experience next?) and long run uncertainty (i.e. what potential sequences of epochs will my system experience in the future?) allows analysts and decision makers to develop dynamic strategies that can enable system value sustainment. Key challenges in application of EEA up to this point involve eliciting a potentially large number of relevant epochs and eras, conducting analysis across these epochs and eras, and extracting useful and actionable information from the analyses. Schaffner[6] showed that the number of potential eras to consider can grow very quickly, becoming computationally infeasible. As an example, an epoch space represented by 5 epoch variables, each with 3 levels, would result in $3^5 = 243$ possible epochs. If the length of our eras is 10 epochs and each epoch can transition between any other epoch then the size of the potential era space would be $243^{10} \sim 10^{24}$ eras. This means that for many problem formulations it is not feasible to evaluate systems across all or even a large fraction of potential eras.

EEA provides a powerful way of framing the problem of deciding among actionable alternatives given uncertainty, but comes at the expense of a potentially large and complex data set. The data that must be evaluated can be difficult to process, visualize and interpret by a decision maker. Traditional engineering and scientific visualization techniques may be inadequate for extracting insights from such data sets, but recent work in the area of visual analytics may prove helpful in mitigating these shortcomings. Visual analytics extends beyond traditional scientific visualization and focuses on extracting insights from data using interactive visual interfaces[7]. The research agenda in this area seeks to develop "the science of analytical reasoning facilitated by interactive visual interfaces"[8]. Good overviews of the state of current research on visual analytics are provided by Icke[9] and Keim[10]. While there is much overlap, generally speaking researchers have been tackling the research from three angles: (1) data reduction and handling of large amounts of data; (2) specific types of visualizations that improve human cognition; and (3) methods to facilitate user interaction with data. Prior work has demonstrated promise for such capability and insight improvement when interactivity is added to tradespace exploration[11]. Supplying the decision-maker with immediate visual feedback on the consequences of their decisions could be enabled through

simultaneous coordinated views of the design, performance and value spaces. Enabling users to interact with their data through visual interfaces of this type is an area of active research[12,13,14]. Integrating interactive data visualization and advanced systems engineering methods is seen as key to the current research effort on IEEA.

3. Framework for Interactive Epoch Era Analysis (IEEA)

IEEA leverages human-in-the-loop (HIL) interaction to manage challenges associated with the large amounts of data potentially generated in a study, as well as to improve sense-making of the results. By allowing the structured evaluation and visualization of many design alternatives across many different futures and potential lifecycle paths, this new approach enables the design of systems that can deliver sustained value under uncertainty.

3.1. Extension of Prior EEA-based Methods

The framework described in this paper is based on prior research on methods and processes for applying EEA constructs. The Responsive Systems Comparison (RSC) method, proposed by Ross et al.[15,16] as a prescriptive method for applying MATE and EEA, was developed to study system value sustainment through changeability. More recently, Schaffner[6] proposed the RSC-based Method for Affordable Concept Selection (RMACS) that expands the original seven processes of RSC to nine and explored the application of multi-attribute expense (MAE) to more effectively capture all resources expenditures required to realize a given system.

IEEA differs from both RSC and RMACS in that it strongly emphasizes iteration and human-in-the-loop (HIL) interaction throughout the process. Iteration is necessary because the analysis is inherently exploratory in nature. HIL interaction is necessary because the problem is not strictly deterministic or necessarily intended as a reliable prediction of system performance or future events. Often, there is both uncertainty and the potential for errors in assumptions or model implementation. This necessitates human judgment to make sense of the data, therefore this is not by its nature a problem that can be handed over completely to an automated optimization algorithm. Though some level of automated analysis could be beneficial as an aid to the user.

3.2. Description of IEEA Framework Modules

The purpose of IEEA, much like the purpose of RSC as described by Ross et al.[15], is to "guide the...practitioner through the steps of determining how a system will deliver value, brainstorming solution concepts, identifying variances in contexts and needs (epochs) that may alter the perceived value delivered by the system concepts, evaluating key system trade-offs across varying epochs (eras) to be encountered by the system, and lastly developing strategies for how a designer might develop and transition a particular system concept through and in response to these varying epochs". To that end, as shown in Figure 1, the IEEA framework is characterized by 10 individual processes that can be abstracted into six main modules:

1. **Elicitation** of relevant epoch and design variables (often through interview),
2. **Generation** of all epochs, eras and design tradespaces (often including enumeration),
3. **Sampling** of epochs and eras in which to evaluate design choices,
4. **Evaluation** of designs in sampled subset of epochs and eras
5. **Analyses** of design choices in the previously evaluated epochs and eras, and finally
6. **Decisions** of final designs based on iterative evidence from previous modules.

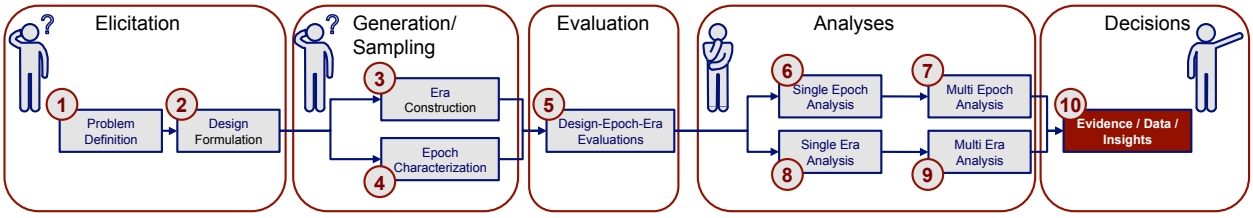

Fig. 1. Interactive Epoch-Era Analysis process and modules.

While the sequence of these modules flows logically, IEEA is intended to be an iterative process where users can go back and change responses within earlier modules at any point to reflect what they have learned from later ones. The six modules are composed of the 10 processes, but depending on the nature of the study and the type and fidelity of information available to the analyst, it is not strictly required that each process step be applied. Many of the techniques discussed in Curry et al.[17] can be applied to augment and facilitate a practical implementation of the workflow. For example, OLAP techniques may be applied to improve data handling, and search algorithms may improve our ability to offer more informed recommendations to decision-makers during the epoch-era analysis process. Similarly, enhanced human interaction techniques and visualizations may aid in the analyses of the vast amounts of information required to reach an informed decision.

4. Results: Space Tug Demonstration Case

To demonstrate the application of the IEEA framework, a case study aimed at designing a multi-mission orbital transfer vehicle, or space tug, was selected. A space tug may be used for a variety of missions including observing, servicing or retrieving on-orbit spacecraft. The original case study described by McManus et. al[18] is, at first glance, a seemingly simple trade study, but despite the simplicity of the system model the analysis is actually nontrivial. Fitzgerald[19] expanded upon this case as a demonstration of his valuation approach for strategic changeability (VASC). The case study demonstrated here (in 10 processes) replicates the one by Fitzgerald[19]. This provides for an interesting comparison since the application of IEEA leads to different insights that impact previous conclusions.

4.1.1. Process 1: Value-Driving Context Definition

The first process defines the stakeholders, problem statement, exogenous uncertainties and the basic value proposition for the system. The problem statement, as described by Fitzgerald[19], is that the project sponsor would like to develop a space tug that can provide services to customers that collectively have eight different missions they need to perform. The space tug delivers value by meeting the demands of as many of those customers as possible for as long as possible. The ability to do so is driven not just by the nature of a given design alternative, but also by external factors like technology level that directly impact the performance attributes of the system.

4.1.2. Process 2: Value-Driven Design Formulation

The second process begins by defining the needs statements for all stakeholders, which become the attributes of system performance, along with utility functions describing each stakeholder's preference for each attribute. For this study 8 different missions are defined, each with a different weighted preference for three system performance attributes: payload, speed and ΔV. The value delivered by a given design alternative is different in each mission because they have different requirements (needs) and thus use different multi-attribute utility functions to calculate a measure of value based on the performance attributes of the design. For example, in the debris collector mission the single attribute weighting on speed is lower than in the rescue mission because that attribute is less important for that mission. The multi-attribute utility (MAU) function for each mission is developed from the weighted combination of the individual single attribute utilities (SAU). Each performance attribute for each mission has a different mapping to a SAU value. For each design alternative, after computing the SAUs corresponding to the performance attributes, the MAU value can be computed as a weighted sum of the SAUs for each mission.

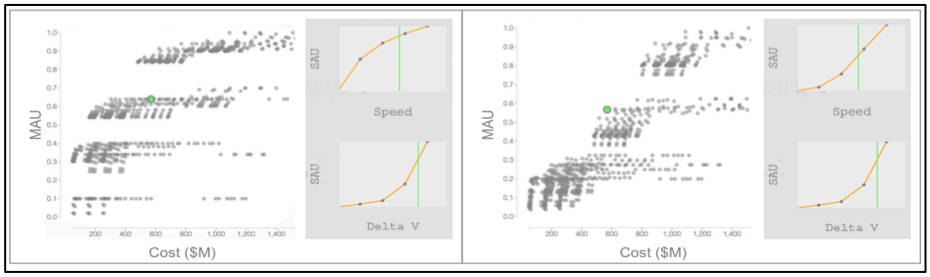

Fig. 2. Prototype Application for Interactive Visualization of MAU weightings showing (a) Initial tradespace and preferences over performance attributes; (b) Revised preferences and final tradespace (Ricci, et al., 2014).

Ricci, et al.[20] previously discussed a simplified version of the space tug case study as an example of how these SAU functions could be developed and weighted interactively using a HIL application as shown in Figure 2. A stakeholder may benefit from this type of interaction if the qualities of the system they believe to be valuable are not well articulated. This type of application is an example of how interactivity can often be a useful or necessary component of this process when eliciting stakeholder value statements.

4.1.3. Process 3: Epoch Characterization

In process 3 the key contextual uncertainties are identified so that epoch variables can be characterized. In addition to different preference sets, value delivery for design alternatives in this case study is also affected by a single context variable, technology level, which has two levels, present or future. Technology level can directly impact the system performance attributes through fuel efficiencies and vehicle mass fraction. It can also impact some transition costs when executing change options. A full-factorial design of all combinations of the 8 preference sets and 2 contexts results in 16 epochs.

4.1.4. Process 4: Era Construction

This process constructs era timelines composed of multiple sequences of epochs each with a set duration to create long-run descriptions of possible future scenarios a system may encounter. Simulating lifecycle performance in this way allows an analyst to evaluate path-dependent effects that may only arise when uncertainty is time-ordered. The activities in this process are in many ways analogous to those used in narrative or computational scenario planning. The future timelines can be constructed manually with the aid of expert opinion (narrative) or by implementing probabilistic models (computational), such as Monte Carlo simulation or Markov chain models, that define epoch transitions. For this case study, eras with a total length of 10 years, comprised of epochs uniformly distributed in duration between 1 to 12 months, were constructed according to the rules previously described by Fitzgerald[19].

4.1.5. Process 5: Design-Epoch-Era Evaluation

The first four processes defined the relevant elements of the models that will be evaluated in the fifth process. The previously defined models are integrated to map design and epoch variables into stakeholder value (MAU) and expense (MAE). For this case study the only expense considered is the system cost. Fitzgerald[19] chose design variable levels as shown in **Table 1** below. These are similar to the levels chosen by McManus et al.[18] except that a fourth design variable, design for changeability (DFC) level, is added. Both authors chose to use full-factorial experimental designs to enumerate the space of system performance attributes. A full-factorial enumeration of this space results in 432 designs, but not all designs are feasible. Due to compatibility constraints between propulsion type and fuel mass there are only 384 feasible designs.

Table 1. Design variable levels

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

Since the space tug model is relatively simple the computational time required to evaluate all design-context pairs is small. For more complex system models, fewer design levels or more sophisticated enumerating via experimental designs, such as central composite designs, may be required to lower the computational burden. Selecting the best way to enumerate the input space is another potential opportunity for improvement in this process through HIL interactivity, but this has not yet been explored. After evaluating the performance space of available alternatives the value models developed in process 2 can now be applied to map the performance of each design-context pair into the value delivered in each of the 8 missions. This results in 6,144 design-epoch pairs (384 designs * 2 context * 8 preference sets) to consider. The following sections will discuss how these design-epoch pairs can be better understood through interactive visualization as demonstrated through various prototype applications.

4.1.6. Process 6: Single Epoch Analyses

Single epoch analysis is comparable to what is often traditionally referred to in practice as tradespace exploration. Within a given epoch a scatter plot of cost (MAE) versus benefit (MAU) can be constructed that is fixed for short-run periods of stable context and needs (i.e., an epoch). Typically, a decision-maker wants to identify the frontier of Pareto optimal designs or, more generally, designs that are "close enough" to the Pareto front. Here the notion of "close enough" is operationalized through a metric called Fuzzy Pareto Number (FPN)[21] which is used to quantify the distance from the Pareto Front for each design in each epoch. FPN is a "within-epoch" metric and its value for a given design will change in different epochs. A decision-maker can gain insights regarding the difficulty of a particular context and needs by visualizing how points move in the design space as the epoch and FPN values change. Additional insights may come from interactively filtering the design, performance or value variables. This can be performed with the aid of the filtering application shown in Figure 3a that allows the decision-maker to interact with their data to identify designs and epochs of interest. It also allows them to assign any of the defined variables to the radius, color or x-y location of the points in the scatter plot to explore the data in four dimensions and better comprehend the behavior of the designs.

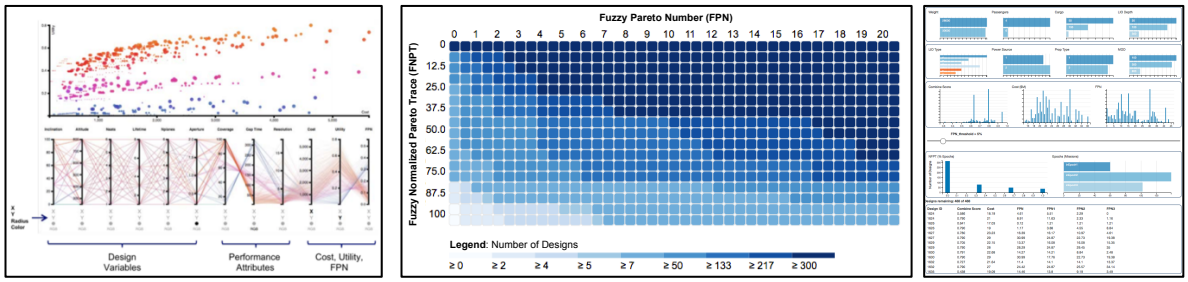

Fig. 3. (a) Interactive Filtering Application; (b) Interactive heatmap visualization; (c) Interactive Filtering Application implementing OLAP.

4.1.7. Process 7: Multi-Epoch Analysis

The activities of process 7 allow a decision-maker to gain deeper insights by evaluating metrics between and across epochs to gauge the impact of uncertainties on system value. This includes the evaluation of short run passive and active strategies for achieving value sustainment such that systems can maintain value delivery across different missions or changing contexts. A system that is passively robust is insensitive to changing conditions and continues to deliver acceptable value. Alternatively, a system that suffers deterioration in value due to evolving conditions may benefit from the use of change options that make them flexible, adaptable or resilient.

4.1.7.1. Evaluating passive strategies for value sustainment (Robustness)

Ideally a design candidate would be Pareto optimal in each of the 16 defined epochs and be within the required cost and performance constraints set by each stakeholder. This is often unrealistic, however, so a decision-maker may be required to settle for a design that is close enough to the Pareto front across most epochs. As was the case in process 6, "close enough" is operationalized through the FPN metric, but this analysis also must define a metric that captures the frequency at which a particular design meets a threshold FPN across epochs. To accomplish this the Fuzzy Normalized Pareto Trace (FNPT) metric[16,19] is defined as the percentage of epochs in which a given design appears within a range from the Pareto front defined by the analyst. Applying these two metrics a decision-maker can set a threshold FPN and evaluate how frequently a design appears close to the Pareto front across all epochs. Assuming no designs are Pareto optimal in every epoch, a decision-maker can choose to relax the acceptable distance from the Pareto front by increasing the FPN threshold or accept a lower FNPT indicating decreased Pareto efficiency of the design in some epochs.

In past studies the trade-off between FPN and FNPT has been a very manual process that may benefit from implementation in an interactive application. The single-epoch analysis application shown in Figure 3a can be impractical for this analysis if the number of epochs and/or designs is large. Binned aggregation techniques as discussed in Curry et al.[17] can be applied to overcome these types of issues. The interactive heatmap visualization in Figure 3b shows the tradeoff between FPN and FNPT using color to encode the number of designs that satisfy the

threshold at each level. Clicking on any square in the heatmap brings up a separate list of the designs that meet the cutoff. If an analyst would like to concurrently examine the impact of various FPN and FNPT trades on design and performance variables a more complex visualization can be implemented using OLAP to handle issues that arise with more data dimensions and an increasingly larger data set that must be manipulated in real-time. As an example, the interactive visualizations shown in Figure 3c applies OLAP, multiple coordinated views and binned aggregation to allow trade-offs between Pareto efficiency (FPN) and frequency of acceptable epoch performance (FNPT). This application also allows a decision-maker to determine not just the percentage of acceptable epochs, but also which epochs are most difficult for candidate designs. This is an insight not previously available or discussed in prior applications of multi-epoch analysis for this case study. These types of previously undiscovered relationships and patterns within the dataset may be useful for indentifying "problem epochs" or when determining cases where it might be more appropriate to build a combination of systems to satisfy all possible future epochs.

Applying this approach to the space tug case study it can be shown that none of the enumerated designs are Pareto optimal (FPN=0%) all of the time (FNPT=100%). Depending on the preferences of the decision-maker, using the interactive filtering application they could now choose to relax the FPN or the FNPT constraint to identify acceptable design compromises. Holding the requirement on Pareto efficiency (FPN=0%) constant and relaxing the requirement on FNPT it can be determined that 3 designs are Pareto optimal in 14 of 16 (FNPT=87.5%) of enumerated epochs. Alternatively, if a decision-maker is willing to relax both the FPN and FNPT requirement, more designs remain after filtering as shown in **Table 2**. Comparing the designs identified here to those previously identified as passively robust by Fitzgerald[19], it can be seen that only 2 of the 5 designs are the same (designs 128 and 191). Notably, these two designs were shown by Fitzgerald to be among the best performing of his identified designs in subsequent multi-epoch and multi-era analysis.

Table 2. Designs within 1.0% (FPN) of Pareto optimal in 87.5% (FNPT) 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

4.1.7.2. Evaluating active strategies for value sustainment (Changeability)

The multi-epoch analysis metrics described above show how value sustainment through design robustness can be evaluated for this case study. A design that is not robust to changes in needs or context, however, may still be able to sustain value through the use of design change options. A system that is equipped with a design feature, or option, that allows it to change its state may do so to restore value if a future epoch is encountered that causes a loss of value. Typically these change options are built into a design at the beginning of its life for an additional cost, but not used unless a particular future unfolds. There may also be an associated cost in money, time or other resources to execute the option. For this case study there are six change options defined as shown in **Table 3**.

Table 3. Available Change Mechanisms

No.	Change Option	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

A logical series of questions that a decision-maker would want to answer next are, "Which of these options should be implemented to allow a candidate system to sustain value, what metrics allow that to be assessed and are the options worth the cost?" A useful metric proposed by Ross[4] is Filtered Outdegree (FOD), which represents the number of change paths out of a design to various target designs given a set of filtering constraints on resource usage such as execution time and expense (cost). Since FOD only captures the number of change paths, not

necessarily whether they are valuable or useful, several follow-on works attempted to define metrics for various versions of Value-Weighted Filtered Outdegree (VWFO)[22] to assess the utility gain that could be achieved through execution of various change options. Focusing more on long run strategies, Schaffner[6] provides a convincing argument that FOD may be a more appropriate metric than any of the proposed VWFO metrics since in many cases it may be beneficial to execute a change to affect a short-term loss of utility in order to achieve a longer-term net gain. Schaffner[6] further notes that most past applications of FOD have focused on single arc change paths to determine the number of target end states that an original design can achieve via execution of a change mechanism. His proposed metric for Fully Accessible Filtered Outdegree (FAFO), which also captures additional end states that can be reached through multiple change mechanisms, is adopted for the research presented here on IEEA.

While FAFO can provide a proxy metric for desirable system behavior the strategy for how and when to execute it is equally as important when assessing the potential for a system to sustain value delivery. For a system that has one or more change mechanisms, the decision as to which option to execute or whether an option should be executed at all depends on the change strategy assumed. Fitzgerald[19] and Schaffner[6] describe several epoch-level change strategies that may be considered such as "maximize utility" or "maximize efficiency". For the "maximize utility" strategy, as the name implies, it is assumed that a system will execute the change option or options that allow it to achieve the highest utility end state in a given epoch. Similarly, the "maximize efficiency" strategy will execute whichever options allow it to maximize Pareto efficiency and get closest to the Pareto front even if that results in a lower utility. The two authors also proposed other strategies, such as "Survive" and "Maximize Profit", but it is possible that additional as yet undefined strategies may exist.

Though adjacency matrices have previously been used to visualize design change networks, interactive force directed graphs, as shown in Figure 4, might facilitate deeper insights from changeability analysis. For instance, the existence of clusters of designs related to one another through change mechanisms is apparent even without applying clustering algorithms such as the Louvain community detection method. Also, compared to the static adjacency matrix representations shown by Fitzgerald[19], interactive visualization allows the represented network to be explored using dynamic data filtering and by changing the variable assignments of the visual elements. Using controls and filters that allow an analyst to assign node color, node radius, link width, link length and link color to different data dimensions an analyst can more readily identify unexpected results. In the example shown in Figure 4 the visualization on the right shows the result from interactively assigning network centrality metrics for betweeness to both node color and radius. Doing so provides immediate visual feedback that designs, even within the same cluster, are not necessarily changeable in the same way in terms of available end states and costs to reach them.

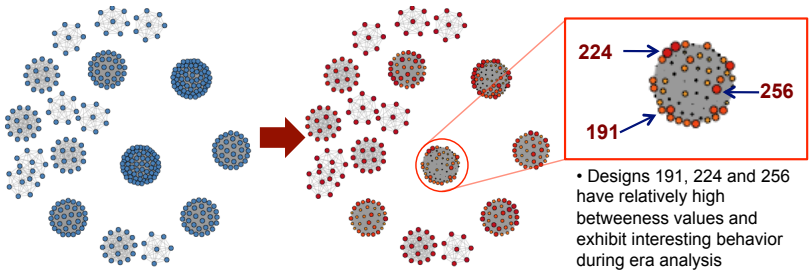

Fig. 4. (a) Interactive force-directed graphs of change mechanisms between designs; (b) Betweeness centrality metric assigned to node radius.

The value of a change mechanism to a given design will vary based on the strategy assumed. To evaluate the benefits of various strategies and change option pairs for a set of designs, two metrics, effective FPN (eFPN) and effective FNPT (eFNPT), can be used[19]. The eFPN and eFNPT metrics can be evaluated for a particular design across all epochs for each strategy. If the change strategy dictates that an original design changes to a particular target design in a given epoch, then the target design is evaluated. If the change strategy dictates that a starting design does not change in that epoch, then that starting design is evaluated[6]. Assuming a usage strategy, we could now evaluate the valuable changeability of enumerated designs via the interactive application shown in Figure 8. Though not shown in this example, rule removal studies as proposed by Fitzgerald[19], could also be implemented in

this interactive application to allow a decision-maker to develop intuition regarding the value to a system of having a particular change options. These have been omitted from the current discussion for brevity.

4.1.7.3. Summary of Multi-Epoch Analysis

The analyses outlined in this section provide a way for decision-makers to interactively evaluate the performance of multiple design alternatives across multiple futures. This creates opportunities for new insights at the expense of a potentially large and complex data set that can be difficult to make sense of even for this simplified case study. The application of an interactive framework allows the user to visualize and engage with the data in new ways that may facilitate improved comprehension and decision-making. The insights that can be extracted from this approach allow the decision-maker to understand the characteristics of designs that can sustain value in all possible futures through passive robustness or active changeability. Note that while it has been demonstrated here as two separate analyses it would be desirable, though not yet implemented, to concurrently evaluate robustness and changeability of designs. Designs that are moderately effective at both may be preferable to superior performance in only one.

4.1.8. Process 8: Single-Era Analyses

Epoch-analysis is focused on the evaluation of short run passive and active strategies for achieving value sustainment. In contrast, era-analysis focuses on long run sustainment of system value delivery across different missions or changing contexts. This process examines the time-dependent effects of an unfolding sequence of future epochs created in Process 4. By examining a particular series of epochs for a given length of time, decision-makers can identify potential strengths and weaknesses of a design and better understand the potential impact of path-dependent, long run strategies for value sustainment.

For many system design applications, subject matter experts may identify eras from one or more likely narratives that may play out. When analyzing any one of those eras a decision-maker would then want to identify the right combination of inherent robustness, changeability and operational strategy that allow a system to meet a specified performance threshold across all future time steps. As an example, assume a design is desired that remains within a given distance of the Pareto front (e.g. FPN close to zero) across all time. A plot of the FPN versus time can reveal how each candidate design performs, but it is difficult to compare performance between designs across the era. Previous applications of era analysis[19,23] used variations of time-weighted average performance across an era to compare designs to one another. They also focused on utility, rather than FPN, as their metric of interest which is not necessarily appropriate since utility values are not comparable in different epochs. Schaffner[6] identified several additional metrics that can be applied to evaluate additional characteristics of performance across an era including expedience, variability, time-weighted average, greatest instant rise/fall, and range. These additional metrics provide an improved ability to describe era performance at the expensive of increased information that a decision-maker must consider when selecting a design.

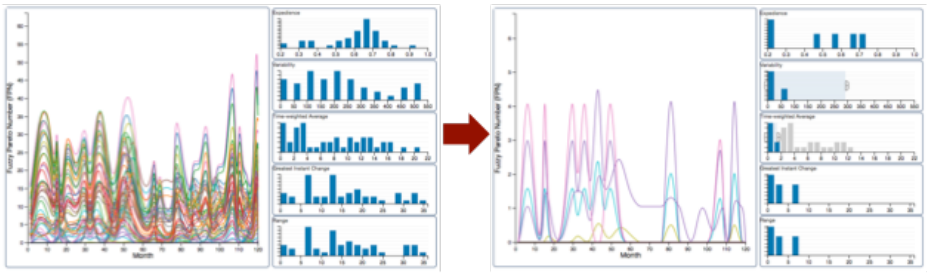

Fig. 5. Interactive application showing candidate designs across a single era (a) before filtering; and (b) after.

As demonstrated for previous IEEA processes, decision-making in single-era analysis can also benefit from the application of techniques such as multiple coordinated views, interactive filtering and OLAP. An example application, shown in Figure 5, shows the FPN performance of all designs across time for the specified era. The five histograms to the right display aggregated data on the performance of the candidate designs for the era metrics identified by Schaffner[6]. Interactive filtering on those metrics allows a decision-maker to rapidly identify interesting

designs based on their individual preferences for average performance and stability of performance across time. It also allows them a way to better comprehend design behavior that has not previously been demonstrated.

4.1.9. Process 9: Multi-Era Analysis

This process extends Process 8 by evaluating the dynamic properties of systems across many possible future eras, identifying patterns of strategies that enable value sustainment across uncertain long run scenarios. When looking at only a single era it is possible to compare how individual designs perform relative to one another using the era metrics previously discussed that capture temporal aspects of value delivery. This is not practical when analyzing many possible eras. In fact, it has been previously shown that it would be impossible to characterize the entire era-space[6,17]. The goal then for multi-era analysis is focused more on understanding the aggregate behavior of designs given different long-run strategies for operating a system. Specifically, it is useful to better understand any possible path dependencies that may arise due to either external perturbations/shifts or the application of operational strategies that define usage rules for available design change options.

In past research on path-dependency analysis for multiple eras, the progression of epochs within an era has been modeled as a directed acyclic graph† or tree of events[6]. This is similar to how path-dependency analysis is conducting in programs that analyze strategy games such as tic-tac-toe where the decision tree is searched using variants of the minimax algorithm to determine the best move at each step. In more complex games, such as chess, partial tree searches are typically required to keep the problem computationally tractable and the decision approaches optimal with increasing depth of the search through the tree‡. HIL interaction, however, can be leveraged to enable the decision tree to be searched more efficiently. The benefits of HIL interaction has been demonstrated on related path-analysis problems such as the traveling salesman problem[26] and "human-machine" chess matches that demonstrated a human player, coupled with chess software, can fairly consistently beat computer-only players[27]. This suggests that multi-era path analysis could also benefit from the right combination of interactive applications that leverage the experience of subject matter experts (SME) to identify beneficial or detrimental path-dependencies within eras.

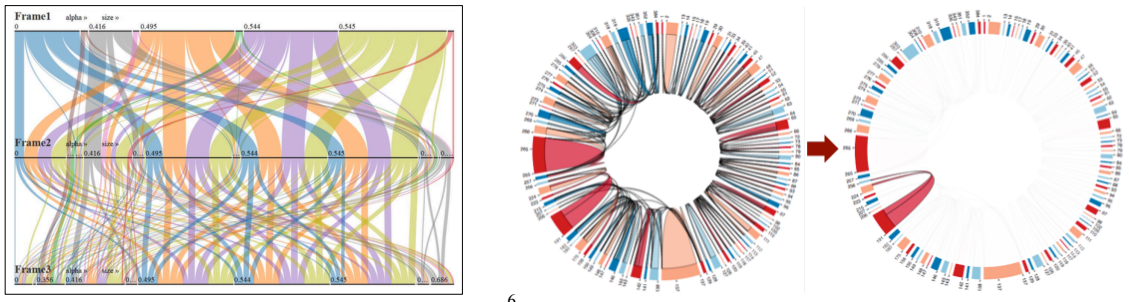

Fig. 6. (a) Visualization showing eras visualized using parallel sets[6]; (b) Interactive chord diagram used to visualize design change behavior.

As an example of how interactive multi-era analysis can generate insights in to system behavior and long-run value delivery we can look at path dependencies that arise due to changeability usage for the space tug case study. Prior multi-era research[6] has examined the use of a parallel sets to visualize the proportion of design occurrences within the time duration of a particular epoch as shown in Figure 6a. This type of visualization is useful in visualizing the temporal aspects of change across an era, but can become cumbersome for analysis across many long eras with many epochs. A new visualization, an interactive chord diagram, is introduced here as one possible way of representing aggregate change behavior in a more compact form. As shown in Figure 6b, the chord diagram can be used to represent the proportion of the time that a source design executes a change option to reach various target designs across multiple eras. All the designs that use change options to sustain value are enumerated around the circumference of the diagram and quadratic Bézier curves show the proportion of each source design changing to

† Note that eras could also be modelled using a directed cyclic graph. For instance if Markov Chain Monte Carlo (MCMC) methods were applied and transitions between a finite number of defined epochs were modelled probabilistically as was attempted by (Fulcoly, 2012).

‡ The exception is so called "pathological" game trees (Nau, 1983).

each target. The source and target arcs represent mirrored subsets of aggregate change behavior. Detailed analysis using this visualization allows an analyst to quickly identify designs that rely on changeability (rather than robustness) to maintain value and which options and end-state designs that are frequently used for various strategies.

The multi-era change path dependency analysis shows that while the network of changes (due to execution of options) that manifest during the space tug analysis are complex, interaction can allow specific insights to be extracted. For example, from the interactive chord diagram visualization shown in Figure 6b we see that only a small fraction of designs, 109 out of 384 (28%), actually use changeability to maintain value when implementing the multi-era maximize efficiency strategy. By hovering over a specific design we can gain more detailed information about its behavior across eras. In this example, design 191 is shown to exist in a change "limit cycle" with designs 224 and 256. When executing a change option design 191 will change 29% of the time into design 224 and 71% of the time into design 256. We can also observe from this interactive visualization that design 191 is the target end state rather than the source design 8 times less frequently. When it is the end state, design 224 is the source 66% of the time and 256 the remainder of the time. That these 3 designs never transition to any of the other designs within their reachable network (family/community), which contains 32 total designs, highlights their relative importance in this strategy. This behavior can be shown to vary significantly with the strategy assumed. This emphasizes the point that system value delivery is sensitive not only to variables related to design, change options and context, but also to operational characteristics that must be considered.

4.1.10. Process 10: Decisions and Knowledge Capture

The purpose of this process is not only to capture the final decision that is made, but also the chain of evidence that led to that decision which can be captured in a database or other knowledge management system. This information may prove useful to future studies by allowing post-hoc analysis of the rationale and specific assumptions that went into a decision. Though not demonstrated for this case study, the capability to capture and store key information about the reasoning behind a decision is an advantage of implementing IEEA in an integrated applications such as the web-based application demonstrated here.

5. Conclusion

The research presented here introduces the Interactive Epoch-Era Analysis (IEEA) framework which provides a means for analyzing lifecycle uncertainty when designing systems for sustained value delivery. Application of IEEA to a case study for a multi-mission on-orbit servicing vehicle demonstrates key concepts and prototype interactive visualizations. IEEA extends existing EEA frameworks with new analytic and interactive techniques that fundamentally enable new capabilities and insights to be derived from EEA, resulting in superior dynamic strategies for sustainment of system value delivery. These extensions enable the framing and analysis of large-scale problems, such as those posed by the DoD's Engineered Resilient Systems (ERS) efforts.

Future work will further extend interactive techniques to allow for improved analyses and decision-making. Improvements to IEEA processes for multi-era analysis, which has been covered less in existing literature than single and multi-epoch analysis, is an especially important area of future research. Active research in this area includes potential extensions of existing metrics, visualizations and analytical methods.

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