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Approaches for exploration, analysis, and visualization of tradespace for engineering decision-making

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Abstract

This paper discusses approaches for tradespace analysis, exploration, and visualization to address multi-objective decision-making. Next, computational tools for early-stage tradespace analysis to enhance programmatic decision-making are introduced via a vehicle design example to demonstrate the effectiveness and capability of the method. Using a smaller sample of technologies in this problem a synthetic tradespace spans the space of potential and available solutions and provides an opportunity for design engineers to develop an insight into possible technologies and solutions within the tradespace.

Keywords: tradespace exploration, optimisation, decision making

1. Background on decision making in the context of tradespace exploration

The tradespace of a design problem is the space of all potential solutions spanned by completely enumerated design variables. While it is useful to construct a tradespace, much of the value from the exercise comes from exploring the tradespace and analyzing the tradeoffs it presents. Tradespace exploration (TSE) can be defined as the utility-guided search to find optimal solutions within the tradespace (Ross et al., 2004), or as the process of analyzing the inputs that produce the closest to optimal solutions, based on desired response variables (Specking et al., 2019). Further studies define TSE as a method that provides decision makers with an understanding of capabilities, gaps, and the potential compromises that can facilitate the achievement of the overall system objectives (Spero et al., 2014). TSE requires the consideration of various trade-offs (Specking et al., 2019) and prompts practitioners to ask how much achievement in one attribute can be sacrificed to make a known improvement in another attribute (Zuloeta Bonilla et al., 2021). Thus, in this paper TSE will be defined as the search for more optimal solutions, guided by utility, that provides decision-makers with an understanding of the capabilities, gaps, compromises, and tradeoffs inherent in deciding on a solution (Sutton et al., 2023).
Tradespace exploration is, at its core, a way of making decisions about design architecture. TSE activities can occur as early as the specification phase of the design process (Pahl and Beitz, 1996); thus, the outcomes of TSE decisions can have far-reaching consequences for the overall design. The decision-making process that underpins TSE has been studied from different perspectives, with much of the effort focused on characterization. Decision-making can be characterized by two main methods: decision-making styles (Garber et al., 2015) and decision-making spaces (Tan and Moser, 2018).
Apart from the efforts to study decision-making in TSE, tools and methods to support the TSE process have also been researched. Framing, visual steering, and visualization tools, among others, are examples

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of the efforts made to support TSE decision making. Framing deals with multi-stakeholder decision making and the way design problems are presented. The theory suggests that instead of framing participants as individuals first and groups second, the problem can be framed as a group exercise first to better establish initial reference points and encourage group consensus (Fitzgerald and Ross, 2014). Visual steering is a method that allows a decision maker to guide an "exploration engine" around a tradespace to select and control which regions of the tradespace are populated (Yukish et al., 2007). Therefore, decision makers can redirect the exploration and optimization processes to make improvements to a found solution (Stump et al., 2007). Visual steering and other selective tradespace sampling methods (Lego et al., 2010) are typically incorporated into specific TSE visualization tools, which will be discussed in further detail in Section 4.

The overall objective in the present work is to provide designers and decision makers an insight into methods and computational tools for multi-attribute decision analysis in the early design stages. The remainder of this article is structured as the following: Section 2 provides a framework for understanding best practices in tradespace exploration and analysis which are summarized from observed trends and patterns in the existing literature. Section 3 presents findings from a case study of organizational TSE practices. Section 4 is allocated to the computational tools studied and developed to overcome current challenges in performing tradespace activities. Section 5 summarizes the major findings and limitations of the study and presents avenues for future research in tradespace exploration, analysis, and visualization.

2. A framework for understanding and categorizing best practices for tradespace analysis and exploration

To identify the best practices in tradespace exploration and analysis, a systematic literature review was conducted as part of the authors' prior work with two overarching objectives: 1) to develop a comprehensive understanding of tradespace activities as related to complex system design, and 2) to provide insight into the existing tradespace practices across multiple entities: academia, industry, and government. The details of this literature review, including the classification of the eighty reviewed publications and the iterative thematic analysis conducted on them, are presented in (Daniels et al., 2022a). From the thematic analysis, five overarching themes emerged. These themes were used to construct a framework that can be used to understand and categorize best practices for tradespace activities.

2.1. Framework for tradespace best practices

The thematic analysis conducted in prior work (Daniels et al., 2022a) revealed five themes: 1) System Modeling and Analysis, 2) Optimization and Decision Strategies, 3) Dataflow Architecture, 4) Software and Support Tools, and 5) Workplace Culture, which were used to construct a framework to categorize the activities, strategies, tools, and behaviours that comprise the best practices for tradespace exploration and analysis. Each of the major themes were divided into categories, which were then further decomposed into subcategories where appropriate. These themes and the resulting framework are described in more detail in the following subsections.

2.1.1. Theme 1: System modeling and analysis

The first theme encompasses modeling approaches for tradespace analysis, ranging from limited fidelity descriptive models to probabilistic simulations. The categories that fall under this theme include the following:

- Defining the Tradespace (5 subcategories, including tradespace exploration, tradespace analysis, and conceptual distinctions)
- Capabilities Based Assessment (CBA) (3 subcategories, including key performance parameters and key system attributes)
- Descriptive Models (3 subcategories, including cost models and utility models)
- Deterministic Analysis Methods (3 subcategories, including stakeholder analysis and capability gap analysis)

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- Probabilistic Analysis Methods (5 subcategories, including sensitivity analysis, risk assessment, and uncertainty characterization)
- Stochastic Simulation (1 subcategory: design of experiments).

2.1.2. Theme #2: Optimization and decision strategies

The second theme focuses on optimization and decision-making strategies. Among these approaches, formal mathematical programming and decision-making strategies are often employed, along with Machine Learning and Evolutionary Computation. The integration of these approaches is reasonable as the available datasets underlying TSE are often large, making it difficult to analyze them fully or quickly. The categories comprising this theme are as follows:

- Logic-Based Models
- Machine Learning and Data Mining (2 subcategories: Artificial Neural Networks and Reinforcement Learning)
- Evolutionary Computation
- Mathematical Programming
- Evaluation Criteria (5 subcategories, including Weighting Factors, Scoring, and Ranking)
- Decision Strategies (4 subcategories, including Decision Mapping and Decision Automation)

2.1.3. Theme #3: Dataflow architecture

The categories comprising the third theme, Dataflow Architecture, detail methods for coping with a burgeoning concern for the management of data within tradespace exploration and analysis. The amount of data available for tradespace analysis has risen dramatically in recent decades, causing many organizations to face challenges in curating and processing available datasets to identify points of interest in the multi-dimensional tradespace, such as Pareto points. The three constituent categories are the following:

- Data Collection, Handling, and Management Plan (4 subcategories, including Data Availability, Data Retrievability, and Data Interoperability)
- Computation Methods
- Tradespace Visualization (5 subcategories, including Graphical Techniques, Data Clustering Algorithms, and Pareto-Optimal Solution Sets)

2.1.4. Theme #4: Software and support zools

The fourth theme details the various types of tools, software or otherwise, available to support tradespace activities. In addition, it includes various methods by which a practitioner may evaluate or select a specific support mechanism. The software tools are organized into categories based on which elements or features they support during the execution of the trade study. Some examples of software support tools include the Whole System Trades Analysis Tool (WSTAT), ARIES, and TradeStudio used by the US Army Ground Vehicle Systems Center (GVSC) to support their tradespace activities, or the more publicly available software JMP, a visual statistical tool for data analysis activities. The categories under Theme 4 include the following:

- Database Management System (DBMS) (3 subcategories: Data Collection, Data Storage, and Data Transfer)
- Tradespace Exploration Tools
- Tradespace Analysis Tools
- SysML or MBSE Modeling Tools
- Post-Processing Features (3 subcategories: Visualization, Reporting, and Decision Support)
- Current Challenges and Limitations
- Advantages of Existing Tools
- Software Evaluation Criteria (9 subcategories, including Key Features, License Type, User Interface, and Supported File Formats)

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2.1.5. Theme #5: Workplace culture

Workplace culture plays a critical role in the emergence of best practices and performance gaps within tradespace groups. The culture of the workplace, such as the communication structure and how workers interact, also influences how decisions, including trade study decisions, are made. The constituent categories of Theme #5 are presented below.

- Organizational Structure and Member Identity (7 subcategories, including Roles and Responsibilities, Project Workflow, and Subject Matter Experts)
- Communication Strategy (3 subcategories, including Interdepartmental Collaboration and Communication Channels, Activities, and Tools)
- Control Systems (3 subcategories: Open-System Focus, Project Documentation, and Feedback and Reporting)
- Standards and Protocols (4 subcategories, including Controlled Vocabulary and Internal Protocols)
- Strategic Assessment (4 subcategories, including Participant Reflections and Recommendations for Workplace Culture)

3. Case study: Organizational practices of tradespace analysis

Using the framework based on literature findings and described in Section 2.2, a case study was performed to answer the following research questions:

- How do organizations practice trade activities?
- Do organizations implement the best practices as identified from the literature?
- What capability gaps do practitioners notice in their current practice?
- How can the identified capability gaps, if any, be addressed?

3.1. Methodology

An interview-based study was designed, comprising seven interviews conducted with the personnel at the U.S. Army Ground Vehicle Systems Center (GVSC). The interview structure and questions are discussed in (Daniels et al., 2022b). Participants were recruited based on their work in or with the Tradespace Exploration Group at GVSC. The interviews aim to understand each participant's role or involvement in trade studies, as well as their perspectives on TSE and their experiences and perceptions relevant to TSE activities at GVSC. Questions were also asked about the recommended practices, current gaps, and the desired state of TSE at GVSC. When the interviews were completed, interview transcripts were coded using thematic analysis based on the framework presented in Section 2. This was performed using a bottom-up approach, including an inductive coding process to enable data-driven exploration of the data, avoid unnecessary limitations on the findings, and allow new themes to emerge. A pair of raters each examined the interview transcripts in a line-by-line manner, noting important responses. They then assigned these specific words or phrases from the interviewee responses to one or more of the categories or subcategories of the best practices framework, which was used as the code scheme for the analysis. A summary of the codes assigned with respect to frequency and the categorical clusters found using the frequency of the keywords based on each emergent theme are presented in (Daniels et al., 2022b). To establish the reliability of the developed coding scheme and reduce the risk of bias, the percent agreement between two coders was calculated for the coding of the first two interviews. The interrater reliability can be determined using Cohen's Kappa (κ), where the Kappa coefficient calculates an adjusted level of agreement with respect to chance. According to the multivariate categorical data analysis methodology (Landis and Koch, 1977) that characterizes the strength of agreement using the calculated Kappa, the found Kappa values of 0.7465 for the first interview, 0.6173 for the second interview, and 0.6810 normalized indicate substantial agreement between the raters and subsequently support the validity of the developed framework.

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3.2. Identification of capability gaps

To identify current challenges and capability gaps of tradespace activities, categorical cluster analysis was employed following the thematic analysis and framework-based encoding. In this analysis, categorical data was clustered by matching similarities between categorical objects with respect to a set of observable variable characteristics. For this study, the observed codes were grouped with respect to the five themes comprising the framework presented in Section 2. These data clusters were then used to assess common trends across the datasets. Codes assigned to the data were grouped thematically and prioritized based on the frequency of occurrence. The most frequently discussed overall theme was Theme 5: Workplace Culture, mentioned in 119 instances, with specific focus on the Communication Channels and Tools subcategory, discussed 25 times. This was followed by Theme 1: System Modeling and Analysis, discussed 97 times. The most prominent subcategories of that category were Capabilities Based Assessment and the Challenges of Trade Studies, both mentioned 11 times. Theme 4: Software and Support Tools was also frequently mentioned with a total of 93 instances. Data Transfer and Data Collection were the most mentioned subcategories, each discussed 10 times. Discussion of Themes 2 (Optimization and Decision Strategies) and 3 (Dataflow Architecture) occurred much less frequently, with only 27 and 35 total mentions, respectively. The categorized mentions from the interviews do not denote whether the discussion of a topic was positive or negative, merely that the topic was discussed. The categorized mentions were then re-analyzed with regards to their polarity and clustered again, giving rise to five capability gaps: 1) The Data Exploration-Exploitation Dilemma, 2) the Lack of a Data Repository, 3) Information Silos, 4) the Lack of Standardization, and 5) Visualizing and Communicating the Tradespace.

3.2.1. Gap 1: The exploration-exploitation dilemma

A key challenge of the tradespace for GVSC and industry alike is finding the optimal balance between exploratory efforts and exploitation strategies. The tradespace is a highly complex multi-objective optimization problem across many domains. While performing an exhaustive search of the tradespace may yield a high-fidelity model of a system’s solution, a trade-off must be made between data exploration and computational demands. The challenge comes in identifying the point at which it is more advantageous to cease exploration efforts in favor of exploiting the best available information.

Another challenge surrounding the exploration-exploitation trade-off is the multi-relational nature of the system parameters. Early concept development is often limited by uncertainty surrounding the independent relationships of the trade-offs. For a given system, the tradespace is driven by a set of non-traditional design criteria, or “ilities” (e.g., accessibility, flexibility, or mobility) serving as critical system attributes. Consequently, the design of complex systems has historically been limited by the fidelity of the physics-based models describing the system. These tradeoffs are often intricately interconnected and cannot be performed in isolation. A framework developed by McManus et al. (2007) suggests implementing Epoch-Era Analysis when incorporating “ilities” in complex system design. Additionally, one interviewee suggested the Exploratory Data Analysis (EDA) approach as another potential technique for rectifying the high complexity arising from system “ilities” within a tradespace, since a significant aspect of tradespace exploration involves experimentally breaking a requirement and examining the effect on other areas.

3.2.2. Gap 2: Lack of data repository

A current limitation of trade studies performed within GVSC is data accessibility, management, and tracking. For data to be effectively exchanged, a commonly accessible database should be developed that prioritizes data interoperability, compatibility, and flexibility. Current capability gaps regarding data interoperability include both the technical aspects of data exchange and how well the system functions as an information-sharing environment with respect to basic end-to-end operations.

3.2.3. Gap 3: Information silos

A particular challenge reported by several participants was an organizational reluctance to share information. Trade studies involve many groups either conducting their own simulations or using

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waterfall data strategies in which one group feeds data into another group. Information spread out across different organizations must be effectively shared between all involved parties. Information silos, in which information generated is not properly communicated, integrated, or aggregated into the collective knowledge of the organization, occur when organizational members or groups are either unable or unwilling to cooperate with adjacent parties. Information silos risk hindering or, in some extremes, completely halting the communication process and thus pose a significant threat to the success of a trade study. Ideally, information sharing should serve as a feedback loop between the multiple agencies. Unfortunately, a common pitfall of trade studies is that the communication process operates as a one-way passage of information between groups.

3.2.4. Gap 4: Lack of standardization

The lack of consensus or standardization for tradespace operations introduces ambiguity surrounding decision-making. This is amplified by the tendency of the involved members to communicate differently. Although a more technical or detailed standard procedure is likely infeasible due to the broad scope of potential studies, a general guideline to tradespace exploration and analysis may provide a clearer path and improved organization, particularly when approaching a new study.

3.2.5. Gap 5: Visualizing and communicating the tradespace

An existing gap between the available data visualization techniques and tradespace communication needs is the ability to interactively visualize and communicate the tradespace. Effectively explaining a problem and current approach and then reinforcing that understanding through visualization techniques enables SMEs to make better recommendations for capturing the correct data to use in the tradespace model, as opposed to just dictating what data is needed. Additionally, improving tradespace visualization tools and techniques presents an opportunity for stakeholders and SMEs to gain a more in-depth understanding of the trade-offs driving the tradespace.

4. Computational tools for early-stage tradespace analysis: Addressing capability gaps

With an understanding of the capability gaps practitioners face in their tradespace activities, attention can then turn to methods to alleviate these gaps. In this section, methods and suggested best practices for visualizing tradespaces will be introduced in an attempt to overcome Gap 5. This will be followed by a discussion of a synthetic tradespace strategy that could aid designers and SMEs with their early stage tradespace activities to overcome some of the challenges of Gap 1.

4.1. Tradespace visualization tools

An effective tool to support tradespace exploration is visualization, in which users are provided with opportunities to see and interact with the tradespace and direct the TSE process. A summary of three TSE visualization support tools proposed for use in industry, including the ARL Tradespace Visualizer, Rave, and JMP, is provided in (Sutton et al., 2023). These visualization tools allow users to customize information presentation methods, as well as select what data types are shown to them. In doing so, this may allow for better information communication and increased understanding for decision-makers, thus addressing Gap 5. Additionally, literature discussing visualization heuristics and evaluation procedures was interrogated to ensure that any introduced visualizations are effective. Some commonly used heuristics as well as general dashboard design guidelines are presented in (Sutton et al., 2022). In addition to carefully designed dashboards and visualizations which could significantly affect TSE, Immersive Reality approaches such as Virtual and Augmented Reality (VR and AR) are gaining attention from tradespace researchers and practitioners. In particular, immersive reality may be suitable for use with distributed or virtual teams, especially in light of the COVID-19 pandemic and the increased emphasis on remote work. This intervention can address Gap 5 by improving the ability to interactively visualize and communicate the tradespace. It may also address some of the information siloing effects discussed in Gap 3, since even distributed users may interact with the same virtually-presented scenarios and information.

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4.2. Synthetic tradespace

In early stages of the design process, various conceptual designs can be explored through the use of a morphological matrix, in which different solutions for the various functional components of a design can be considered in a combinatorial fashion. When a morph chart is developed, individual designs can be compared against the established requirements to determine their feasibility. If the solutions are found to be feasible, they can then be evaluated against performance requirements to determine the individual solution's performance value. The design with the highest performance value is considered the preferred design. This practice is, in essence, a tradespace exploration and analysis. Though morph charts are commonly used and helpful tools, their development can be cost- and labor-intensive. For instance, the tradespace at GVSC, which allows for the consideration of more than 1,021 vehicles, took more than two years and required the efforts of multiple staff and SMEs to complete. While this tradespace is expansive and allows for high levels of exploration, constructing it required a sacrifice in the ability to exploit the contained data. This illustrates the challenge of Gap 1. Thus, approaches other than the traditional comprehensive technology survey must be sought to enhance programmatic decision-making, especially in earlier stages of design. As an early-stage computational tool, a simulated tradespace created using synthetic data is herein introduced. Though of lower-fidelity than a complete tradespace, the synthetic tradespace model could be an effective tool to test and verify the developed approaches for design analysis and speed up early-stage decision making.

4.2.1. Model generation example

For this work, a synthetic tradespace model was developed using a small set of technology examples representing the US Army Squad Mission Equipment Transport (SMET) vehicle. The goal of TSE is to establish the bounds and priorities of various requirements by making decisions between components of the "-ilities", known as Functional Objectives (FOs). FOs define a performance attribute of a system, and can be composed of Derived Attributes, Defined Constants, Input Variables and even of other Functional Objectives (Turner et al., 2022). For the initial prototype model, Input Variable and Defined Constant values are generated and the Derived Attribute and Calculated Parameter values are determined using a tab-delimited text file processed by MATLAB. To limit the complexity of the model, only sub-FOs were calculated. The model is composed of 12 derived attributes, 9 defined constants, and 54 input variables. To demonstrate the synthetic tradespace model, a problem is presented where designers seek to minimize the back deck overhang of the vehicle, while maximizing the running gear contact area and minimizing both the overall vehicle length and the vehicle curb-to-curb turning diameter. To visualize the resulting tradespace, 1000 random design concepts were generated. Since visualizing the resulting four-dimensional space of the design problem would be challenging, the tradespace is presented as two subspaces, each comparing two sub-FOs against each other. The Pareto frontier of solutions can be found on each subspace. Notably, in the first subspace, the Pareto frontier appears to represent a single solution as shown in Figure 1a. However, if that solution is projected over to the other subspace, it is seen that the projection is not one-to-one and that the singleton Pareto frontier of Figure 1a actually represents two solutions, as shown in Figure 1b.

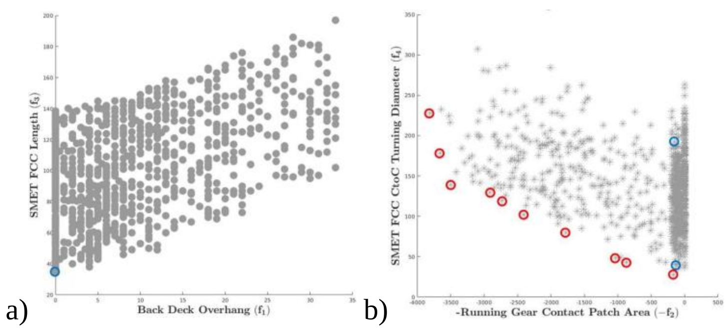

Figure 1. a) The Pareto solution for the subspace composed of Back Deck Overhang vs. Vehicle Length; b) The Pareto solution from the first subspace as projected into the second subspace (Running Gear Contact Area vs. Turning Diameter); along with the Pareto frontier in the second subspace

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This is indicative of the challenge in analyzing the behavior of the tradespace. Pareto solutions in one subspace may not be Pareto solutions in other subspaces. However, near Pareto solutions are often recognized as being valuable and perhaps even superior solutions to true Pareto solutions from an engineering standpoint. These near Pareto solutions can be found using a decomposition and coordination approach, as described in (de Castro et al., 2022; Wiecek and de Castro, 2022). The ability to decompose the multi-dimensional tradespace into subspaces may provide more solutions for decision-makers to work with. It may also make the tradespace as a whole easier to explore, while also allowing for the captured data to be more rapidly exploited; through this approach, Gap 1 may be addressed.

5. Conclusions and future work

This study focused on the current practices of tradespace analysis in order to identify the best practices, capability gaps and improvement areas and to introduce strategies to address some of the identified gaps and aid decision makers with their early-stage design decisions. The literature review on tradespace exploration and analysis across academia, industry, and government resulted in the creation of a framework for best practices for trade studies, based around five themes: 1) System Modeling and Analysis, 2) Optimization and Decision Strategies, 3) Dataflow Architecture, 4) Software and Support Tools, and 5) Workplace Culture. To further understanding of the organizational practices of tradespace activities an interview-based case study was conducted with personnel from GVSC. Thematic analysis and coding of the interview responses based on the developed framework revealed five capability gaps regarding tradespace practices within GVSC: 1) The Data Exploration-Exploitation Dilemma, 2) Lack of a Data Repository, 3) Information Silos, 4) Lack of Standardization, and 5) Visualizing and Communicating the Tradespace. Results from the interview study directed the search for tools to overcome these capability gaps. To address Gap 5, robust visualization tools with opportunities for customization for TSE were identified. Additionally, to overcome the challenge of cost and labor-intensive development of a full tradespace model using a complete technology survey, which underpins the challenge of Gap 1, a synthetic tradespace was introduced as an effective early-stage tradespace decision making tool. This can be used along with the decomposition and coordination method for multi-objective decision analysis to enhance programmatic decision making.

Limitations of this study do impact the applicability of the findings. One of the most prominent limitations is the small population investigated in the case study, which included only seven tradespace practitioners from the government sector. All seven participants worked within a department specifically focused on tradespace activities; their responses may not be reflective of the wider span of decision-makers often involved with tradespace decisions. Tradespace activities may involve decision-makers from a variety of fields, including dedicated practitioners, manufacturers, use-case-specific SMEs, and non-technical end users, all of whom may have different reflections on the challenges and strengths of the tradespace process. Additionally, the case study focused on tradespace activities as conducted in the government sector. While there are similarities between government-related processes and general industry, there can also be significant differences. Thus, the findings from the study may not capture all the nuances of wider industrial practices. Tradespace practitioners in the industrial sector may agree with the capability gaps presented herein, but they may face additional challenges. Also, they may have previously faced these gaps in capability, but have since found methods to overcome them. Since this case study does not involve any industrial practitioners, these potential challenges or tools are not captured.

The findings in this study could be furthered by considering an interactive exploration and visualization of the tradespace via human-in-the-loop machine learning tools for multi-objective collaborative optimization. Additionally, potential future research directions include the development of a data-driven surrogate model-based Bayesian learning and optimization framework for adaptive and interpretable sequential engineering design decision-making. With regards to TSE visualizations, future studies can be conducted to understand the effects of visualizations such as integrated immersive reality on decision-making outcomes; these studies can also integrate other TSE interventions such as group framing. The synthetic tradespace model can be further improved by considering a more complex model with additional FOs. In fact, the advanced version of the present model is currently in development and evaluations are ongoing to determine if the model produces satisfactory results. Further developments

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to the modeling process involve the modeling of technologies and technology development, developing reusability in the definitions of Derived Attributes and FOs, and incorporating tradespace evaluation metrics into the model formulation process.

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