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# CURRENT PRACTICE OF VISUALIZATIONS FOR TRADESPACE EXPLORATION: A LITERATURE STUDY

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## ABSTRACT

*Tradespace exploration (TSE) is a key component of conceptual design or materiel solution phases that revolves around multi-stakeholder decision making. The TSE process as presented in literature is discussed, including the various stages, tools, and decision making approaches. The decision-making process, summarized herein, can be aided in various ways; one key intervention is the use of visualizations. Characteristics of good visualizations are presented before discussion of a promising avenue for visualization: immersive reality. Immersive reality includes virtual reality representations as well as tactile feedback; however, there are aspects of immersive reality that must be considered as well, such as cognitive loads and accessibility. From the literature, major trends were identified, including that TSE focuses on value but can suffer when not framed as a group decision, the need for testing of proposed TSE support systems, and the need to consider user populations and cognitive loads when developing new visualizations.*

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## 1. MOTIVATION

In the engineering design field, a key component of the design process is tradespace exploration (TSE). In the engineering design process specified by Pahl and Beitz, tradespace exploration activities can occur as early as the specification phase, in which designers search for solution principles and evaluate their findings against technical and economic criteria [1]. In the defense acquisitions process, tradespace exploration is conducted as part of the analysis of alternatives (AoA) process in the Materiel Solution phase prior to Milestone A [2]. In both cases, tradespace exploration is typically conducted in groups, with multiple stakeholders attempting to reach a mutually beneficial solution. Thus, it is important to understand how decisions are made within the TSE process, as well as the methods and technologies used to support this decision making. These topics will be discussed in further detail in the following sections. Section 2 will define the events within the TSE process, while Section 3 will explore the efforts that have been made to support TSE, with a major emphasis on visualizations. In Section 4, immersive reality efforts that can be used to support TSE will be discussed, followed by discussion of trends and conclusions in Section 5.

## 2. UNDERSTANDING TRADESPACE EXPLORATION

Tradespace exploration can be defined as the utility-guided search for more optimal solutions within the tradespace, in which the tradespace is the potential solution space spanned by completely enumerated design variables [3]. Other definitions of TSE add more nuance, explaining that it is the process that analyzes which inputs produce the closest to optimal solutions, based on the desired response variables [4]. TSE requires the consideration of various trade-offs [4] and prompts the parties conducting TSE to ask how much achievement in one attribute can be sacrificed to make a fixed amount of improvement in a second attribute [5]. Others define TSE as a method that provides decision-makers an understanding of the capabilities, gaps, and the potential compromises that can facilitate the achievement of the overall system objectives [6]. An oft-mentioned description of the TSE process compares it to a “design by shopping” paradigm, since associated decision makers learn about the problem through exploration of the tradespace, form preferences, and “shop” around in the tradespace to find designs that are most preferred [7]. With TSE defined as a whole, it is therefore important to break down the process into its constituent stages, in order to best understand the opportunities for visualization aids to be implemented.

### *2.1. Stages of TSE*

TSE can be used in various contexts and, as such, the specific stages associated with the process can differ. When TSE is framed as “design by shopping,” the process begins with constructing the tradespace, followed by allowing the decision makers or designers to explore the design space and determine their preferences as well as what is possible. With these preferences and limitations established, designers can then choose an optimal solution [8].

In a resilient systems context, the approach to TSE is centered around value: value-producing objectives are developed, followed by the identification of alternatives. With these in mind, decisions can then be made based on the value various alternatives provide across the specified objectives [6]. This same value focus underpins the Multi-Attribute Tradespace Exploration (MATE) method, which attempts to avoid sub-optimal outcomes by using stakeholders’ perceived value as decision metrics and supporting systematic design development and exploration throughout the design process [9].

MATE is typically supported by numerical models that allow for the evaluation of large design data sets and provide attribute metrics that can be plotted to form the tradespace. MATE occurs in three phases: mission definition, in which requirements and analysis metrics are determined; concept generation, in which the design data set is populated; and design evaluation, in which the tradespace is evaluated [5].

Concurrent design can incorporate MATE strategies in a five-phase process known as MATE-CON. The five stages include need identification, architecture solution exploration, architecture evaluation, design solution exploration, and design evaluation [3].

## *2.2. Decision Making in TSE*

Tradespace exploration is, at its core, a way of making decisions about design architecture. Thus, it is necessary to understand the decision making process in order to fully understand TSE.

One of the most common decision-making approaches when uncertainty is present is mean-risk analysis, which can identify an efficient solution set if the distributions of decision criteria are precisely known [10]. Despite this suitability for TSE applications, this analysis can be expensive, especially with large sets of alternatives [10]. Thus, sequential decision making is used. This can be considered as a sequential reduction in the solution space by ways of distinct solution sets. The initial “universal set” contains all possible choices, and is reduced to the “awareness set,” which contains only the choices that the decision maker is aware of. These are further reduced to the “consideration set,” which includes only the potential solutions, until the final “choice set” is constructed, which contains the alternatives considered prior to a final choice [11].

The decision making process within TSE has been studied from different perspectives. One study examined the teamwork behaviors and noted that understanding of those behaviors could be improved by detecting the events of the three spaces involved in the TSE decision making process: problem space, solution space, and social space. The decision making process affects all three spaces [12]. Another study sorted members of the decision making group according to their perspective on their preferences. This resulted in a four-class taxonomy for decision making with two or more people; classes represented decision making styles and included negotiation, cooperation, voting, and consultation [13].

Frameworks have also been developed for use with multi-stakeholder decision making. The framework presented in [14] uses a conditional-value-at-risk as a quantifiable metric to systematically compare the effects of different compromise solution on the satisfaction of stakeholders, which allows values to be implicitly assigned to metrics that are difficult to monitor. The work in [15] proposes a decision making framework that is collaborative, trust-based, interest-based, and dynamic and that produces a consensus outcome, in order to guarantee agreement from all participants.

## *2.3. General Decision Making*

Additional studies have been done into more general aspects of collaborative, multi-stakeholder, or team decision making. In one such study, members of multi-stakeholder teams were found to have a positive perception of value if collaborative decision making occurred [16]. Emotional aspects were a common area of study. For example, the development of a consensus, regardless of the depth of the definition, was found to benefit team motivation [17].

Satisfaction with teams conducting decision making was found to be impacted by multiple variables. Team self-efficacy and perception of decision comprehensiveness were found to positively influence individual satisfaction with the team, while satisfaction was found to decrease when team members felt their individual views were not reflected in the final team [18]. With regards to management control in new product development teams, professional control was found to have the strongest effect on increasing job satisfaction; it also helped to reduce role ambiguity and conflict when team participation was low [19].

Trust and its development were frequently studied in multi-stakeholder contexts, including interpersonal and inter-organizational trust [20]. In a new product development context, which depends heavily on trust between stakeholders, conceptualizations of this trust were developed, including the willingness to rely on a teammate and the belief that a teammate's word was binding and that they would thus fulfill their obligations [21].

Other decision making-related studies focused on methods, tools, and approaches to improve the decision making process. These suggested interventions ranged from using games to increase inter-team learning [22] to incorporating pluralist sense-making processes [23] to choosing specific parameter levels in order to avoid groupthink [24]. The various multi-criteria decision making methods in use were detailed in the literature review in [25], while [26] discussed discourse types and activity roles. Three assessment tools were proposed in literature: the first described four components of team performance [27], the second used both observer and participant-based measures to evaluate the team performance and process [28], while the third was used to document problem solving activities and team member behaviors in order to conduct analyses [29].

Observational studies have often been completed in the team decision making domain. One such study examined cross-sectional teams to determine if the internal factors, external circumstances, case complexity, and interaction process would impact the quality of decision making [30]. Another examined decision making interactions in time sensitive environments to understand the role of human factors, and collected multiple forms of data, including direct in-person observation, a posteriori interviews, and chat logs [31]. In [32], team decision making was studied in both virtual and face-to-face environments. The results from this study showed that virtual teams had lower trust, but that this positively impacted performance, especially in non-routine tasks, because it increased scrutiny. Additionally, it was found that teams performed better when asked to choose the best option, rather than reaching a consensus [32]. The study in [33] examined the differences in TSE decision making procedures between novice and expert users. Novice users were found to require informative feedback and support methods towards task completion, while expert users desired brief, non-distracting feedback and rapid responses.

## 3. EFFORTS TO SUPPORT TRADESPACE EXPLORATION

Outside of the efforts to understand and support decision making, additional work have been undertaken to support the TSE process as a whole. Some of these are summarized here. These papers range from fundamental changes in the way the TSE problem is presented to dashboards and presentations to tools and indices used to characterize the tradespace.

### *3.1. Framing*

A series of articles by Fitzgerald and Ross summarize their work in framing for multi-stakeholder TSE. The first paper discusses the fact that traditional value-measuring techniques, such as multi-attribute utility theory, operate on an individual basis and thus can break down when combining group preferences. A suggestion to remedy this is to incorporate lessons learned from the literature on negotiation and behavioral economics; rather than framing participants as individuals first and groups second, as in the current practice, it is suggested to frame the problem as a group exercise first to better establish initial reference points [34].

The next article on the topic of framing discusses the role of the BATNA, the best alternative to negotiated agreement, with respect to problem framing. An individuals' BATNA serves as their reference point for multi-stakeholder TSE as it marks the cutoff between gains and losses. In the corresponding experiment, two groups of users conducted a TSE exercise; one group used traditional tools and visualizations, while the second group used visualizations that supported the group-first framing. Experimental results showed that the BATNA was more fully understood and used within the group framing, thus demonstrating the potential effectiveness of the framing change [35].

The final work on framing summarized the recommendations for framing in multi-stakeholder TSE. In this work, definitions were given for macro- and micro-framing; macro-framing deals with large-scale beliefs and perspectives, while micro-framing is a function of specific problem formulation, information presentation, and task performance. Both types of framing have a role in enhancing TSE processes. The article proposes specific interventions with regards to the framing types for different phases in the TSE process. For example, the problem formulation phase should capture macro frames and determine individual stakeholders' BATNAs, whereas in the exploration phase, BATNAs should be emphasized, strictly-individual analysis should be limited, and macro-frames should be referred back to [36].

### 3.2. Visual Steering

Many of the studies that frame TSE as a "design by shopping" paradigm use the concept of visual steering to support the TSE process. Visual steering is a method of involving decision makers in the TSE process by allowing the decision maker to guide a so-called "exploration engine" to various regions of the tradespace, thus allowing users to control which regions of the tradespace are populated [37]. Visual steering, along with graph morphing, allow users to redirect the exploration and optimization process in order to improve the found solution [8]. Visual steering commands can take the form of three user-guided samplers: the first samples the entire design space, the second focuses on a specific point of interest, and the third samples within a high-preference region [8]. Alternately, visual steering can be conceptualized as the "exploration engine" which randomly travels around the model and creates different system concepts. While the "exploration engine" runs, the user visually explores the tradespace and can then steer the "engine" to areas of interest by placing and specifying various attractors within the tradespace [38].

### 3.3. Miscellaneous Support Efforts

More recent studies into tradespace exploration have also produced efforts to support the TSE process. For example, the study in [39] discusses a tool for tradespace analysis for satellite constellations that includes a user interface, a tradespace search request system, and a tradespace search iterator, in addition to specific modules for dedicated systems. Another intervention is proposed in [40], in an attempt to increase the overall efficiency of the TSE process. To do this, an N-squared diagram-based dashboard is proposed; it presents performance desirability, economic viability, and technical feasibility simultaneously to the stakeholders on a single screen [40]. The idea of Pareto shape indices is introduced in [41]. These shape indices quantify the shape of two-dimensional Pareto fronts and have been shown to both reduce the amount of tradeoff regions that must be explored and to help users prioritize exploring objective pairs of tradeoffs. The shape indices also can be used to rank objective pairs to facilitate a posteriori TSE through active preference articulation [41].

### 3.4. Visualizations

One of the largest opportunities for support for tradespace exploration is in the form of visualizations, which allow users to see and interact with the tradespace and direct the exploration process. Data visualization is known to support abstract, multi-dimensional data analysis [42]. Some of the early and most recent efforts in

**Table 1: Summary of Visualization Efforts from Literature**

| Source | [43] | [44] | [45] | [46] |
|---|---|---|---|---|
| Program | Glyphmaker | Virtual Data Visualizer | Miner3D | Glyphcreator |
| Program Details | - Allows custom creation of graphical representations<br>- Has exploration tool for inexperienced users to understand data and guide selection of best visualization<br>- Highly responsive and detailed controls to create visualization<br>- Accommodates data filtering and transformations | - System of tools for exploratory data visualization<br>- Can focus on multiple data types<br>- Based on Glyphmaker<br>- Application-agnostic<br>- First VR-based system to use customizable glyphs | - Two main parts: viewer software and communication protocol<br>- Viewer software creates graphic window, enables feedback and interactivity<br>- Communication protocol transfers model properties and visualization content | - Creates circular glyphs, used for artistic appeal and encoding polar coordinates<br>- Circular glyphs are difficult to create and there is no large data set to train a neural network on<br>- Glyphcreator accepts input of images and data<br>- Associated neural network extracts layout and visual encodings, creating dataset for CNN model training<br>- Users can combine datasets with layouts and obtain rendered glyphs |

**Table 2: Dashboard Design Guidelines as discussed in literature**

| Source | Dashboard Design Guidelines |
|---|---|
| [47] | - Dashboards design should use goal, questions, and measures approach to identify what questions are asked and what data is needed to answer<br>- Dashboards can be for information push or information pull scenarios |
| [48] | - Dashboards can show data visualizations that improve situational awareness<br>- Data utility can be easily masked by noise created by numbers, which takes additional time to mine for value |
| [49] | - Visualization metrics: readability, interactivity, expressiveness, and effectiveness<br>- Intrinsic characteristics of the data set should be used as the primary driver for the choice of visualization |

visualization technology are summarized in Table 1.

While incorporating visualizations into the existing TSE process is an avenue for improving the process and increasing its efficiency, it is important to ensure that the visualizations being introduced are actually of good quality. To that effect, literature discussing visualization heuristics and evaluation procedures was interrogated to determine the best practices. Oft-mentioned information visualization heuristics are summarized in Table 3, while general dashboard design guidelines are collected in Table 2.

## 4. IMMERSIVE REALITY SUPPORT

While carefully-designed dashboards and clever visualizations can significantly impact the practice of TSE, there are other avenues to improve the process. Immersive reality options, including virtual reality (VR) and augmented reality (AR), have become more tenable than ever before. Moreover, immersive reality may be exceptionally well-suited for use with distributed or virtual teams, especially in light of the COVID-19 pandemic and the increased emphasis on remote work. Thus, example interventions will be discussed, followed by aspects of immersive reality that may need significant work before the technology can be widely adopted.

### *4.1. VR Interventions*

Few of the current implementations of virtual reality actually occur within the TSE domain; however, lessons can be learned from implementations even in different fields. Low-cost VR is experiencing increased application within

**Table 3: Common Heuristics for Information Visualization**

| Source | Visualization Heuristics List |
|---|---|
| [50-53] | • Information coding<br>• Minimal actions<br>• Flexibility<br>• Orientation and help<br>• Spatial organization<br>• Consistency<br>• Recognition rather than recall<br>• Prompting<br>• Remove the extraneous (ink)<br>• Data set reduction |
| [54] | • Visualization facilitates answering questions about the data<br>• Visualization provides a new or better understanding of the data<br>• Visualization provides opportunities for serendipitous discoveries<br>• Visualization offers rapid parallel comprehension for efficient browsing<br>• Visualization provides mechanisms for quickly seeking specific information<br>• Visualization provides a big picture perspective of the data<br>• Visualization provides an understanding of the data beyond individual data cases<br>• Visualization helps avoid making incorrect inferences<br>• Visualization facilitates learning more broadly about the domain of the data<br>• Visualization helps understand data quality |
| [55] | • Ensure visual variable has sufficient length<br>• Don’t expect reading order from color<br>• Color perception varies with size of items<br>• Local contrast affects color and gray perception<br>• Consider people with color blindness<br>• Pre-attentive benefits increase with field of view<br>• Quantitative assessment requires position or size variation<br>• Preserve data to graphic dimensionality<br>• Put the most data in the least space<br>• Remove the extraneous ink<br>• Consider Gestalt laws<br>• Provide multiple levels of detail<br>• Integrate text wherever relevant |
| [56] | • Visualization makes important information visually salient<br>• Visualization uses visual components appropriately<br>• Visualization successfully presents multiple relevant facts as a single visual pattern |
| [57] | • Generate figures programmatically<br>• Multivariate data needs multivariate representation<br>• Showing the data is better than just mean and standard deviation<br>• Choose color maps that match the nature of the data<br>• Use small multiples<br>• Do not use vendor exports naïvely |
| [58] | • Make data interpretable at a glance<br>• Enable exploration of patterns in time series data<br>• Enable discovery of trends in multiple data streams<br>• Turn key metrics into affordances for action |
| [53, 59] | • Visibility of system status<br>• Match between system and real world<br>• User control and freedom<br>• Consistency and standards<br>• Recognition rather than recall<br>• Flexibility and efficiency of use<br>• Aesthetic and minimalist design<br>• Spatial organization<br>• Information coding<br>• Orientation and help<br>• Data set reduction<br>• Flexibility<br>• Consistency<br>• Remove extraneous ink |

the field of product development, as it reduces time, effort, and cost in the actual development cycle. Additionally, it allows for rapid iteration and easier design optimization [60]. VR has also been used for prototyping of assembly methods, in which it serves to simulate real-world behavior and interactions between parts. The virtual assembly application is underpinned by constraint-based assembly and physics-based modeling, but still lacks realistic haptic interactions and feedback [61].

### 4.2. Tactile Feedback Intervention

Tactile or haptic-related interventions are less common than visual-related aspects of immersive reality but do present unique advantages. As mentioned in Section 4.1, haptic feedback can increase a user's sense of presence and immersion in an immersive reality situation, making the overall effect feel more realistic. Vibrotactile feedback is a possible transmission method for grasping forces and other tactile stimuli [62]. Additionally, tactile information presentation is a suitable choice since it is one of the more popular forms of sensory substitution [62] and it can travel along attention pathways that may be underutilized, especially for high-attentional tasks that may saturate audio and visual information channels [63]. Furthermore, information that is shared between senses allows for reinforcement of that information, thus creating stronger representations and more internal consistency [62].

### 4.3. Cognitive Load Consideration

If additional information channels are to be used to enhance the immersive reality support provided to a decision maker, care must be taken to not overload their cognitive processes. The term cognitive load refers to the pressure experienced by the human central information processing system, including the perception, learning, memory, and logical reasoning domains, when an individual is subjected to multiple simultaneous stimuli [64]. Cognitive load, or mental workload, is a product of the specific task demands and the capacity of the person performing the task [65]. Reducing cognitive load is a critical method to make multitasking more effective, as multitasking, such as is done during TSE decision-making, can cause users to reach or exceed their cognitive resource limits [66]. Cognitive load levels can be predicted based on key principles related to modality, including the dual-channel theory and the dual-loading theory [67-68].

The cognitive load levels can subjectively be assessed using dedicated workload assessment techniques. One popular and easy to implement technique is the NASA-TLX assessment, which generates an overall workload score based on weighted averages across six sub-scores relating to mental, physical, and temporal demands, performance, effort, and frustration levels [69]. Cognitive load can also be used to understand the efficacy of team decision making, which is a further potential application to TSE [70].

### 4.4. Cognitive Loads in VR

The specific set of conditions within a virtual reality environment can lead to distinct challenges with regards to cognitive loads. For example, the simulation environment may require high levels of attention and working memory resources, both of which are key components of cognitive loads; additionally, any fidelity issues in the representation of the physical environment can also contribute to cognitive loads. [71]. A variety of cognitive load measurement techniques have been proposed for use with VR environments: self-reports, secondary tasks, and physiological indices [71]; physiological measures, subjective measures, and behavioral measures [72]; and sensed reality, reported reality, and observed reality [73].

### 4.5. Accessibility in VR

Another aspect of virtual reality environments for TSE that must be considered is that of accessibility. If immersive reality is to be implemented for use in multi-stakeholder TSE, it is critical that all stakeholders can access and work with the information equally. There are many aspects of accessibility that should be considered, but in this instance, particular emphasis is placed on accessibility menu design and features, as well as visual limitations.

Two papers explored the creation of accessibility menus and examined their effectiveness. The initial article detailed the development of the basic accessibility features, including zooming, inverting colors, auto-reading, text-to-speech, subtitles, and context-based cursors, as well as the means to access the features through menus [74]. This was then followed by a study that evaluated the efficacy of the developed features by observing disabled users following a script with several tasks [75].

Other studies examined how users with visual disabilities or stereoblindness interacted with 3D visualizations and VR. A test protocol for assessing visual acuity for visually disabled users is discussed and implemented in [76]; various visual aspects including color location, size, brightness, and contrasting movement were evaluated. Subsequent observations from the same test group revealed that motion and voice controls were preferred by the users [76].

Additional papers studied the way people with stereo-deficiencies interacted with 3D environments and displays. In [77], experiments were conducted to determine the information that people without measurable stereo-acuity were using to perceive stereoscopic depth. Changing disparity over time and intra-ocular velocity difference were found to be the key factors contributing to perception of depth. A method for assessing stereo-acuity with digital displays is discussed in [78]. In this work, it is proposed to assess stereo-acuity using the same visualization conditions and equipment as will be used for the task, thus allowing for assessment of a subject with the exact same stereo parameters that will be required to perform the task [78]. The study in [79] examined whether or not people with stereo-deficiencies could use head-mounted displays to have a rich 3D experience and found that the head-mounted displays contributed to a richer experience than just a 3D projection screen. Additionally, no significant differences were found in the performance of the task between users with and without stereo-acuity [79].

## 5. DISCUSSION AND FUTURE WORK

The literature reviewed in this paper reveals several key trends and opportunities for future work. The first key trend is that tradespace exploration generally revolves around maximizing value; however, each stakeholder involved with the project may have a different value in mind. Thus, it is important to frame the decision making process as a group process, with all stakeholders working together towards a common goal, instead of having each individual stakeholder trying to maximize their own goal, with little to no regards for how it may impact the other stakeholders. Examining the effects of framing on the TSE outcomes and stakeholder satisfaction would be two prime areas for future work.

Additionally, multi-stakeholder teams may be able to benefit from learning about the different modes of decision making. These may provide new avenues for collaboration, and studies into this topic might show increased satisfaction or teams reaching outcomes that are not clear consensuses. Furthermore, since many tools have been developed to assess team decision making, another area for future work would be to use the new tools to determine the efficacy of current TSE processes.

Another trend revealed from the literature is that many efforts to support TSE have been developed but have not seen extensive testing. Testing these new methods and tools with both small- and large-scale TSE projects and experienced and inexperienced users would be an avenue for future work.

A final trend demonstrated by the literature is that while immersive reality, and virtual reality in particular, has immense opportunities for integration with the TSE process, there are some aspects that should be taken into consideration before immersive reality is widely implemented. Cognitive load, which affects the amount of information a user is able to receive from a scenario, and accessibility, which affects the populations able to use a specific system, should be examined in more detail. Opportunities for future work include developing a TSE process with integrated immersive reality, assessing the cognitive loads generated by the resulting system on a representative population, and testing the system with a diverse population to determine what accessibility features need to be implemented and how effective those features are once implemented.

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