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Designing for System Value Sustainment using Interactive Epoch-Era Analysis: A Case Study from Commercial Offshore Ships

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Abstract

This paper applies the Interactive Epoch-Era Analysis (IEEA) framework on a case study from commercial offshore ship design, incorporating techniques from visual analytics such as interactive visualizations to gain insight from large, high-dimensional data sets resulting in improved strategies for value sustainment. New prototype visualizations are described which are motivated by a need to address design questions that are not well-suited for analysis with metrics, often applied in other EEA case studies, such as fuzzy Pareto number (FPN) or fuzzy normalized Pareto tract (fNPT) alone. For the offshore ship design case, this includes assessing the trade-off between designs optimized to target the primary mission versus being robust for uncertain subsequent missions. Further, considerations related to the implementation of interactive visualization applications, such as scalability and latency, are discussed emphasizing a need for continued research on methods for effectively handling large, high-dimensional data sets in design of complex systems under uncertainty.

Keywords: systems engineering; tradespace exploration; resilience; epoch-era analysis; interactive; visualization; visual analytics; ship design;

1. Introduction

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 [1,2]. Epoch-Era Analysis (EEA) has demonstrated its usefulness in prior research studies, but still faces some challenges to practical applications for informing decision-making for many real world problems. Although methods for implementing EEA constructs have been developed and applied in case studies, a prescriptive framework that explicitly considers human interaction does not exist. Furthermore, EEA can result in large, multivariate datasets that are difficult to generate, visualize and perform analysis on. To make informed decisions and design successful strategies for value sustainment, effective visualization and analysis techniques are needed to derive valuable insights from this data.

Interactive Epoch-Era Analysis (IEEA) is an iterative framework for concept exploration that provides a means of applying EEA constructs while controlling growth in data scale and dimensionality [3,4]. 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 a deeper understanding of the underlying data which can lead to improved decision-making. The extension of interactive visualization to system design problems with lifecycle uncertainty can 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. Methods: 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.

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. [5,6] as a prescriptive method for applying MATE and EEA, was developed to study system value sustainment through changeability. More recently, Schaffner [7] 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. However, some level of automated analysis could be beneficial as an aid to the user.

2. Description of IEEA Framework Modules

The purpose of IEEA, much like the purpose of RSC as described by Ross et al. [5], 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.
6. **Decisions** of final designs based on iterative evidence from previous modules.

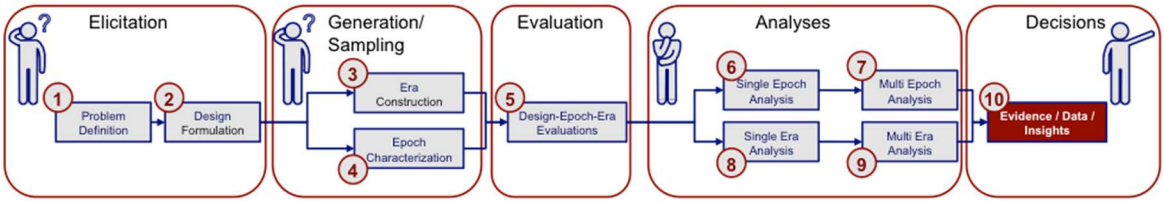


Figure 1: Interactive Epoch-Era Analysis process and modules.

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.

3. Implementation of a Visual Analytics Application for IEEA

Visual analytics applications in other domains have shown promise for solving problems whose size, complexity, and need for closely coupled human and machine analysis may make them otherwise intractable [8,9]. A primary focus of research on the IEEA framework has been towards the development of visual analytics applications that can be applied to evaluate and demonstrate how enhanced human interaction techniques and visualizations can aid in the analyses and sense-making of high-dimensional multivariate EEA data sets.

The exact visualization and interaction approaches for implementing each of the process steps are non-unique and various issues can arise depending on the specific way in which a visual analytics application is implemented. For example, the specific software implementation of an interactive visualization application requires trade-offs in development effort, extensibility, comprehensibility, scalability and interaction latency. The exact visualization or analysis that is most useful to an analyst applying the IEEA framework is largely case-dependent. Therefore, the prototype visualizations developed for this research are not intended as a one-size-fits-all application, but rather as examples that demonstrate techniques and interactive visualization types that can be customized for a specific case.

Many of the techniques discussed in Curry et al. [3,4] can be applied to facilitate a practical implementation of IEEA. For example, online analytical processing (OLAP) techniques can be applied to improve data handling which enables scalability to larger data sets with more designs, epochs or other data dimensions. Interaction latency is a common issue as the size of the data set grows and prior research has shown that increasing latency can adversely affect user performance in exploratory data analysis [10]. This is largely task dependent, however, so a user-centric approach is recommended rather than focusing on reducing latency across all analysis stages. For operations that are sensitive to latency, such as brushing and linking between coordinated views, methods such as caching, pre-computing and pre-fetching can be applied to minimize latency. Trade-offs must be considered though, because it is not always beneficial or possible to pre-compute every conceivable piece of data that the user might be interested in evaluating.

3. Commercial Offshore Ship Case Study

This case study is based on the case described by Rehn et al. [11], and the reader is advised to visit that paper for further case specific details.

Offshore ships, in contrast to traditional deep sea cargo ships, are ships that are designed to provide special operational services typically related to the offshore oil and gas industry. This group of ships is comprised of platform supply vessels (PSV), inspection maintenance and repair (IMR) and offshore construction vessels (OCV), to mention a few. A recent period of high oil prices and deep sea petroleum discoveries have spurred the development of offshore oil and gas fields. Following, there has been a

growing need for offshore services, including well maintenance and intervention services with light, riserless technologies. OCVs have taken an increasingly large part in the development of these, in particular for the marginal fields, due to their price competitiveness. Additionally, the Deepwater Horizon oil spill in 2010 in the Gulf of Mexico has changed some of the focus for the offshore shipowners towards being able to provide various deepwater emergency and rescue operations. This strong-market period has characteristically driven the design of offshore ships towards multifunctional, *gold-plated* and expensive solutions [12]. However, the recent oil price collapse of 2014 has had significant impact on the offshore markets, rendering many of these multi-functional ships less competitive to specialized and cheaper ships. The current situation in the offshore industry serves as good example of the importance of focusing on value robustness and operating flexibility as key factors for success in this highly volatile industry.

Offshore ships are usually built either for a specific long-term contract, or on speculation. A long-term contract may last 5-10 years, and these ships are often specialized for the particular mission. Ships built on speculation tend to be multifunctional, to be able to take on different contracts. If these ships do not get any lucrative long-term contracts, they are often offered in the sport market to take on various short-term contracts. If a ship does not get a contract, it is idle for short periods or laid up over longer periods. This case study motivates several questions, the evaluation of which may aided by the use on interactive applications described in this paper and prior IEEA case studies:

1. What is the trade-off between optimizing for the primary contract and making the design robust to more than one contract in terms of the number of acceptable designs in the tradespace?
2. What is the impact in terms of both cost and reduced performance when attempting to ensure that designs satisfy all contracts?
3. What are the benefits and drawbacks of active versus passive value robustness?
4. Which contracts or stakeholders are most challenging to satisfy?

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 business opportunity for a new offshore ship design emerges from an expected strong demand for offshore oil and gas over the next couple of decades, despite recent short term oil price volatility. The Deepwater Horizon accident has further resulted in an increased focus on being able to provide advanced offshore emergency services in the Gulf of Mexico. Two offshore ship owners form a joint venture targeting this business opportunity, and specifically a potential five-year contract for a large oil company. The fundamental strategies of these stakeholders are different. Stakeholder 1 focuses on providing a wide range of operations within the Gulf of Mexico, and is interested in being the first subsea contractor in the Gulf of Mexico by building and operating a fleet of profitable OCVs. Stakeholder 2 is a world-wide operator focusing on light well intervention (LWI) services, and is interested in continuing to be a leading provider of high quality offshore solutions by adding advanced, environmentally friendly and profitable OCVs to the existing fleet.

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. The system boundary for the single ship design is around the single ship itself, and does not consider, for example, the total profitability of the overall shipping companies. The idealistically solution-neutral value attributes are derived from the value propositions of each stakeholder separately. The value attributes for stakeholder 1 are originality, replicability and profitability, where originality represents whether the design will introduce new, advanced equipment to the area, replicability represents the simplicity of rebuilding the design at another yard, and profitability is a measure of the ability of the design to generate profits per time, operationalized through the contribution margin metric. The value attributes for stakeholder 2 are eco-friendliness, fleet integrability and profitability, where eco-

friendliness represents the ability of a design to reduce emissions during operation and transit, fleet integrability represents the ability of a design to integrate with the advanced fleet of stakeholder 2. Even though *value focused thinking* involves exploring various high-level solution forms, in this case we assume the form of a standard single-hull OCV for demonstration purposes in this case study. The following ship-level design variables are considered: length, beam, depth, power, accommodation, main crane, light well intervention tower, moonpool, fuel type, dynamic positioning and remotely operated vehicle (ROV) capability.

3. Process 3: Epoch Characterization

In process 3, the key contextual uncertainties are identified so that epoch variables can be characterized. Based on the system boundary defined, eight central epoch variables are identified, as illustrated in Figure 2. These epoch variables represent mainly the details of missions for a ship, operationalized through the contract rate and technical requirements, and the details of the operational area including the sea state and water depth.

Figure 2: System boundaries and epoch variables *[11]*.

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.

Three narrative scenarios are considered in this case study. In two of the eras the ship gets the targeted five-year contract initially, and a relatively strong market the rest of the assumed 20-year lifetime. In the third era the ship does not get the targeted contract due to a market collapse. For additional insight, an era simulation model is also considered. The targeted offshore service market is assumed driven by the oil price as an explanatory variable with time lag, modeled as a stochastic process. The probability of taking the intended five-year contract can then be considered explicitly, to better understand the trade-off between optimizing for the targeted mission and being robust for a wider range of missions. Other potential established and emerging market scenarios can be explicitly considered in addition to the initial targeted offshore oil and gas market, including offshore wind, aquaculture and mining.

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). This step connects the value space and the design space in a mapping process, often via an intermediate performance space. For the offshore ship, the various key performance indicators are estimated based on simple relations from the design variables, including speed, deck area, dead weight, maximum depth of operation, maximum significant wave height of

operation, contribution margin, acquisition cost and operational costs. The maximum depth of operation, contribution margin and operational costs are dependent on both design variables and epoch variables. The single attribute utilities are estimated for each design, and assigned weights based on the market state, as defined in [11]. Designs that are violate the technical requirements in an epoch are rendered infeasible. A multi attribute expense (MAE) function can be used to include a weighted combination of various costs for assessment in a tradespace, but for simplicity in this offshore ship design case, we only consider acquisition cost in the tradespace analyses.

6. Process 6: Single Epoch Analysis

Single epoch analysis is comparable to what is often 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 the Fuzzy Pareto Number (FPN) [13], 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 set of 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 3 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.

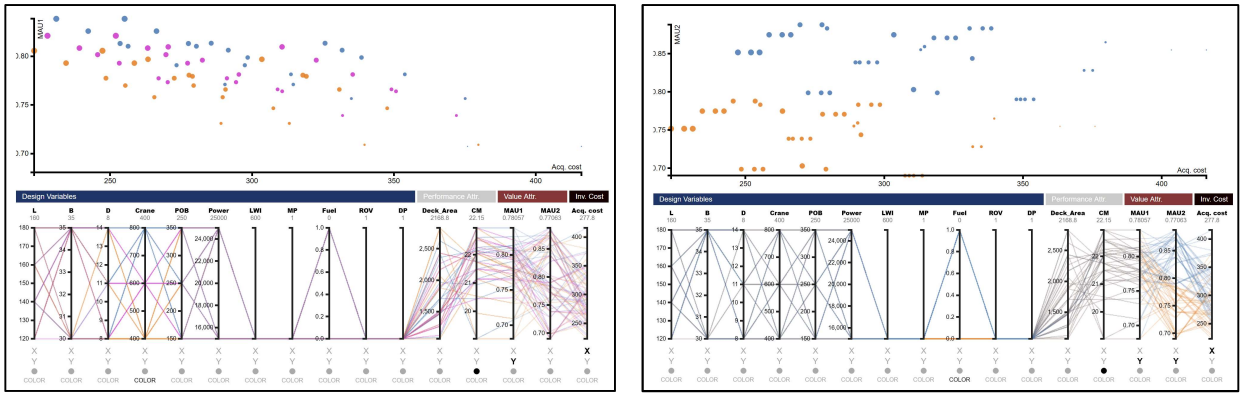


Figure 3: Interactive Filtering Application for stakeholder 1 (left) and stakeholder 2 (right) for the targeted contract epoch,

Figure 3 illustrates the tradespace for the feasible designs for each stakeholder in epoch 1 (primary contract) with the context and needs in the five-year contract that is targeted. The interactive filtering can aid in visualization in the exploration process of understanding the individual design variables’ relative significance, as illustrated.

7. Process 7: Multi-Epoch Analysis

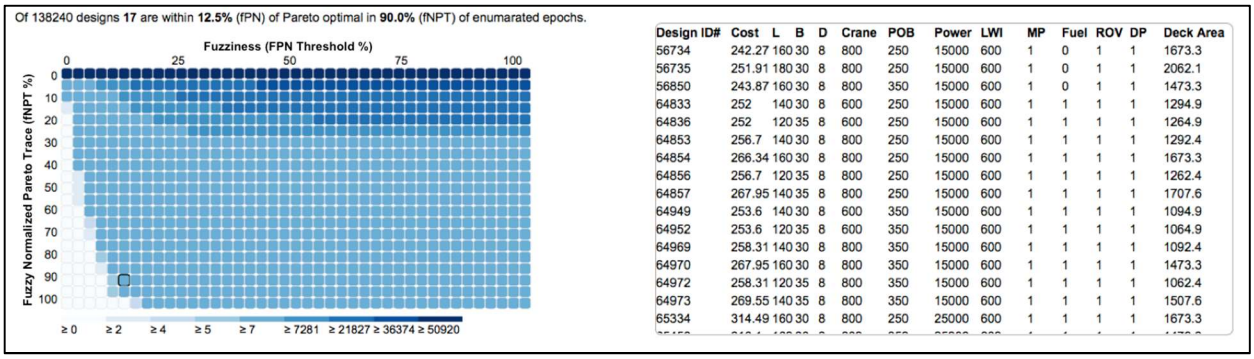
The activities of process 7 allow a decision-maker to gain deeper insights by evaluating metrics between and across epochs to gauge the impact of uncertainties on system value. This includes the evaluation of short run passive and active strategies for achieving value sustainment such that systems can 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.

4.7.1 Evaluating passive strategies for value sustainment (Robustness)

In general, we want to have the cheapest ship that can fulfill the technical requirements of a contract or mission. Since the ships that do not have the required technical equipment for the epoch are considered infeasible, the tradespaces will change significantly depending on the epochs. Equipment is typically a large cost driver, hence trade-offs are likely required between optimality in any one epoch versus how many of the enumerated epochs can be satisfied when using passive strategies only. Proper exploration of the trade-off between the "closeness" to the Pareto front (FPN), and the passive robustness across various epochs (fNPT), is therefore important when extracting insight from these high dimensional, big data datasets produced.

When examining this trade-off, attempting to look at all data dimensions of all possible designs across all possible epochs can be daunting for decision-making. Even with clever visual encoding, visualizations that show all the data could likely incur additional cognitive load for the user rather than reduce it. Fortunately, an internal mental representation of all data is not strictly necessary for an analyst depending on the task they are focused on. The interactive heatmap visualization shown in Figure 4 is one example of a simplified visualization that can show the compromise between Pareto efficiency (FPN) of designs within an epoch and the frequency with which they maintain that level of efficiency across multiple epochs (fNPT). This is illustrated in Figure 4 for the offshore case for both stakeholders, and we can see that there is no design that is Pareto optimal in all enumerated epochs. Excepting designs slightly away from the Pareto front or relaxing the constraint that all epochs must be satisfied allows additional design candidates to be identified. The fuzziness (e.g. threshold FPN value) needs to be relaxed to approximately 17% in order for any designs to be in the fuzzy Pareto set for all epochs.



Design ID#	Cost	L	B	D	Crane	POB	Power	LWI	MP	Fuel	ROV	DP	Deck Area
56734	242.27	160	30	8	800	250	15000	600	1	0	1	1	1673.3
56735	251.91	180	30	8	800	250	15000	600	1	0	1	1	2062.1
56850	243.87	160	30	8	800	350	15000	600	1	0	1	1	1473.3
64833	252	140	30	8	600	250	15000	600	1	1	1	1	1294.9
64836	252	120	35	8	600	250	15000	600	1	1	1	1	1264.9
64853	256.7	140	30	8	800	250	15000	600	1	1	1	1	1292.4
64854	266.34	160	30	8	800	250	15000	600	1	1	1	1	1673.3
64856	256.7	120	35	8	800	250	15000	600	1	1	1	1	1262.4
64857	267.95	140	35	8	800	250	15000	600	1	1	1	1	1707.6
64949	253.6	140	30	8	600	350	15000	600	1	1	1	1	1094.9
64952	253.6	120	35	8	600	350	15000	600	1	1	1	1	1064.9
64969	258.31	140	30	8	800	350	15000	600	1	1	1	1	1092.4
64970	267.95	160	30	8	800	350	15000	600	1	1	1	1	1473.3
64972	258.31	120	35	8	800	350	15000	600	1	1	1	1	1062.4
64973	269.55	140	35	8	800	350	15000	600	1	1	1	1	1507.6
65334	314.49	160	30	8	800	250	25000	600	1	1	1	1	1673.3

Figure 4: Interactive heatmap visualization (left), inspection table (right) for the ships in the selected tile in the heatmap.

The interactive heatmap provides a high-level overview of trades between efficiency and robustness, but what if an analyst wants to examine more complex trade-offs. For example, how do restrictions on cost or other performance attributes impact the trade-off between FPN and fNPT? Alternatively, what if an analyst wants to identify whether certain epochs, stakeholders or context variables are more problematic than others for system value sustainment or have a disproportionate effect on restricting the space of available alternatives. This type of information cannot be obtained from the heatmap visualization or aggregate measures like fNPT. More complex or nuanced questions like these require the examination of additional data dimensions that can be difficult to visualize and can also present added computational challenges.

This type of analysis is possible, however, with the aid of a more sophisticated visual interface like the example shown in Figure *5* that applies a combination of online analytical processing (OLAP) and binned aggregation for fast filtering and interaction with larger data sets. This visualization can also be easily

scaled to case studies involving millions of designs and large numbers of data dimensions. This is possible because rather than plotting every data point, each dimension is binned into a histogram that allows filters to be placed on individual data dimensions to see how that impacts the other dimensions in coordinated views. A list of candidate designs that match the filters is then displayed in the list on the right.

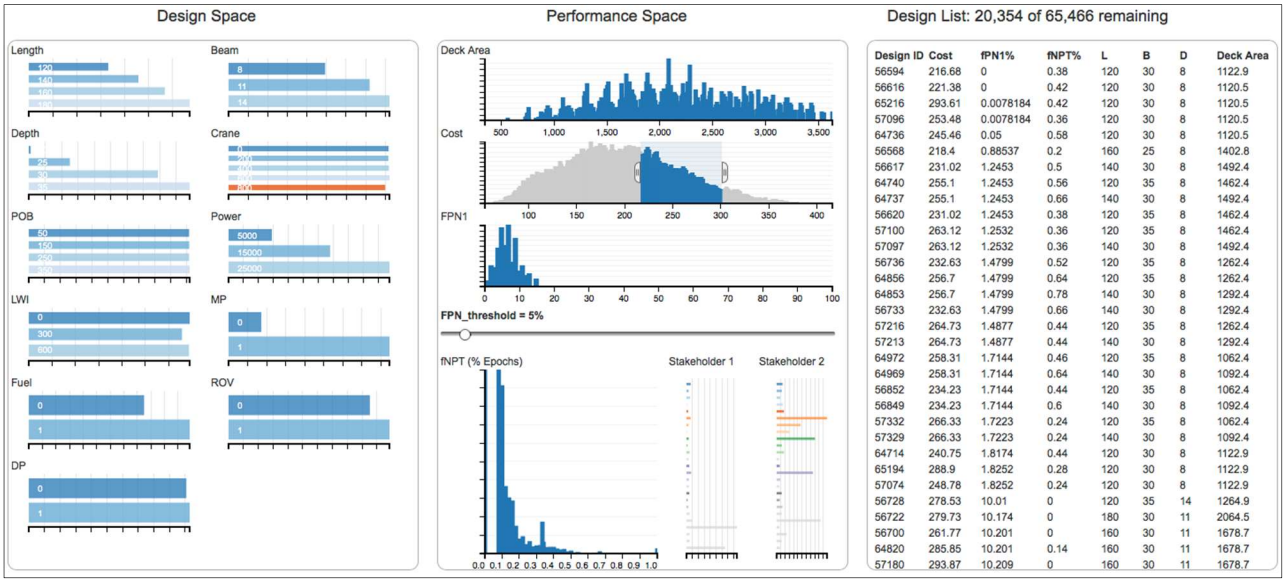


Figure 5: Interactive Filtering Application implementing OLAP for the offshore case.

An analyst using this type of interactive visual interface can extract deeper insights about various trade-offs by setting filters on various data dimensions to explore how those constraints impact other data dimensions or the list of available designs. For the commercial ship case study this can be applied to gain a better understanding of the impact of fuzziness (FPN) and cost constraints. For instance, while designs that are acceptable in all epochs can be found by relaxing the fuzziness threshold to 17% these designs tend to be among the most expensive in the tradespace. In fact, no matter how much the fuzziness threshold is relaxed, there are no designs that satisfy all epochs for a cost lower than $230M.

4.7.2 Evaluating active strategies for value sustainment (Changeability)

Implementation of changeability in the offshore ship case enables the system to mitigate risk and take advantage of opportunities in the future operation context. This is enabled by initially optimizing for the targeted contract, but also providing the flexibility to be able to change the design later based on the next state of operation, which is uncertain at the initial design stage. An offshore ship may be seen as a movable flexible platform that can carry equipment that enables the ship take on contracts of various types. The size of the platform may also change, through for example elongation (jumboisation), but at a higher cost, time and duration, compared to a traditional equipment retrofit on deck. Though not yet demonstrated for this case study, interactive visualizations may aid in assessing different classes of changeability for the offshore design case as demonstrated in prior case studies using IEEA [4].

4.7.3 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 analyze. 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.

4. Conclusion

The research presented here applies 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 commercial offshore ship design demonstrates key concepts and prototype interactive visualizations. IEEA extends existing frameworks with new analytic and interactive techniques that enable new capabilities and insights to be derived which can lead to improved dynamic strategies for sustainment of system value delivery. In addition, these extensions enable the framing and analysis of large-scale design problems with uncertainty, such as the case study presented here. Future work will extend the case study presented to include epoch-level analysis of options for changeability as well as era-level analysis of time-dependent aspects of system value.

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