7.0 Case Study 2 – Commercial offshore ships

The space tug case study described in Chapter 6 provided an example for how the IEEA framework could be applied in detail to a simple, but non-trivial, system design problem. Though the problem was a familiar one studied in prior research [30] interactive visualizations allowed the discovery of new insights that can impact previous conclusions. As a next step, this chapter explores the application of IEEA to a new problem domain and examines issues related to scalability of both the framework and interactive visualization applications. Issues related to scalability can derive from four primary aspects, depending on the nature of a particular case study [77]:

1. Amount of data
2. Dimensionality of data
3. Complexity of data
4. Dynamic data

Though the system model considered for this case study is of greater complexity, scalability as illustrated in this chapter will primarily center on issues that arise due to the quantity and dimensionality of the data. This chapter applies the IEEA framework to a case study focused on commercial offshore ship design, incorporating interactive visualizations, similar to those shown in the previous case study, to gain insight from large, high-dimensional data sets to facilitate improved strategies for value sustainment. The application of IEEA to this problem is motivated by a need to address design questions that are not well-suited for analysis solely with metrics, often applied in other EEA case studies, such as fuzzy Pareto number (FPN) or fuzzy normalized Pareto trace (fNPT). 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. This case study is based on the one described by Rehn et al. [164]. A basic description of the case is provided throughout this chapter, but the reader is referred to the paper by Rehn et al. for a more detailed discussion of the case setup.

7.1 Case Background

Offshore ships, in contrast to traditional deep-sea cargo ships, are designed to provide special operational services typically related to the offshore oil and gas industry. This group of ships comprises 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 has spurred the development of offshore oil and gas fields. As a result, 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 ship owners 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 [165]. However, the recent oil price collapse of 2014 has had a significant impact on the offshore markets, rendering many of these multifunctional ships less competitive against cheaper, specialized ships. The current situation in the offshore industry serves as a good example of the importance of focusing on value robustness and operational flexibility as key factors for success in a highly volatile maritime industry [166,167].

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 more 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 spot 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 be aided using interactive applications described in this thesis and by 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 potential contracts?
3. What are the benefits and drawbacks of active versus passive value robustness?
4. Which contracts (e.g. epochs) are most challenging to satisfy?

7.2 Elicitation

The following subsections describe the processes of the elicitation module of IEEA.

7.2.1 Process 1: Value-Driving Context Definition

The first process defines the stakeholders, problem statement, exogenous uncertainties and the basic value proposition for the system. For this case, 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. An offshore ship owner wants to target this business opportunity, and, in particular, a potential five-year contract for a large oil company. The ship owner values a solution that is both profitable and environmentally conscientious (e.g. eco-friendly).

7.2.2 Process 2: Value-Driven Design Formulation

The second process begins by defining the statements of needs, which become the attributes of system performance; along with utility functions describing the preference for each attribute. The system boundary for the single ship design is around the ship itself and does not consider, for example, the total profitability of the overall shipping company. Profitability is a measure of the ability of the design to generate profits, and eco-friendliness represents the ability of a design to reduce emissions during operation and transit. The non-monetary and monetary value attributes are kept separate due to their temporal differences in the model, which is further discussed in Rehn et al. [164]. In the model, profitability is considered at the era level, while eco-friendliness is considered at the epoch level.

Even though value focused thinking involves exploring various high-level solution forms, the form of a standard single-hull OCV is assumed 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, remotely operated vehicle (ROV), pipe laying capability and design for changeability level.

7.3 Generation / Sampling

The following subsections describe the processes of the generation and sampling modules of IEEA.

7.3.1 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 epoch variables are identified, as illustrated in Figure 7-1 and described in Table 7-1. These epoch variables represent the details of a missions for a ship, operationalized through the contract type, technical requirements, and operational area. The contract type implies the rate (K$/day) that can be earned by the ship if the contract is accepted. The technical requirements are driven by which one of the 12 missions shown in Table 7-3 is associated with the contract. The contract also specifies one of four operational areas which each impose different requirements on what sea state and water depth the ship must be able to handle as shown in Table 7-3.

Figure 7-1: System boundaries and epoch variables [164].

Table 7-1: Epoch variables **[164]**

	Epoch Variable	**Unit**	**Values**
Contract Parameters	Contract Type	[-]	[Spot, Term]
	Operational area	[-]	[Gulf of Mexico, Brazil, North Sea, West Africa]
Technical Requirements	Light well intervention requirement	tonnes	[0, 300, 600]
	Module weight req.	tonnes	[0, 200, 400, 600]
	Accommodation req.	POB	[50, 150, 250, 350]
	ROV requirement	[-]	[0, 1]
	Dynamic positioning requirement	[-]	[0, 1]
	Deck area req.	m^2	[0, 1000]

Table 7-2: Missions associated with technical requirements [168]

Mission
Subsea installation & Construction
Inspection, maintenance and repair
Light well intervention
Offshore accommodation
Offshore cable laying
Offshore pipe laying
Offshore platform supply
Emergency response
Offshore mining support
Offshore aquaculture support
Field decommission support
Offshore wind support

Table 7-3: Operational area requirements [164,168]

Operational Area	Depth requirement (m)	Wave height requirement (m)
Gulf of Mexico	1600	2.0
Brazil	2500	2.5
North Sea	200	3.0
West Africa	1800	1.0

7.3.2 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. The intent is to capture some insigts regarding the volatility of the oil market by having eras corresponding to rising, flat and declining oil prices, respectively. In two of the eras the ship gets the targeted five-year contract initially, and experiences 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. The three areas, described by their technical requirements, contract rates, operational area and mission type, are shown in Figure 7-2. Each epoch is assumed for simplicity to have a fixed duration of one year. Rehn et al. [164] describe the three eras as follows:

1. *Era 1 represents a baseline scenario, with the initial targeted tender and a strong offshore market continuation.*
2. *Era 2 represents a similar start with the targeted tender, followed by a weakened market that ends with offshore decommissioning in the later years of the lifecycle.*
3. *Era 3 represents a market collapse, where the initial targeted contract is not won.*

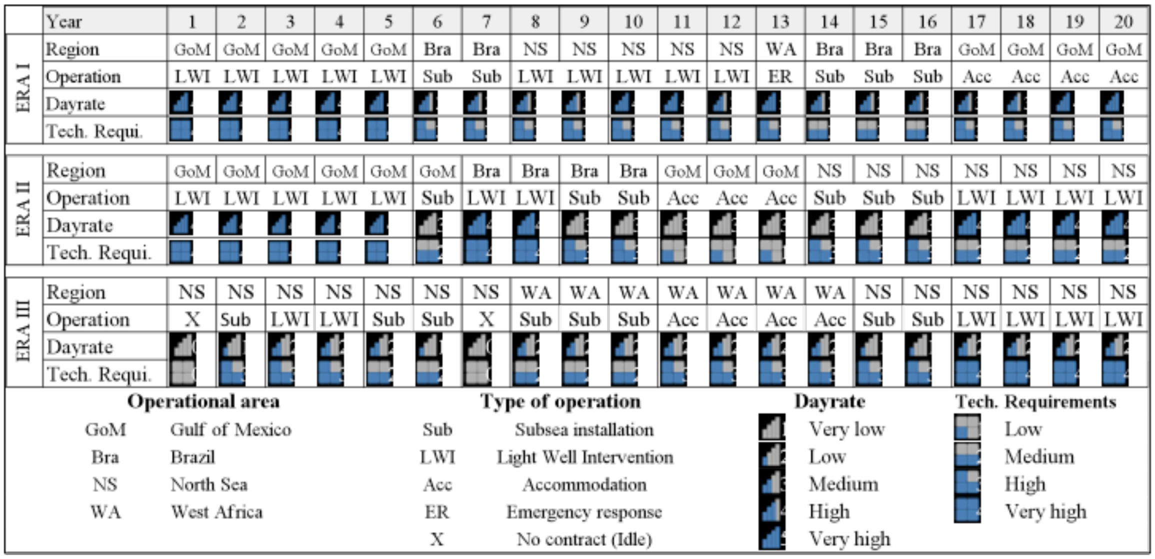


Figure 7-2: Descriptions of 3 narrative eras [164,168]

7.4 Evaluation

The following subsections describe the processes of the evaluation module of IEEA.

7.4.1 Process 5: Design-Epoch-Era Evaluation

As was done before with the space tug case study, in this process step the previously defined models are integrated to map design and epoch variables into stakeholder benefit and expense. For the offshore ship, the various key performance indicators are estimated based on an integrated performance model that maps the design variables to the performance attributes, including speed, deck area, dead weight, and eco-friendlessness score. Expense attributes, including acquisition cost and operational costs, are estimated in a similar manner. The design variables and levels considered in this analysis are shown in Table 7-4. A full enumeration of the design space would yield 124,416 designs, but not all design variable permutations are considered feasible. A component compatibility matrix is used to cull some designs from the full factorial enumeration of the design space resulting in 41,024 designs that are feasible within at least one epoch. Furthermore, during epoch analysis, designs that violate the technical requirements in an epoch are rendered invalid within that particular epoch.

Table 7-4: Design variable levels [164,168]

Design Variable	Levels
Length (m)	120, 150, 180
Beam (m)	20, 25, 30
Depth (m)	8, 13
Installed power (MW)	15, 25
Accommodation (persons)	50, 250, 400
Main crane capacity (tonnes)	0, 400, 800
Light well intervention (tonnes)	0, 300, 600
Moonpool	No, Yes
Fuel type	Marine Gas Oil, Dual Fuel
Dynamic positioning capability	DP2, DP3
Remotely operated vehicle	No, Yes
Pipe/cable laying equipment	No, Yes
Design for changeability level	0, 1, 2, 3

Table 7-5: Performance attribute levels across all evaluated designs

Performance Attributes	Range
Maximum Speed (knots)	[15.8, 24.4]
Deck Area (m^2)	[20.7, 3032.3]
Dead Weight (tonnes)	[4127.6, 30155.0]
Eco-friendliness score	[0, 10]

Table 7-6: Expense attribute levels across all evaluated design

Expense Attributes	Range
Acquisition cost ($M)	[86.8, 416.1]
Operational cost ($M/yr)	[20, 500]

The epochs for this case study are based on the available contracts. As described in section 7.3.1 the contract definition is comprised of its type, operational area and mission. Therefore, there are 2 (contract types) * 4 (operational areas) * 12 (missions) = 96 possible epochs. The epoch space is considerably larger than the one previously described for the space tug case study which imposes some data management and transformation challenges. To consider the feasibility and value delivery of all possible design-epoch pairs a total of 41,024 (designs) * 96 (epochs) ≈ 4 million evaluations are necessary. The scale of the data required for this case study creates unique challenges, but the analysis using interactive applications is similar in many ways to what was demonstrated for the space tug case study. The following sections will discuss the analysis of this case in further detail.

7.5 Analysis

The following subsections describe the processes of the analysis module of IEEA.

7.5.1 Process 6: Single Epoch Analyses

As was done earlier in this thesis with the space tug case study, the analysis of the ship case begins with single epoch analysis. Figure 7-3 illustrates the tradespace for the primary contract for the offshore ship design base case, that is the targeted contract with no technical requirements (e.g. epoch 1). At this stage, an analyst can focus on understanding the dynamics of the underlying system. In this particular case study, the MAU function is only comprised of one single attribute utility function, that is eco-friendliness, even though the figure indicates a multi-attribute utility function on a general basis. The interactive filtering can aid in visualizing the exploration process and understanding the relative significance of individual design variables, as illustrated. For instance, filtering by beam and length, an analyst can see that relatively slender ships tend to contribute to low FPN values which indicate designs that are near-optimal. However, this again makes a design less stable in the water, which restricts the possibilities of retrofitting heavy equipment on deck without intervening with the main hull. Further, one can directly see the trade-offs of adding DFC levels, as design points shift right in the tradespace with increasing DFC due to increased cost.

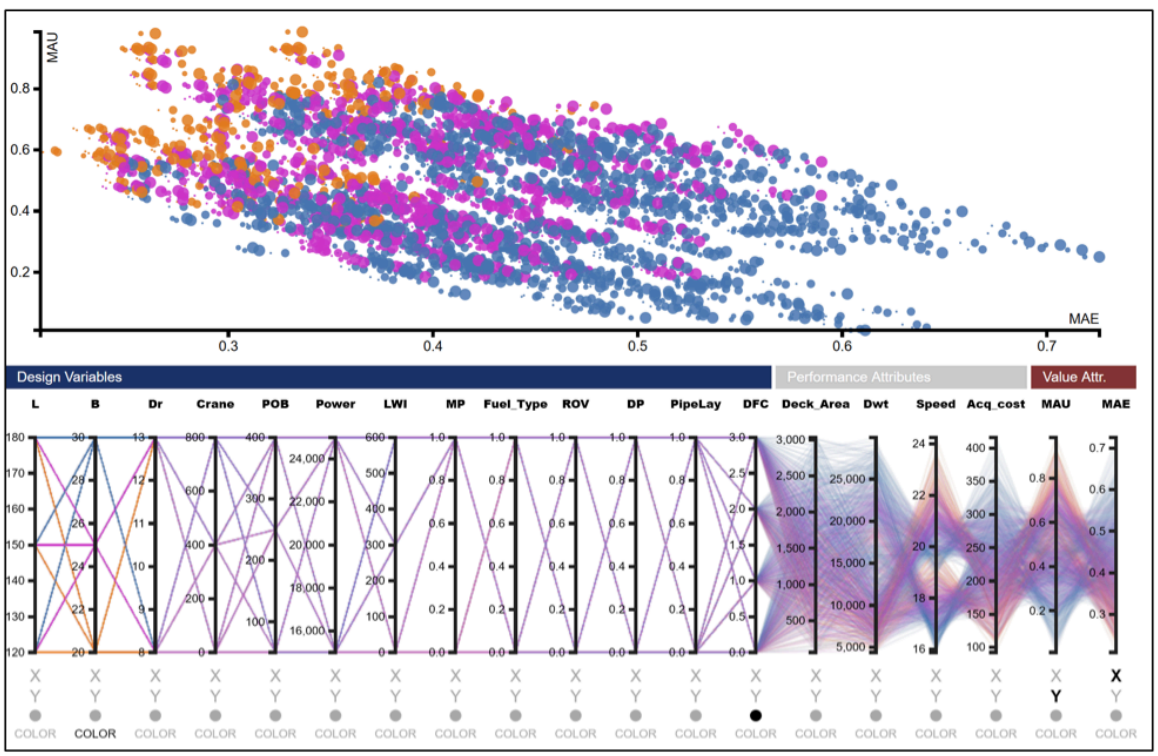


Figure 7-3: Interactive Filtering Application for tradespace exploration for the offshore ship design base case

This case study enumerates over 40,000 design alternatives, which means the number of elements that must be rendered and manipulated on the screen is increased by approximately two orders of magnitude when compared to the space tug case described in Chapter 6. Unlike the prior case study, this case has more designs than can feasibly plotted in the scatter plot without running into issues with visual occlusion due to overlapping points. Furthermore, the large number of elements can lead to latency issues due to memory and processing limitations when the analyst attempts to filter or manipulate the data in any way. Latency issues due to data transmission also occur when the visualization is initially loaded into the browser because of the large amount of data that must be pulled from a flat file or database.

Recall the observation made by Liu et al. that "perceptual and interactive scalability should be limited by the chosen resolution of the visualized data, not the number of records,"[65]. This suggests that a properly conceived interactive application should not be limited by the large number of designs considered in this case, but rather only by the level of granularity at which an analyst needs to perceive the data in order to comprehend it. Several of methods described in Chapter 3, including filtering, sampling or binned aggregation, can be applied in this case to enable scalability of the single epoch interactive visualization application by reducing the resolution of the visualized data. Pre-filtering or sampling the data would be an easily implemented solution, but come with the downside of potentially concealing important data points. However, applying a two-dimensional binned aggregation approach would allow a reduction in the number of visual elements that must be plotted to the screen without losing any information. Shown in Figure 7-4, an example visualization that uses hexagonal bins to display the same information previously shown in Figure 7-3 can reduce the number of visual elements that must be rendered by a factor of 10 (approx. 4000 bins instead of 40,000 points). In this example bin color is used to encode information about the spatial density of design alternatives rather than plotting every single point. By controlling the bin size the analyst can effectively control the resolution at which they would like to visualize the data regardless of the number of data points. For example, the visualization shown Figure 7-5 increases the size of the bins, which results in a further reduction in the number of visual elements by an additional factor of 5 (approx. 800 bins). Adjusting bin size in this way allows the analyst to control the resolution at which they would like to examine the data and scale their analysis relative to the amount of computational resources available to them. Note that while not implemented for this case study, related approaches could also be applied to visually scale the parallel coordinates plot. Approaches for doing so are discussed in Appendix 9.4.

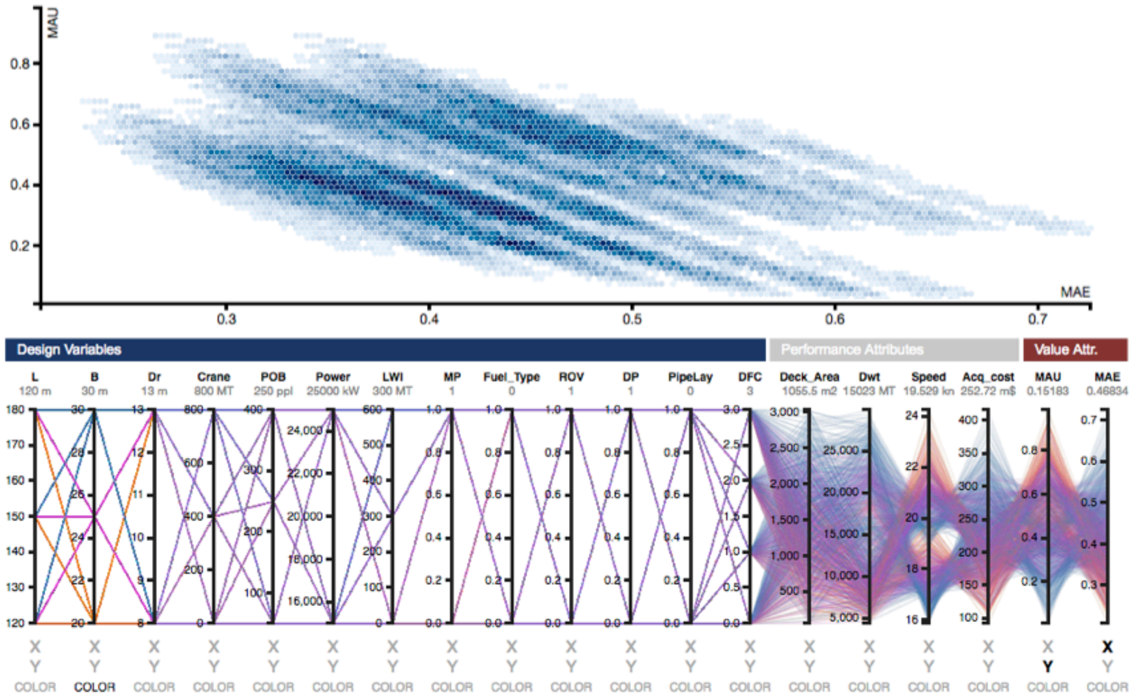


Figure 7-4: Interactive Filtering Application with (fine) hexagonal binning

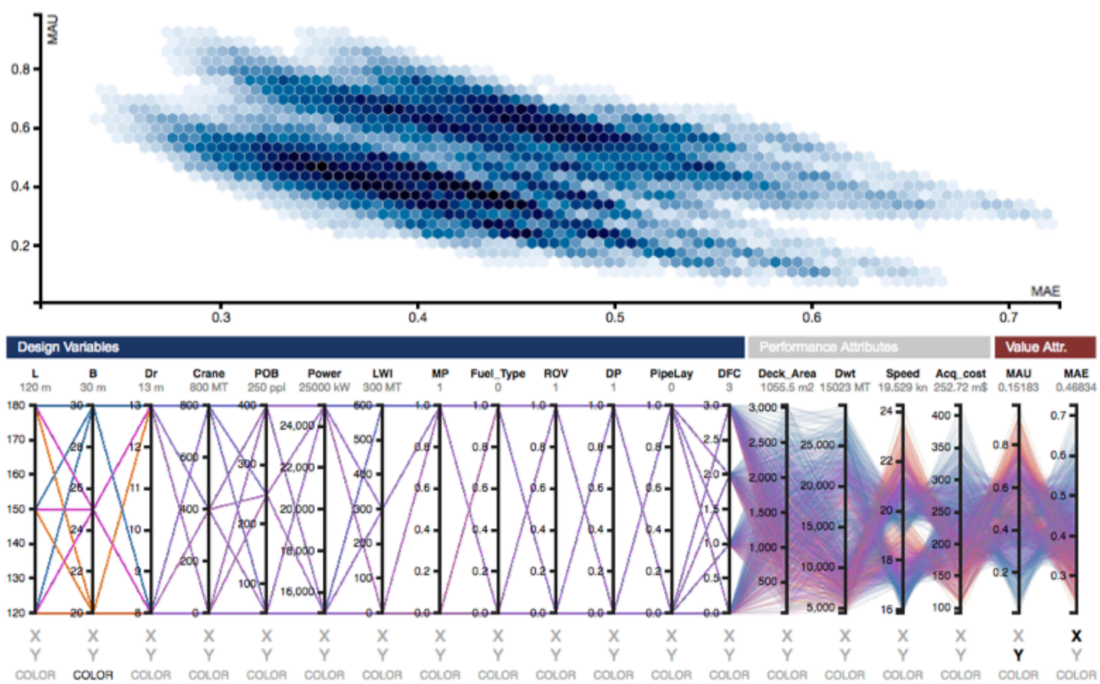


Figure 7-5: Interactive Filtering Application with (course) hexagonal binning

7.5.2 Process 7: Multi-Epoch Analysis

The activities of process 7 allow decision-makers 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 it flexible, adaptable, or resilient. Because multi-epoch analysis must by definition consider a larger amount of data issues with scalability of interactive application can be more apparent. For the analysis discussed in this section, a much larger number of designs and epochs are considered as compared to the space tug case study, which illustrates the extensibility of previously demonstrated applications.

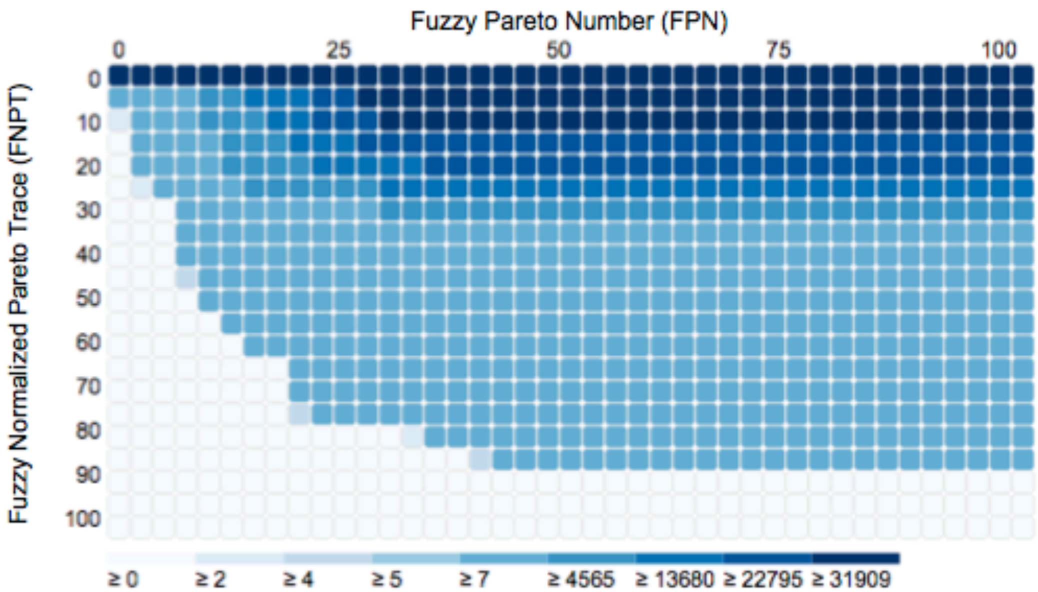
7.5.2.1 Evaluating passive strategies for value sustainment (Robustness)

In general, we want to have the lowest cost ship that can fulfill the technical requirements of a contract. Since ships that do not have the required technical equipment for an epoch are considered infeasible, the number of designs in the tradespace as well as its shape will change 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. As with the previous case study, the percentage of enumerated epochs satisfied at a given fuzziness level is quantified using the fuzzy normalized Pareto trace (FNPT) metric. A proper exploration of the trade-off between "closeness" to the Pareto front (FPN) and passive robustness across various epochs (FNPT) is important when extracting insights from these large, high-dimensional data datasets that are produced in the design process.

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-makers. Even with clever visual encoding, visualizations that show all the data could likely incur additional cognitive load for the users rather than reduce it. It can also be computationally burdensome and a barrier to scalability in case studies with large amounts of data points to consider, as was illustrated by the scatter plot in single epoch analysis. Furthermore, plotting every single data point, even if computationally feasible, can often not even be perceived by the analyst. Fortunately, depending on the task they are focused on, an internal mental representation of all data is not strictly necessary for an analyst. The interactive heatmap visualization shown in Figure 7-6 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).

As illustrated in Figure 7-6 for the offshore case, there are no designs that are Pareto optimal in all enumerated epochs. Note that there are only white tiles, which represent zero satisfactory designs, if we look below the 85% FNPT point on the chart.

Accepting 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 figure shows that the fuzziness (e.g. threshold FPN value) needs to be relaxed to approximately 40% for any designs to be in the fuzzy Pareto set for an estimated maximum 85% of all epochs. This indicates that, in fact, no ship can satisfy all contracts and that the most multifunctional passively robust ship can satisfy a maximum of 85% of the potential contracts requirements. In general, this is shown on the heatmap by noting that more designs become acceptable at a given FNPT level as we move to the right, which represents an increasing allowable FPN value. At FNPT values greater than 35% it can be observed that relaxing FPN further does not increase the number of acceptable designs. This tends to indicate that the limits of what can be achieved through passive robustness alone have been reached and any further gains will require changeability to allow the designs to adapt to changing futures.



Of 41024 designs **4** are within **40.0%** (fPN) of Pareto optimal in **85.0%** (fNPT) of enumarated epochs.

DesignID	Cost [m$]	Length [m]	Beam [m]	Depth [m]	Crane [MT]	POB [ppl]	Power [kW]	LWI [MT]	Moonpool [n/y]	Fuel [n/y]	ROV [n/y]	DP [n/y]	PipeLay [n/y]	DFC [-]	DeckArea [m²]	Dwt [MT]	Speed [kn]
9739	284	180	30	8	800	250	15000	600	1	0	1	1	1	0	1260	9463.9	16.8
10195	308	180	30	8	800	250	15000	600	1	1	1	1	1	0	1260	9463.9	16.8
19995	285	180	30	8	800	250	15000	600	1	0	1	1	1	1	1260	9463.9	16.8
20451	309	180	30	8	800	250	15000	600	1	1	1	1	1	1	1260	9463.9	16.8

Figure 7-6: Interactive heatmap visualization (top), inspection table (bottom) for the ships in the selected tile

An analyst using this type of interactive visual interface can extract deeper insights about 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, the designs that tend to be acceptable in most epochs, explored in the heatmap visualization in Figure 7-6, also 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 more than 85% of the epochs for a cost lower than $285 million. An analyst interested in achieving a lower target cost would need to examine in detail the cost savings that could be achieved by eliminating certain epochs (e.g. contracts, missions) which would result in a lower FNPT.

The interactive heatmap provides a high-level overview of trades between efficiency and robustness. But does not answer the questions: if an analyst wants to examine more complex trade-offs, for example, how restrictions on cost or other performance attributes impact the trade-off between FPN and FNPT, or, alternatively, if an analyst wants to identify whether certain epochs, stakeholders or context variables are more problematic than others for system value sustainment or they 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 7-7, where a combination of online analytical processing (OLAP) and binned aggregation for fast filtering and interaction with larger data sets are applied. 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.

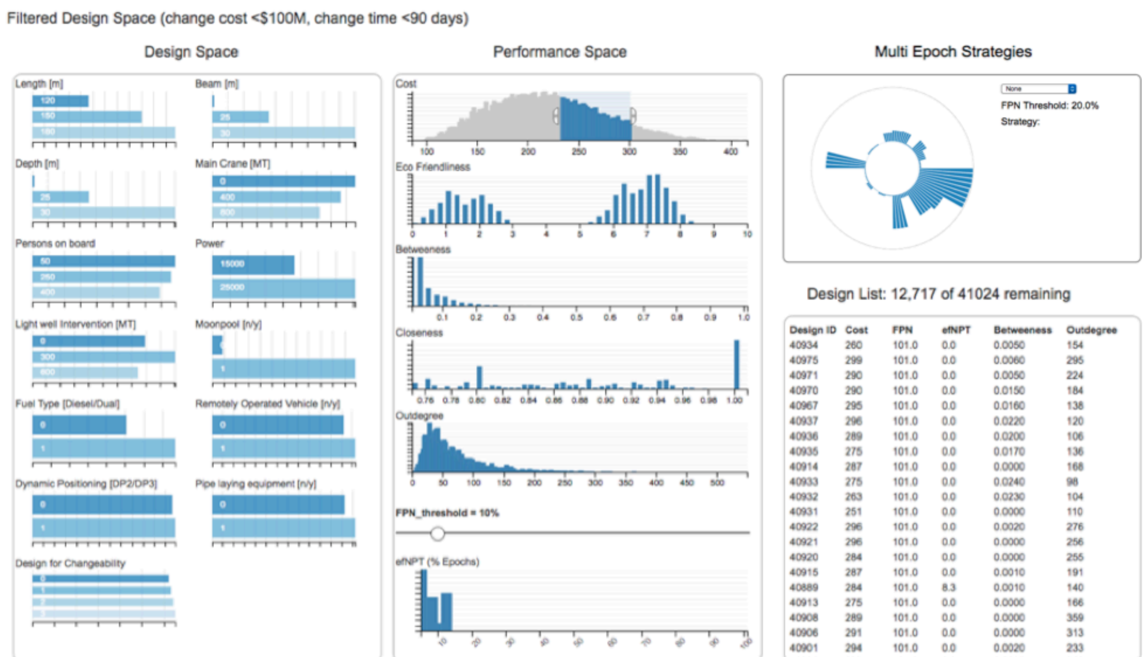


Figure 7-7: Interactive Filtering Application implementing OLAP for the offshore case (Filtered for allowable change cost < $100M and change time < 90 days)

As was the case with the space tug case study, the Nightingale coxcomb diagram is also integrated into the OLAP driven visual interface for this case study in order to provide a comprehensive view of aggregate design performance in each enumerated epoch. For the ship case study the diagram shows all 96 epochs which is a factor of six greater than the number of epochs enumerated for the space tug case study. Figure 7-8 shows how the coxcomb diagram can be used to compare two different FPN thresholds (10% versus 20%) for designs that are passively robust. Note that chart zoom setting is such that the outer ring represents a yield of approximately 50% or, in other words, about 20,000 satisfactory designs in a given epoch. At an FPN threshold of 10% many of the epochs have relatively low yields which illustrates that these epochs are generally more difficult to satisfy. Several of the more easily satisfied epochs still only show yields from 5-20% at this FPN threshold. Increasing the FPN threshold to 20% results in similar efficiency scores for each epoch, but significant gains in yield. Still, the majority of the epochs (80 out of 96) still have yields lower than one-third even at this higher FPN threshold level. This is due in part to the fact that while many of the enumerated combinations of design variables represent feasible designs they do not have particularly good performance in many epochs.

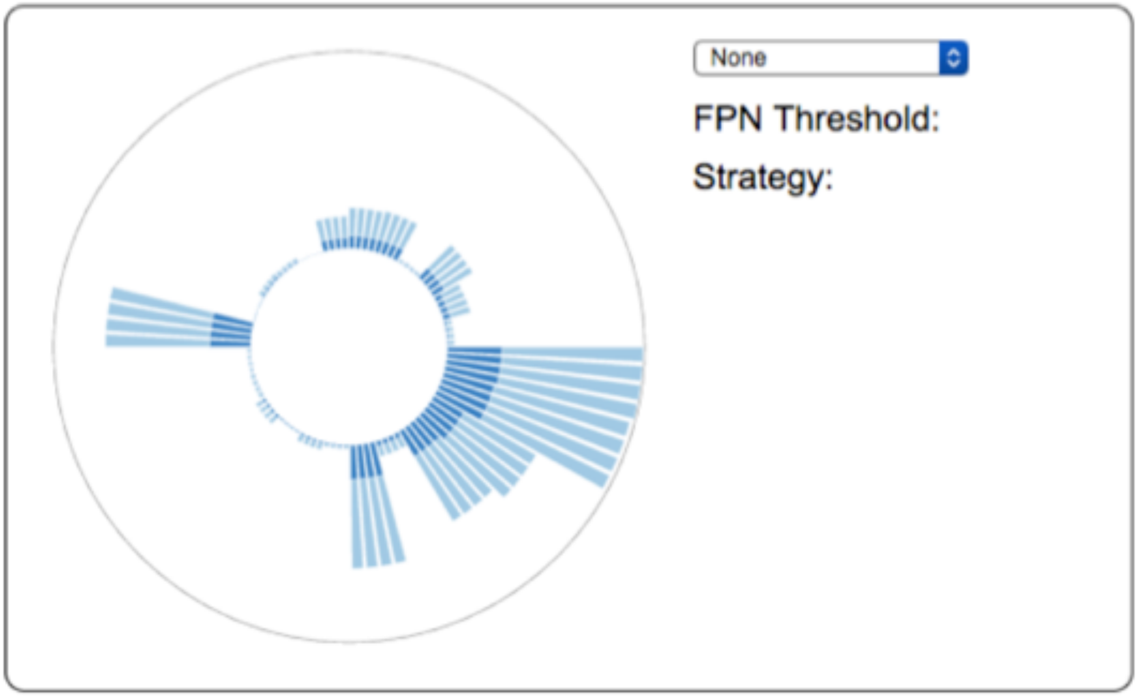


Figure 7-8: Nightingale coxcomb visualization for ship multi-epoch analysis comparing performance at an FPN threshold of 10% (dark blue) and 20% (light blue)

Filtering by epoch or epoch-level variables, though not demonstrated here, may provide further insights about why certain epochs are more difficult than others. This may also be useful for cases with larger numbers of epochs. While the Nightingale coxcomb makes a good compact visualization for a large number of epochs, displaying an infinite number of epochs would not be possible because of the pixel limitations of the screen. Focusing on a smaller number at any given time may not only be more comprehendible to the analyst, but also a necessity due to this limitation. Alternatively, filtering by epoch variables may also help identify what areas of the design may benefit most from adding changeability which will be discussed in the next section.

7.5.2.2 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 a future operational 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 to take on contracts of various types. The equipment on deck can be retrofitted or swapped for equipment with different functionality if the ship has sufficient deck area. The ship must also possess sufficient stability characteristics that are largely driven by the shape of the hull (e.g. length, beam, depth). At an intermediate point in the ship design's lifecycle the size of the platform may be changed, for example, through elongation ('jumboisation'), but at a higher cost, time and duration, compared to a traditional equipment retrofit on deck. Changing the hull generally requires the ship to be taken into port for some period during which time it is cut to be extended, contracted or otherwise reshaped.

Examining alternatives to the passive robustness approach demonstrated in the previous section the benefits of changeable designs can be visualized using the same visual application as before. For this study, the change options are the same as those described previously by Rehn et al. [164]. The change options in this case are operators on the design variables shown previously in Table 7-4. The change options are defined such that any design variable level can be changed to a different level assuming the resulting design is valid. In each case, both a change cost and time are defined. Figure 7-9 shows a comparison between a passive robustness strategy (dark blue) and a changeable strategy (light blue) at an FPN threshold of 10%. When using a changeability approach a maximize efficiency strategy is assumed similar to what was previously demonstrated for the space tug case study in Chapter 6. Looking at this broad overview first, it is clear that adding changeability generally improves the yield in each epoch and has only a small impact on average effective Pareto efficiency (eFPN). In fact, in most epochs, the yield is approximately doubled. Compare this to the result shown previously in Figure 7-8 that showed the impact of raising the FPN threshold and maintaining a passive robustness strategy. For that example, yields were approximately tripled when the FPN threshold requirement was relaxed. This example demonstrates how an analyst or decision maker may consider multiple approaches for finding more acceptable designs. If the FPN threshold cannot be lowered, or the decision maker simply prefers not to, a changeability strategy may be a more acceptable approach for them.

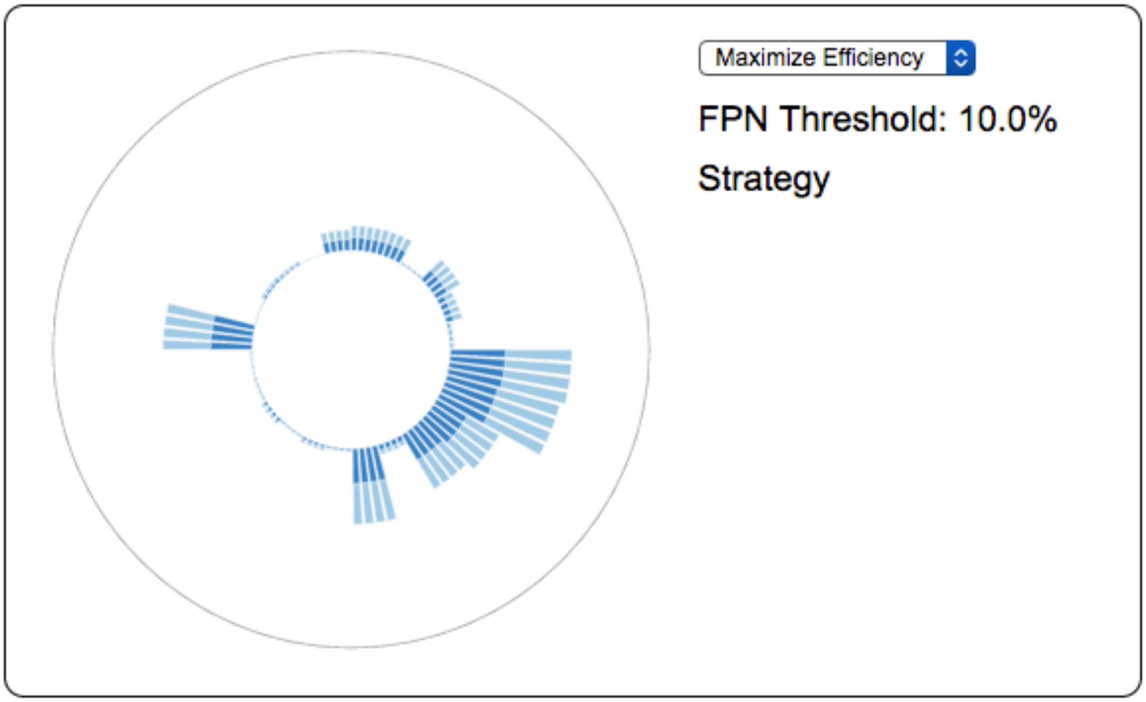


Figure 7-9: Nightingale coxcomb visualization for ship multi-epoch analysis comparing performance at an FPN threshold of 10% without changeability (dark blue) and with changeability using the maximize efficiency strategy (light blue)

But what if a designer wants to examine individual epochs that are either the best or worst performers to gain more insights? For example, consider epoch 25 that is generally a high-yield epoch for both changeable and passive robustness approaches. As with the space tug case study, an analyst can hover the mouse over any of the epoch wedges to get details on demand as shown in Figure 7-10. For this epoch, it shows that the baseline robustness strategy at an FPN threshold of 10% results in a yield for epoch 25 of approximately 13.3% and the yield increases to 29.3% when changeability is considered. Alternatively, if the FPN threshold is relaxed to 20%, the yield for epoch 25 increases to approximately 47.6%. A similar observation can be made for one of the more difficult epochs. Epoch 81, which is shown in Figure 7-11, has a yield of approximately 0.6% in the baseline passive robustness case and this increases to 1.3% and 1.6%, respectively, depending on whether we choose a changeable strategy or relax the FPN threshold as before.

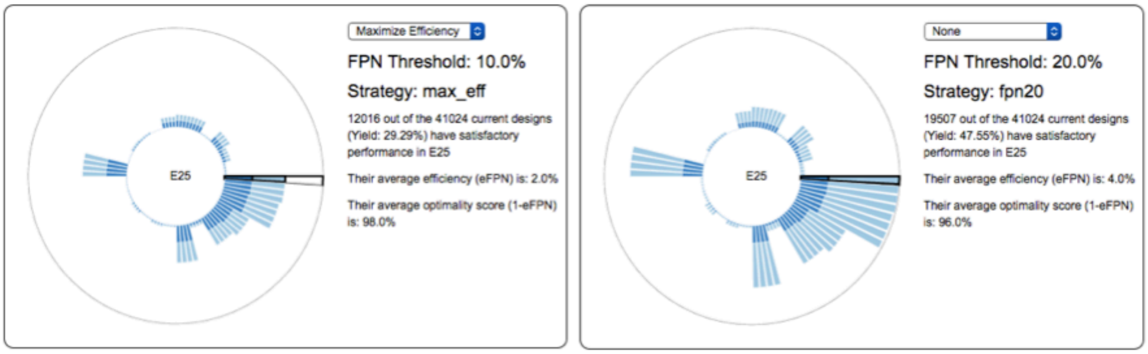


Figure 7-10: Comparing epoch 25 for a changeable maximize efficiency strategy (left) and a passive robustness approach (right)

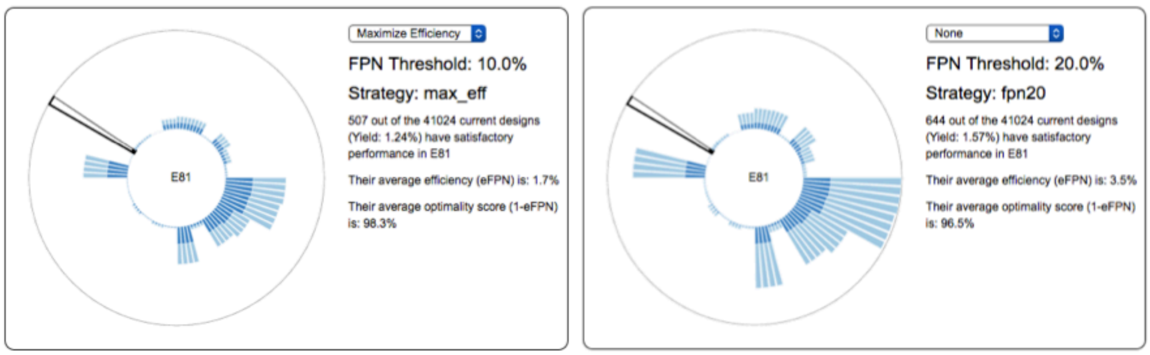


Figure 7-11: Comparing epoch 81 for a changeable maximize efficiency strategy (left) and a passive robustness approach (right)

Examining the designs that tend to perform well when we use a changeable approach with the maximize efficiency strategy reveals some other interesting insights. In general, the designs that perform well across most epochs tend to be ones with larger length, beam and depth that also tend to have large deck areas. This is likely the case because these designs can easily be retrofitted with different equipment to take on new missions. Designs that require modification to the hull must execute change options that are costly in terms of both time and money.

7.5.2.3 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 larger and more complex data set than what was considered for multi-epoch analysis which can be difficult to analyze. The application of an interactive framework and scalable interactive visualizations allows the analyst to engage with the data in new ways that can facilitate improved comprehension and decision-making. The insights that are 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.

7.5.3 Process 8 and 9: 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 several unfolding sequences of future epochs created in Process 4. Subject matter experts identified these epoch sequences as interesting narratives that might play out. By analyzing these particular sequences of epochs for a given length of time, analysts can identify potential strengths and weaknesses of a design and better understand the potential impact of path-dependent, long run strategies for value sustainment. The objective when analyzing these eras is for an analyst or decision-maker 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.

For the ship case study the problem was narrowed to six designs identified by subject matter experts that we would like to evaluate over the three narratively defined eras previously described. Further, two operational strategies described by Rehn et al. [164] were evaluated. These two strategies corresponded to a passive (e.g. no change) strategy and a maximize efficiency strategy. Note that more designs, eras and strategies could be analyzed here with acceptable increases in interactive latency. For instance, if we wanted to examine all the designs rather than just six of them, the histogram for design ID in interactive application shown in Figure 7-12 could be replaced with several histograms that represent the individual design variables to allow individual selection and filtering of all of them. This would not require that many additional visual elements rendered to the screen, but would require the definition of additional dimensions within the OLAP hypercubes. The interactive latency issues associated with the increased number of OLAP dimensions would likely be acceptable or at least easily overcome with additional processing power. However, recall Resnikoff's principle of selective omission described in Chapter 3, which describes how humans simplify and organize sensory information and abstract it to draw conclusions [86]. The conventional reasoning typically goes that even if you could render all possible data to the screen, a user couldn't perceive it or make effective use of it. Choices need to be made at each stage of analysis about how much information needs be analyzed, but this is not necessarily a limitation of IEEA.

Era analyses using interactive visualizations as shown in Figure 7-12 can aid in the assessment of different future lifecycles for the offshore design case. This visualization is an extension of the single-era analysis visualization demonstrated previously for the space tug case and contains four columns of coordinated views. The first column contains three row charts corresponding to designs, eras and strategies and enable filtering if an analyst only wants to view a subset of these at any given time. The second column contains time histories of several metrics of interest (MOI's) that allow the user to adjust the window of time they are interested in focusing on. Each time history window contains one line for each design-strategy-era combination within the existing filters.

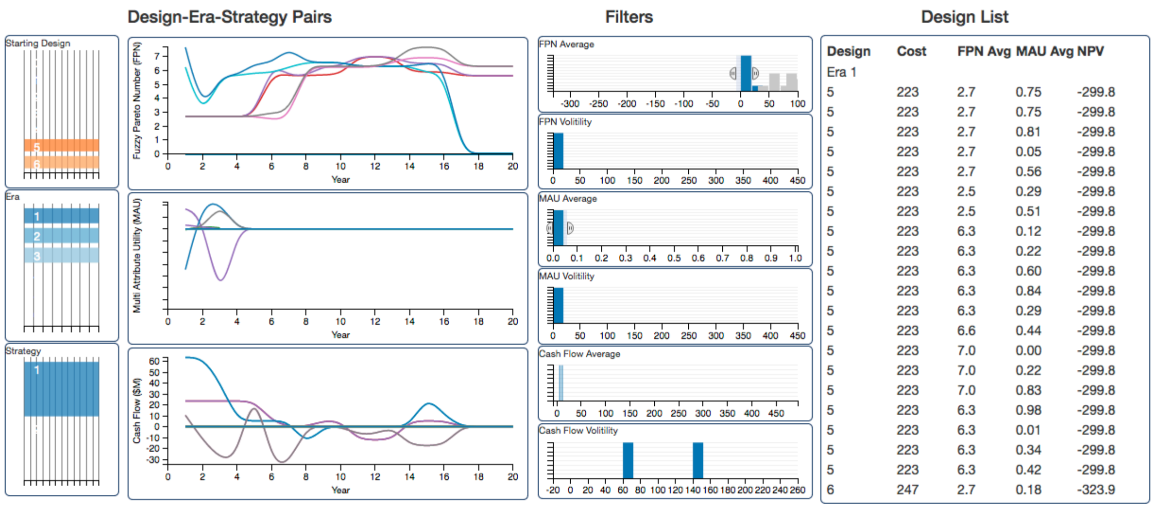


Figure 7-12: Interactive era analysis application implementing OLAP

Whereas the space tug case study focused on a single MOI, this case focuses on several time-varying MOIs beyond simply Pareto efficiency. For this case study, MOIs for both cash flows and multi-attribute utility are made available in addition to efficiency. Coordinated visualizations allow all three of these time-varying MOIs to be filtered by their time-weighted average and variability. The filterable histograms for the average and variability of each MOI are contained in the third column of the visualization. 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. Note that additional MOI's or more descriptive time history metric on the existing MOI's, as described in section 6.4.3, could have also been evaluated if we added additional views into the third column. However, based on expert-based evaluations of this application with ship SME's the current metrics were deemed sufficient. Finally, the fourth column provides the "details on demand" in the form of a scrollable list of designs and detailed information about the designs, strategies and eras remaining within the existing filter.

As demonstrated for previous IEEA processes, decision-making in era analysis can also benefit from the application of techniques such as multiple coordinated views, interactive filtering and OLAP. By limiting the number of visual elements that must be rendered on the screen and providing an efficient backend method for handling the data an analyst can efficiently filter the data to identify interesting design-strategy pairs. Implementing the interactive visualization in this way allows for future scalability to larger case studies as well if necessary.

7.6 Discussion and Conclusions

Application of IEEA to this case study for commercial offshore ship design demonstrates key concepts and interactive visualizations. This particular case study was selected to demonstrate the generalizability of IEEA to design problems in other domains. It also illustrates how the framework and interactive applications can be useful to SME's when applied to larger problems while overcoming issues related to scalability and latency. The primary hypothesis of this research is that leveraging research from the field of visual analytics to extend EEA can better address the design challenges that arise due to the quantity and complexity of data produced. In Chapter 3, four key areas of techniques from visual analytics were discussed: (1) heuristic and methodological guidance, (2) visualization, (3) data management and transformation, and (4) Interaction.

Regarding the first two areas, this case study demonstrates that they can, for the most part, be incorporated in the exact same way using the using interactive visualizations previously applied to the space tug case study. This strengthens the claim to generalizability, but it is worth pointing out a few of the challenges that were unique to this case study. First, for single epoch analysis, the large number of points that must be plotted in the interactive scatter plot can lead to issues with occlusion and increased interactive latency. To mitigate these issues, two-dimensional hexagonal binning was used to reduce the number of visual elements displayed and it was demonstrated that the perceptual scale can be modified by changing the bin size. This has the advantage of decreasing latency issues, but reduces functionality slightly because dot color and size can no longer be used to encode additional information. With further development, a modified version of this visualization may demonstrate functionality that allows the hexagonal bin size to be adjusted in real time by the user. Presumably, if they continued to make bin size smaller and smaller it would eventual be a representation of each point individually. Though more complex, this is a potential compromise that would improve scalability without limiting functionality. Another observation related to visualization scaling was that the wedges of the Nightingale coxcomb were significantly smaller in arc length as compared to the space tug example. Though they were still useful for comparing strategies in the example they may run into issues due to the pixel limitations of computer displays for case that had even larger numbers of epochs. This motivates a need for continued research and development into novel ways of displaying this information in follow-on research on IEEA.

The third area, data management and transformation, also showed some of the benefits and limitations of the techniques incorporated from visual analytics. While this case study showed that larger numbers of designs and epochs could be analyzed, no implementation will allow data to scale without eventual limits on storage and processing. Generation of the data for this study relied on parallel computing performed on a multi-core cluster that would not be available to all or even most users. Even when all the data can be generated, many of the data files associated with this case study were over 1GB in size which is approaching the limit of the amount of memory that can be allocated for these browser based tools regardless of the amount of local machine memory.

This closely relates to challenges observed with the fourth area through this case study, interaction. While the specific methods of interacting with the data were the same and OLAP techniques were extremely useful for manipulating and transforming the data, interactive latency could still quickly become a problem as data grows further. As with the space tug case, this case used tools that performed the OLAP data operations client-side. In other words, in the browser memory, which limits continued growth. Shifting many of the OLAP operations to backend server-side operations would be desirable as data sets continue to grow. Another option worth considering is GPU-based processing using WebGL as was demonstrated in research on the imMens technology demonstration [65]. In summary, this case study demonstrates the scalability, usefulness and generalizability of IEEA, but also illuminates some areas that are potentially ripe for future research. Additional research in these and other area may enable greater capabilities. These areas will be discussed in further detail in Chapter 8.