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Recommendations for Framing Multi-Stakeholder Tradespace Exploration

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Abstract. Tradespace exploration is a rapidly advancing design and decision support paradigm that is particularly applicable to complex systems with many value-driving dimensions. These systems commonly have multiple stakeholders that can exert critical influence on the system's conceptual design, necessitating the satisfaction of their needs, and often requiring negotiation. Previous research has suggested that classic tradespace exploration activities may reinforce negative negotiation behaviors through their framing of the multi-stakeholder problem. This paper presents active research in recommendations for supporting inter-stakeholder and stakeholder-data interaction. These recommendations include the reframing of standard tradespace activities and visualizations using the combined insights of the negotiation, framing, and TSE literature and extend from problem formulation through exploration of the data.

Introduction

As modern engineering systems increase in size and scope, it has become increasingly necessary to consider the perspectives of multiple stakeholders in the conceptual design process (Garber et al., 2015). Stakeholders most commonly enter the design process as the definers of value – the desired attributes of the system and the reasons for which it is being designed. Many methods for approaching the multi-stakeholder problems choose to aggregate stakeholder preferences, reducing the dimensionality of the problem and providing powerful leverage for algorithmic design and optimization. However, these methods are only mathematically rigorous under specific axiomatic conditions and are by definition a simplification: often underrepresenting the true complexity of the problem (Scott and Antonsson, 2000). Additionally, and perhaps even more importantly, many stakeholders are reluctant to abdicate their decision-making authority to a model and therefore may reject normative frameworks for combining value functions. When stakeholders can exert influence on the design process up to and including potential veto power, the multidimensional comparison of *each individual stakeholder* is necessary in order to identify alternatives that are both "good" at their intended purpose and "fair" in accordance with the social dynamics between the stakeholders. Designs that lack either of these qualities may find themselves useless or unable to generate the buy-in necessary to continue with, and complete, detailed design and eventual operations.

This paper will discuss the ability of tradespace exploration (TSE) and, specifically, multi-stakeholder tradespace exploration (MSTSE) to support early conceptual design of engineering systems with multiple stakeholders. MSTSE has been developed to target design tasks with stakeholders who are unwilling or unable to fit their preferences into a shared normative decision framework but who remain involved in the design process. Framing has been identified as a challenge leading to counterproductive negotiation tactics by previous MSTSE research, but a challenge that is capable of being ameliorated through creative redirection of attention and emphasis on group-dynamic data over individualistic data (Fitzgerald and Ross, 2015). Those results are supplemented here with recommendations for framing adjustments throughout the MSTSE process, including early in the problem formulation.

Multi-Stakeholder Tradespace Exploration

Tradespace exploration is a design paradigm that uses the analysis of many alternatives in order to build understanding of the tradeoffs between value-driving attributes that are available to the designers (Ross and Hastings, 2005; Ross et al., 2010a). Without restricting attention to a particular implementation, generally a TSE project will follow a procedure similar to this:

1. **Problem Formulation** – the structuring of the problem and scope of decision making. This normally includes the definition of the design space used to enumerate potential system alternatives, the context in which those systems will operate, and the stakeholders and value attributes used to assess them.
2. **Modeling/Evaluation** – the development and use of models for the purposes of evaluating the designs. Models can take many forms, which necessitates a selection of modeling technique(s) appropriate to the problem formulation. Creating models is itself nontrivially difficult and normally takes considerable effort without the benefit of reuse of previous models.
3. **Exploration/Analysis** – the attempt to curate insights from the model outputs. Stakeholders and analysts are both capable of performing this step, with different strengths and weaknesses. Exploration is typically intended to generate results capable of justifying a decision to select a given design alternative.

This knowledge-building process is particularly useful when applied to complex systems for which designers or analysts may not have a strong intuition of the dynamics at play. The presence of multiple cooperating or competing stakeholders is one such complexity. Early attempts to incorporate multi-stakeholder analysis into TSE simply used a value model for each stakeholder and used analysts to find design alternatives that satisfied each stakeholder's model. We refer to this type of analyst-driven exploration as "informal" MSTSE, to indicate the unlikeliness of reaching a formal agreement using the tradespace without stakeholder participation (not to imply any sloppiness in the construction or exploration of the tradespace). Informal MSTSE has the advantage of being able to be conducted by experts in a manner similar to most systems engineering activities, with the resulting lessons and insights then communicated to stakeholders before they engage in the "formal" negotiation or decision making process. However, this approach naturally risks costly iteration, as the negotiation may raise new questions that must be sent back to the engineers responsible for tradespace analysis and delay the final decision.

This weakness inspired a new approach consisting of parallel exploration of the data by each stakeholder, with the goal of uncovering emergent insights in the intersection of their exploration and facilitating dialogue amongst the stakeholders that could result in iterative refinement of their value model *during* exploration rather than separate from it (Ross et al., 2010b). Though effective at its intended purpose, this type of multi-stakeholder analysis was conducted entirely with the mindset, supporting visualizations, and metrics of classic TSE. Efforts to formalize the concept of multiple stakeholders engaging with tradespace

data into MSTSE sought to re-examine the latent assumptions in these methods, in order to confirm or reject their suitability for the additional complexity inherent in the multi-stakeholder problem (Fitzgerald and Ross, 2014). Framing was identified as a potential key roadblock to effective MSTSE, due to the aggressively individualistic framing of traditional, single-stakeholder TSE analysis leading to misplaced reference points for decision making and misattribution of gains and losses.

Macro Framing and Micro Framing

The concept of framing has been used in many different ways, to describe many different ideas. In their most basic sense, all the uses of framing share one key feature: the understanding that contextual factors impact human perception and thus human action. The wide scope of framing can sometimes lead to confusion when discussing its implications. An instructive division of the relevant literature is by whether the framing occurs outside or inside the boundary of a specific case, which we call *macro* or *micro* framing issues, respectively. To illustrate the differences between these two types of framing, the following subsections will cover some of the prominent literature in the topics, following that with early research returns on the impact of framing in MSTSE.

Macro framing. Macro framing lies outside the domain of any single decision problem and deals with issues of writ-large beliefs and perspectives. Perhaps the most famous science-oriented discussion of framing is that of Kuhn (1962) on the subject of scientific revolutions. Kuhn describes the progress of science as one of prevailing paradigms that are upset by revolutions in favor of new paradigms. Revolutions are often characterized by heated debate between the scholars of the different paradigms, who frequently have difficulty communicating because they are figuratively speaking different languages. The paradigms can be viewed as frames (or perhaps lenses in this analogy) through which people 'see' an issue. Competing paradigms can make normative arguments in completely different directions, as the norms to which they appeal do not necessarily align. This can affect negotiations even at a mechanical level. For example, there is evidence that *differences* in outcome goal orientation and process goal orientation, two types of mental framing positively correlated with high-value negotiation results, can negatively impact the quality of negotiation outcomes. When measuring each type of goal orientation present in negotiations, similar levels of both key types of goal orientation resulted in better negotiation outcomes than simply having high absolute levels of goal orientation (Katz-Navon and Goldschmidt, 2009).

Schon and Rein (1994) also approach the issue of interpersonal conflict through framing, specifically targeting the realm of policy creation. They stress the importance of "frame reflection": deliberately considering the differing frames of each actor as a preliminary step to effective policy design. Moreover, each actor can balance multiple frames, both rhetorical and action-oriented, that operate on different levels. At the highest level, "metacultural frames" are heuristic frames with highly engrained societal norms. They provide an example of the use of metaphors like "sickness versus health" to justify actions such as urban renewal, which may be in direct conflict with a frame of "family and culture" on the same issue. These metacultural frames influence lower level "institutional" frames (general norms and actions of an institution) and down to "policy" frames (the framing of a particular issue). Though couched in the language of policy, due largely to the prominent role that ideology plays in political debate and policy creation, Schon and Rein's work can be applied to any field with multi-party conflict over issues more fundamental than objective fact. Frame reflection allows participants in the conflict to examine not only where their own beliefs come from but also those of their counterparts. Though Schon and Rein rightly acknowledge the risk of relativist paralysis (e.g. questioning the objective validity of norms can lead to failure to act), they provide many examples, though not directly engineering-related, of frame reflection by key actors resolving entrenched conflicts by clarifying the decision criteria for each party to the other.

More generally, "macro" framing is often a subset of personal philosophy. Of particular interest to negotiation is the issue of fairness or equality, as it has considerable bearing on the evaluation of outcomes

in group problem solving. Raiffa (2002) points out that there are many credible definitions of fairness, which can have dramatic impacts on the "fairest" solution for a given problem. In order to prevent self-interested "gaming" of the system, he recommends that participants in a negotiation agree in advance on an objective criterion of fairness. This is similar to the concept of the "veil of ignorance" central to Rawls' Theory of Justice (1971) because, without knowledge of how it affects one's own well-being, a person will likely choose what they truly believe to be fair. An alternative, more pragmatic, view of the same idea lies in the game theoretic heuristic that the best way to avoid "gaming" is to make the game too complex for players to discern what will improve their outcome, which may be true for the design for some large multi-stakeholder systems. "Macro" framing can also be an influencing factor in the creation of metapreferences on non-functional attributes in the design space for decision makers, such as a favoring of passively robust systems over actively changeable systems despite all-else-being-equal.

Micro framing. In contrast to macro framing, micro framing resides *within* the problem formulation, in the way information is presented and tasks are performed. The most prominent results in this field include bounded rationality (Simon, 1957) and Prospect Theory (Kahneman and Tversky, 2000), which delineate how humans may attempt to act rationally but do not succeed. Bounded rationality refers to the inability of humans to accurately analyze complex problems and find optimal solutions, instead relying on heuristics to reduce the cost of deliberation. Prospect Theory is an empirically derived theory describing the nature of many common deviations from axiomatic rationality. It states that people make decisions by comparing outcomes to a specified reference point. Outcomes are judged as differences from the reference point and are therefore perceived as "gains" or "losses." Reference points are created from available information and are reinforced by anchoring, the observed bias that humans display towards information they are shown first, regardless of its ultimate relevance. Changing a reference point, once established, usually requires a deliberate effort (Tversky and Kahneman, 1974). Perceived value around the reference point is asymmetric, resulting in a higher impact of losses over gains as pictured in Figure 1. It has also been found that decision making in the losses domain is more stressful and more likely to lead to irrational or regretted behavior (Gelfand et al., 2004).

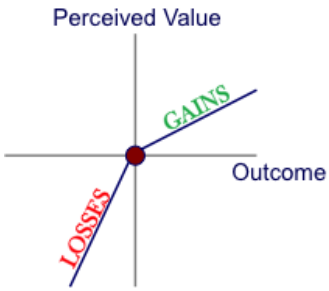

Figure 1. Perceived value around a reference point, according to Prospect Theory

Another common bias covered in Kahneman and Tversky's work is the availability bias, which describes the human bias towards information that is accessible (Tversky and Kahneman, 1974). In this way, information that is provided or readily recalled is implicitly assumed to be more important than hidden or forgotten information. Other biases they cover include insensitivity to probability, misconception of chance, and improper grasps of regression and representativeness.

The phrase *framing effect* is often used in the context of micro framing to denote an observable change in behavior derived only from changes in framing, usually with regards to whether the outcome is characterized as a gain or a loss. For example, switches between positive and negative (gains / losses) phrasing have resulted in dramatic changes in decisions, with people tending to strongly avoid losses over seeking gains (for examples and analysis, see Tversky and Kahneman, 1981; Levin et al., 1998). Additionally, the observed bias toward certainty has led people to be largely characterized as risk averse for gains,

preferring a certain gain to a higher expectation uncertain gain, and risk seeking for losses, preferring a chance at no loss to a guaranteed loss.

Other topics in "micro" framing include the effects of detailed deliberation and expert opinion. Some research has suggested that extensive consideration of preferences can lead to behavior that deviates from expert opinion and leads to decreased satisfaction in decision outcomes (Wilson and Schooler, 1991). Excessive time spent developing a numerical value model, often without seeing the impacts immediately, effectively codifies the *estimation* as a *truth* that must be followed when more satisfaction would be gained by allowing future changes in response to emergent insight. This is a strong argument against overtaxing decision makers, and relates to the theory that the expertise of 'experts' is in fact dependent on a stable frame for them to leverage (Shanteau, 1992).

Finally, the concept of two-path information processing, a theory originally developed in the 1980s by the Elaboration Likelihood Model (Petty and Cacioppo, 1986) and the Heuristic-Systematic model (Chaiken et al., 1989) and recently popularized by Kahneman (2011), outlines two main ways in which humans perceive information and make decisions: heuristically and systematically (in ELM parlance, peripherally and centrally). Heuristic thinking is fast, developed over time and through intuition, allowing people to rapidly assimilate new information that they can fit into an existing mental frame. Systematic thinking is the more in-depth, analytical thought that promotes new learning but requires more effort on the part of the decision maker. The framing of a problem has an impact on which path a decision maker uses, depending largely on how familiar the situation is to them.

Framing in MSTSE. Prior research by the authors was specifically geared toward improving the micro framing of TSE/MSTSE visualizations in order to accurately represent the complexity of the multi-stakeholder problem and promote positive negotiation tactics (Fitzgerald and Ross, 2015). The benefit-cost tradespace scatterplot was predicted, based on the principles of negotiation theory and Prospect Theory, to emphasize the Pareto front as a reference point, thereby potentially miscategorizing some alternative as losses (relative to the front) when they are actually gains (relative to the *best alternative to a negotiated agreement*, or BATNA). Experimental evidence has lent credence to this theory.

However, this theory addressed only a fraction of the complete MSTSE process: micro framing in the analysis phase. To this point, very little consideration has been given to controlling macro framing or the framing of MSTSE problem formulation or modeling activities. Additionally, the benefit-cost scatterplot, though the most prominent tradespace visualization, is far from the only type of exploratory aid used in tradespace exploration. The need for further investigation of all aspects of framing in MSTSE is necessary in order for it to proceed as a viable means of engaging stakeholders in complex systems engineering negotiations.

Macro and micro framing can have a "weakest link" relationship in a negotiation, by which a framing trap in one may pull down the other. For example, if a stakeholder approaches MSTSE with a macro frame that is highly confrontational and individualistic, they will likely favor a micro frame, in the form of a particular visualization for example, that matches their outlook. Alternatively, if only individualistic visualizations are available, a stakeholder's macro frame may be slowly pushed into a similar aggressive, value-claiming mindset in order to reduce cognitive dissonance with their tools. For example, imagine a stakeholder with access only to a list of individually-Pareto-efficient alternatives. Naturally, he will be forced to engage with other stakeholders in the negotiation from the macro framing perspective of "I need one of these designs" rather than "we should find a mutually beneficial design" because he simply does not have the micro frame necessary to identify which alternatives on his list are agreeable to other people and therefore mutually beneficial. This defeats the central purpose of productive negotiation and because of it, management of framing must be continuous, extending from problem formulation all the way through analysis.

Framing Activities and Visualizations

Using the generic three-step outline of a TSE procedure, the following sections will detail recommendations for controlling the framing of common TSE activities in order to support a successful MSTSE application. The success criterion of MSTSE is the ability to find and identify mutually beneficial alternatives, if they exist. To do that, the macro framing of the problem should be aligned with the tenets of principled negotiation as much as possible and the micro framing must accurately represent the value of the different alternatives. The recommendations included here are not intended to be exhaustive but rather instructive advice for potential adopters of MSTSE, based on the combined insights of literature in framing and negotiation. Following these recommendations should improve the communication of preferences and needs between negotiators (a skill not developed or supported by classic TSE) and the value assessment of the alternatives by each negotiator (which is a different, more complex task than in classic TSE). This improves the MSTSE procedure by reducing the likelihood of key failure modes at both the inter-stakeholder and stakeholder-data interfaces, limiting opportunities for negotiation breakdown driven by social conflict or misattribution of value.

Problem Formulation

Problem formulation has a large impact on the resulting direction of a tradespace analysis. It defines the scope of the system to be analyzed, what factors are (and are not) under designer control, and the sources of value that are sought by the stakeholders. Unsurprisingly, the predominant impact of framing in this stage is likely to come from macro framing as the beliefs, perspectives, assumptions, and sometimes biases of the participants work their way into the problem. To address this challenge, communication becomes paramount: explicitly capturing some of the macro frames with which stakeholders and/or analysts are approaching the problem can allow for the identification and mitigation of potential future barriers to agreement before they become negotiation impasses.

Capture macro frames. Note that the objective of these efforts is not to *change* the macro frames with which stakeholders approach the problem, but to capture what they are. Practically, macro frames are developed by a lifetime of experience and opinion, and are difficult to change. More fundamentally, since MSTSE is positioned as a *prescriptive* rather than *normative* analysis technique, it is inappropriate to suggest that one macro frame is the "correct" frame to use (a normative argument). Rather, we are interested in knowing the macro frames favored by each stakeholder so that when *they* attempt to make a normative argument we can understand the frame leading them to make that argument and, hopefully, communicate it effectively to other stakeholders who do not share that frame. This is intended to prevent incidents of the stakeholders "talking past" each other by assuming others share their underlying assumptions.

Some useful frames to consider are:

- Purpose for MSTSE (e.g., to explore and learn about the opportunity vs. to make a funding decision)
- Relative desire for low-cost vs. high-benefit systems
- Relative desire for passively robust vs. actively flexible systems

Record key elements of problem structure. This activity is already a main component of problem formulation for TSE, which requires explicit accounting of the factors impacting the system and their assignment as variables in the tradespace: design variables, context variables, or performance attributes. However, the multi-stakeholder problem has additional structural elements on top of those from single-stakeholder tradespaces that can impact the best micro frames to use in later phases of MSTSE. Explicitly noting these elements during problem formulation can improve later analysis, as certain analysis

types can become more or less relevant depending on these key features. For example, if some attributes of interest to the stakeholders are divisible at-will (e.g. manufacturing costs, which can be split between stakeholders as desired), these can be leveraged by additional analysis later by customizing or sub-optimizing a given alternative. On the other hand, negative pre-existing relationships between the stakeholders may limit the effectiveness of some types of exploration, particularly those that involve directly comparing desired alternatives. Some of the structural elements worth recording include:

- Divisible attributes
- Relationships between stakeholders (personal, professional, etc.)
- Tradespace completeness – could more alternatives be added?
- Constituencies – do the stakeholders represent other people?
- Schedule – how much time is available for the stakeholders to interact?

Determine each stakeholder's BATNA. This is arguably one of the "key elements of problem structure" from the previous point, but is critical enough to merit its own description. The BATNA (best alternative to a negotiated agreement) is, essentially, what each stakeholder will do *on his own* if no agreement can be reached with the other stakeholders. This is an important reference point with respect to the value of any of the design alternatives under consideration as it defines the border between gains and losses. Failure to define and then leverage the BATNA during exploration reduces the situational awareness of the stakeholders.

In some cases the BATNA will be readily apparent, particularly if the stakeholder(s) have *no* viable alternatives to a negotiated agreement. However, in general this task requires careful thought and consideration just like the rest of problem formulation. It can help to consider a variety of "types" of BATNA, in order to prompt brainstorming in multiple areas. Common BATNAs include the following:

- **Do-nothing** – if the MSTSE is strictly exploratory, inaction is likely the course of action should no agreement to proceed be made. Doing nothing typically carries zero cost and zero benefit.
- **Existing system** – for design tasks intended to improve or replace an existing system, the do-nothing alternative actually entails using the current system. This type of BATNA is one that commonly drives differences in stakeholders' bargaining leverage, as some stakeholders may be much better off with the current system than others.
- **Build preferred alternative alone** – some projects seek agreement between multiple stakeholders to reduce the cost borne by each individual. If a stakeholder is capable of affording some or all of the alternatives by themselves, those alternatives become viable BATNAs (though at a higher cost than if they could agree to share one).
- **Other opportunity** – resources that are expended on the alternatives in the tradespace represent an opportunity cost in that they cannot then be spent on other projects, which may be more valuable. This type of BATNA is the most difficult to capture, as the number of other opportunities is potentially limitless, but this fact is true for all design tasks. Usually a small number of known viable or attractive opportunities can be considered without fear of missing drastically better choices.

Identifying the best alternative in each of these categories and then assigning the best of those as the BATNA is an effective way of breaking down the problem. Sometimes it may be difficult to assess which of these choices is the "best" (and thus, the BATNA) at this point, because the evaluative model has yet to be created, particularly for the "build alone" choice. In that case, preserving the list of potential BATNAs and then choosing one after modeling but before exploration is feasible.

Modeling / Evaluation

Engaging in the modeling of the system after completing a thorough problem formulation seems at first glance to be trivial: simply a matter of taking the defined design vectors and finding the right equations to calculate the desired performance attributes, subject to any influencing contextual parameters. However, the modeling task itself can also propagate cooperative versus individualistic framing implicitly into the exploration phase. When multiple stakeholders will be conducting the exploration, it is important to make sure that the modeling is satisfactory to all of them, which requires some additional management.

Joint Fact Finding (JFF). Joint Fact Finding (Ozawa, 1991; Ehrmann and Stinson, 1999) is a valuable use of time in order to build trust in the data that exploration will be based on. It is difficult to reach consensus on a design if some stakeholders disagree with the models being used to evaluate it, making uncoordinated multi-person modeling activities a threat to productive negotiation. JFF seeks to establish credible and objective data, one of the foundations of principled negotiation (Fisher, Ury, and Patton, 1991), to use as the foundation for evaluation of alternatives and discussion of their relative merits. If possible, all efforts should be made to convene stakeholders prior to actual exploration in order to perform JFF in support of the modeling task. JFF also helps to establish a macro frame of cooperation *before* engaging in the negotiation itself, which can help preserve positive, mutually-beneficial bargaining in the face of any naturally developing competitiveness.

Private Information. Not all models can be developed through JFF. If a stakeholder already possesses a model for a piece of the larger system, reusing that model can save time and effort. If they are willing to share that model (both how it works and its results) with the rest of the stakeholders as a part of a larger JFF effort, that is a valuable step in building rapport, in accordance with the principle of Full, Open, and Truthful Exchange (Raiffa, 2002). Some stakeholders may be reluctant to share models, but should be encouraged to do so for the above reasons. However, some models' inner workings may depend on proprietary or classified information that the stakeholder is unable to share. In the case of a stakeholder unwilling or unable to reveal their models, two approaches can be taken: the existing model can either be ignored in favor of a newly-created JFF model (if possible) or "black-boxed" so that other stakeholders can only see its outputs. A black-boxed model can be fully effective if its outputs only impact the value proposition of the stakeholder who owns it. If not, other stakeholders will need to trust that the model is accurate. If a public - but presumably lower fidelity - model is available, it can be used to help validate the black-boxed model and build trust.

Exploration / Analysis

Entering the exploration phase, the dominant framing concern shifts to micro framing: the actions the participating stakeholders are asked to perform and the way the data generated by the previous steps is presented. Macro framing still has a role to play in exploration however, specifically when weighing specific alternatives as potential final agreements.

Emphasize the BATNA. For a proper valuation of the designs in the tradespace, they must be valuated against the BATNA as a reference point. This provides the necessary perspective for determining the value of a design *as a multi-stakeholder agreement* rather than the typical, less-contextualized evaluations *in a vacuum* or *relative to other designs* commonly used in classic TSE activities. Taking classic TSE visualizations and intelligently incorporating a prominent indicator of the BATNA is a functional way of improving negotiation behavior, as demonstrated by the negotiation tradespace in Figure 2: the use of which was shown via controlled experiment to improve gains/losses framing with a more accurate reference point (Fitzgerald and Ross, 2015). Views designed to compare alternatives should always include the BATNA as a "sticky" alternative, even in simple implementations such as tables of performance data.

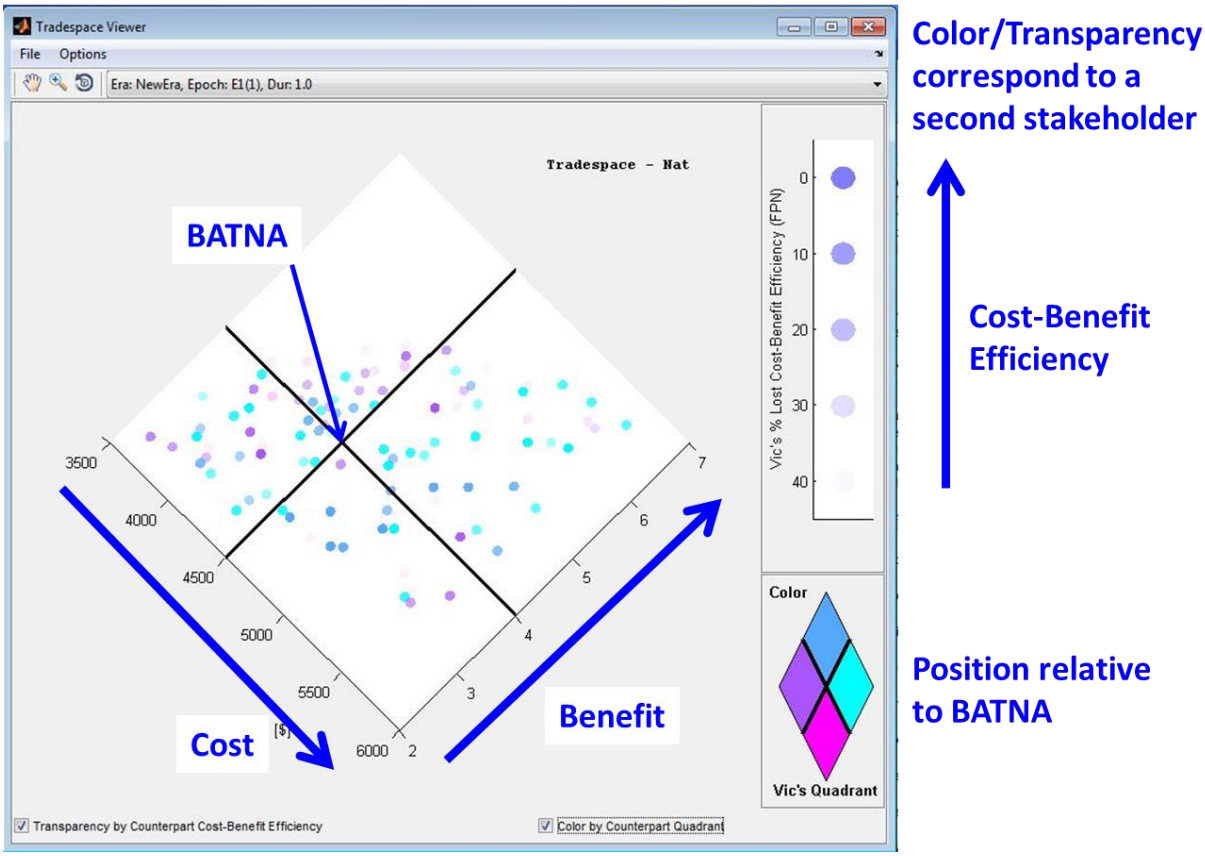

Figure 2. Negotiation tradespace used in MSTSE experiment (Fitzgerald and Ross, 2015) with key features highlighted

Limit strictly-individual analysis. Activities should incorporate the value statements of multiple stakeholders as much as possible in order to consistently keep each participant aware of the "group" aspect of the negotiation problem. This can prevent fixation on alternatives that are very good for one stakeholder but not for others. In the BATNA-centric tradespace, color and transparency accounted for the value of other stakeholders, and the resulting negotiations saw fewer exhaustive search patterns in favor of more direct paths to mutually-valuable solutions. If the participating stakeholders want to utilize a particular analysis of the tradespace using their own value, it should be replicated for other stakeholders and shown together. For example, the benefit-cost efficient solutions on the Pareto front are highly desirable for a given stakeholder, but should be calculated and presented relative to the Pareto fronts of the other stakeholders. This can be accomplished in multiple ways, including the use of Venn diagrams to illustrate overlap between specific stakeholders' preferred alternatives and gridmaps to show the relative sizes of the regions of agreement for all stakeholders (Figure 3). These, and other, visualizations are currently the subject of ongoing research.

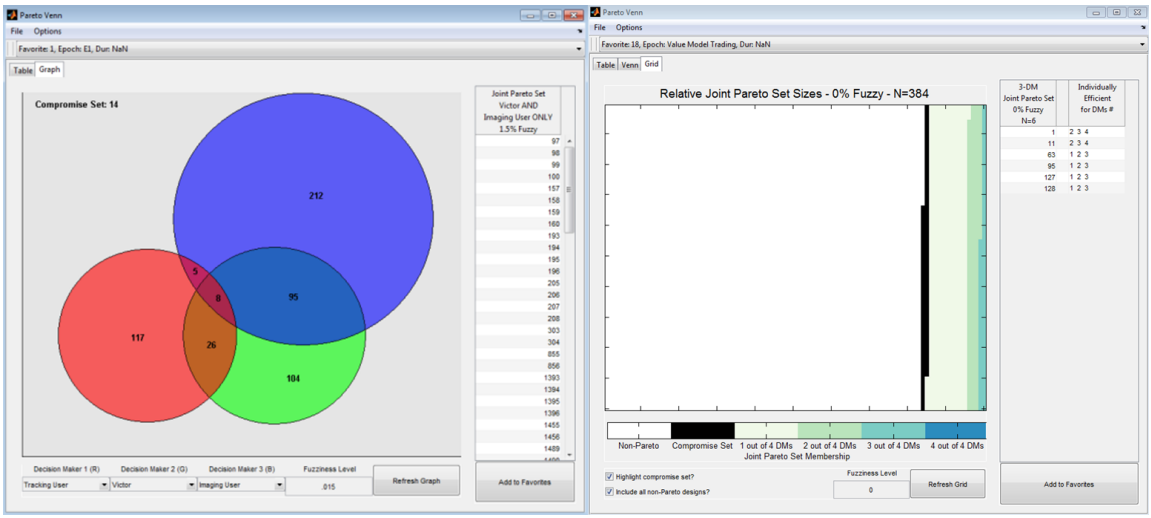

Figure 3. Example Venn diagram and Gridmap for multi-stakeholder Pareto front analysis

Analyze relationships. The relationships between stakeholders in the value domain is a component of the multi-stakeholder tradespace that is not present in classic TSE, but is just as important as the evaluation of the alternatives directly. These relationships, whether or not they are analyzed, will affect the ways stakeholders interact and the designs that they might agree on; thus explicitly considering them is a powerful means of understanding the dynamics at play in the negotiation. Stakeholder relationships in the value domain can be quantified through the correlation of their value metrics, commonly done at the holistic level (e.g. the correlation between Stakeholder A and Stakeholder B using their respective cost-benefit efficiencies) and displayed in a heatmap for all stakeholders at once. This view can visually highlight groups of stakeholders that could form a promising coalition of shared interests, which can be a useful simplification of a many-party negotiation; in Figure 4, separate three-stakeholder and two-stakeholder coalitions with internal correlation greater than approximately 0.6 are apparent in the blocks of green, with an average of approximately 0 correlation between the two coalitions. Additionally, explicitly showing positive correlations indicative of shared interests can be a useful reminder of the potential for mutual gains for stakeholders caught up in a distributive negotiation fallacy or fixated on individually-optimal alternatives.

Correlations can also be displayed on an interest-by-interest basis (e.g. the impact on the correlation of A and B's utility functions caused by A's preference on a specific value metric). The resulting correlation data is combinatorically larger than at the holistic level but can be segmented to provide an intuitive breakdown of how one stakeholder relates to all of the others. This can be used to identify key "free" attributes that do not need to be traded between stakeholders and "pain points" that drive the differences in the value statements for each stakeholder. In Figure 5, the orange-coalition stakeholder Victor's attributes are displayed on the y-axis and it becomes clear that his second attribute ("NumTargetBoxes") is driving a considerable part of both his alignment with his own potential coalition and disalignment with the other stakeholders.

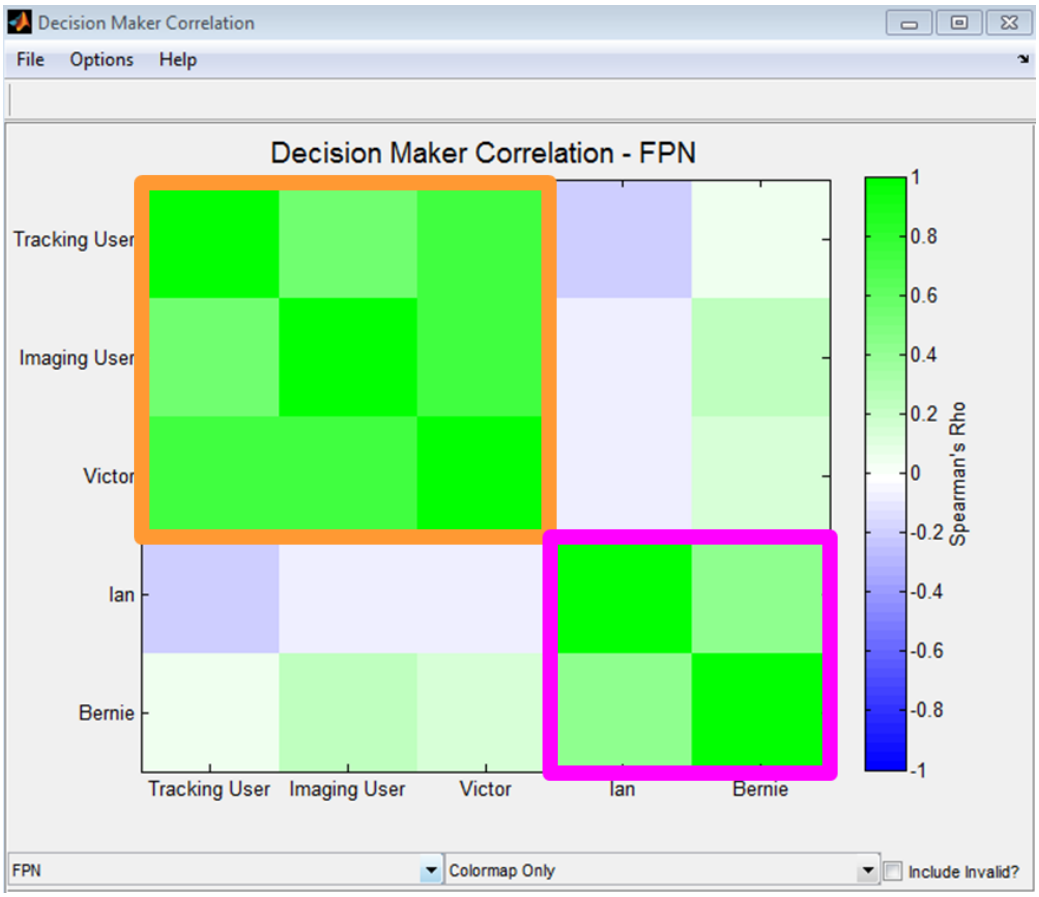

Figure 4. Example Stakeholder-Stakeholder correlation interface for five stakeholders – annotated to highlight two emergent coalitions with high correlation (orange and magenta boxes)

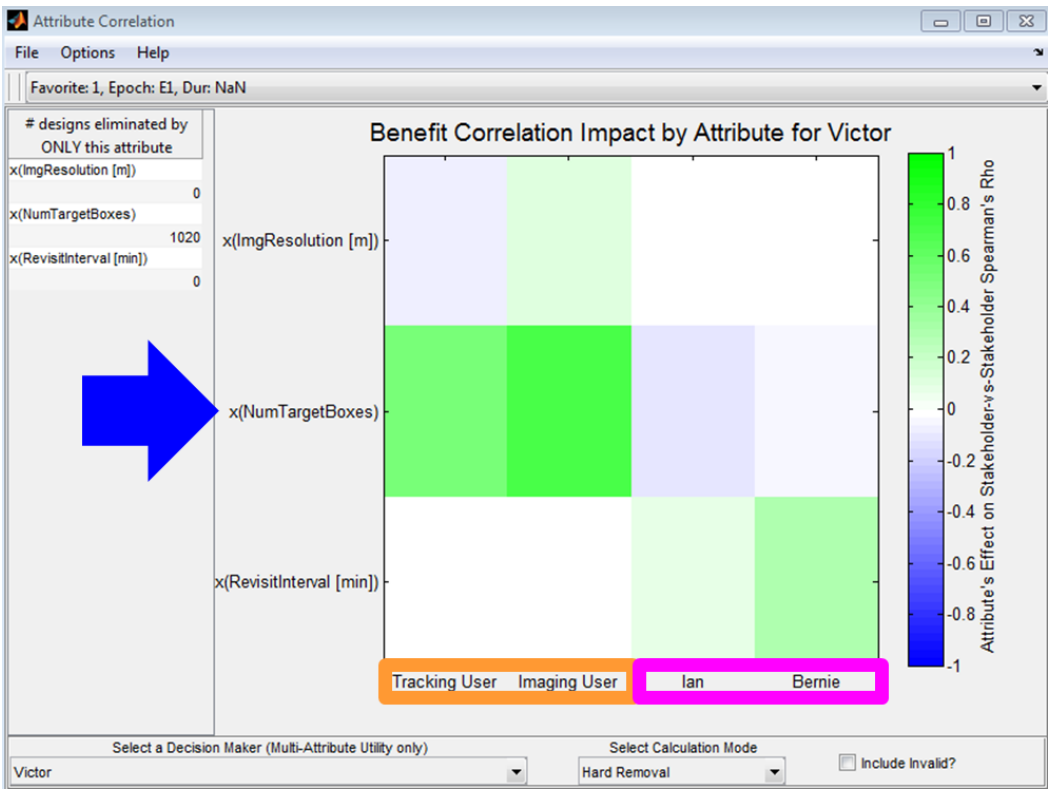

Figure 5. Example Stakeholder-Interest correlation interface – annotated to highlight the attribute most responsible for bringing the orange coalition together and separating them from magenta

Allow stakeholders to change their mind. Negotiation in MSTSE exposes each stakeholder to large amounts of information that they may not have previously known, particularly the preferences of other stakeholders which are not present in classic TSE. New information can change subjective assessments of value (Curhan et al., 2004) and invalidate parts of the original problem formulation. Stakeholders should be encouraged to critically reassess their value statements during the negotiation. Tweaking the value functions to more closely align with a "new" reality can be performed during a session in order to accelerate the iterative design loop (see Figure 6 for example). Additionally, if the value function updates are convergent in a manner leveraged by other consensus-building techniques such as the Delphi method (Golkar and Crawley, 2014), these live updates have the potential to open up new regions of mutual value in the tradespace.

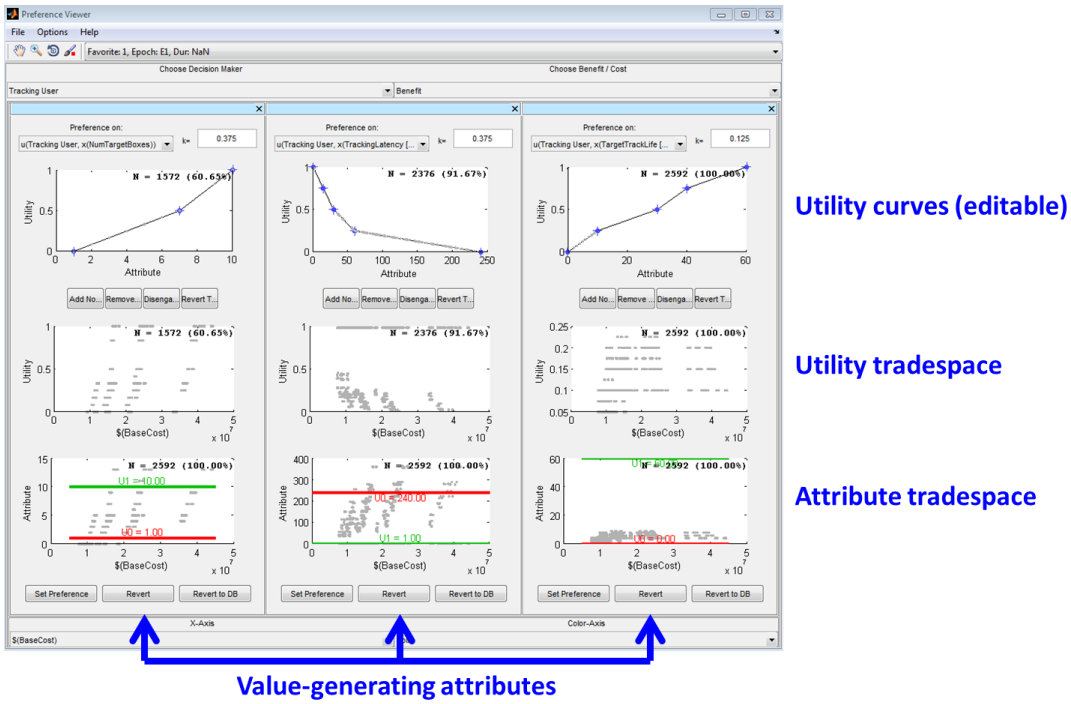

Figure 6. Example interface for live editing of value functions, synced to other visualizations

Refer back to macro frames. When discussing individual alternatives, effort should be made to refer back to the macro frames of each stakeholder. When a stakeholder refers to a design with a subjective assessment like "good", the first question should always be "Why?". Each stakeholder wants a "good" design, but each has different criteria for what is "good" that includes not only their reported value function but also the macro frames with which they choose to make decisions. For example, if Stakeholder A recommends an alternative as "good" on the grounds that it has high benefit for all parties, Stakeholder B can make a more intelligent counteroffer with less chance of sparking a debate over the definition of "good" if it is clear to all parties that he prefers low-cost, high-efficiency solutions over strictly high-benefit solutions.

Discussion and Conclusion

TSE is a continually developing design paradigm, and MSTSE is an even younger offshoot of the main research branch. Considerable work is still needed to flesh out the similarities and differences inherent in exploring a tradespace with one stakeholder versus multiple stakeholders, particularly in the realm of implementation. Framing has the potential to elevate or sabotage group analysis depending on its suitability. This work is an initial attempt to identify framing activities necessary for MSTSE, and to provide recommendations for how to conduct them to greatest effect. Importantly, these framing activities span

problem formulation, modeling, and exploration and include both macro framing and micro framing concerns.

This paper has addressed the framing of MSTSE with active stakeholder participation from problem formulation through exploration – as opposed to "informal" MSTSE relying entirely on engineers and/or analysts, which was mentioned briefly when introducing the evolution of the topic. Given the many constraints on most stakeholders' time, informal MSTSE will likely remain a practical alternative for developing insight into the dynamics and relationships that define multi-stakeholder problems. However, the lack of stakeholder participation imposes some limitations on the types of activities that can be performed effectively. Stakeholder value models and BATNAs will need to be estimated and can't be modified during exploration (as a stakeholder can't "change their mind" without participating). Additionally, some tasks will revert to their standard TSE forms, as Joint Fact Finding is not possible and stakeholders will not be available to discuss macro frames. Table 1 presents a short summary of the recommendations in this paper and the modifications necessary for their adoption in informal MSTSE.

Table 1. Summary of recommendations, with modifications for informal MSTSE

Phase	Recommendation	Informal MSTSE
Problem Formulation	Capture macro frames	All of these apply except for capturing macro frames of other stakeholders. Make best estimates for stakeholders' BATNAs and value models.
	Create many alternatives	
	Record key elements of problem structure	
	Determine each stakeholder's BATNA	
Modeling / Evaluation	Joint Fact Finding	Treat modeling as normal TSE
	Private information	
Exploration / Analysis	Emphasize the BATNA	Continue to use BATNA-centric visualizations and analyze relationships, but limit activities related to changing stakeholder value models without their participation.
	Limit strictly individual analysis	
	Analyze relationships	
	Allow stakeholders to change their mind	
	Refer back to macro frames	

Originally, MSTSE was envisioned to leverage the TSE framework in order to capture insights from the data related to the multi-stakeholder dynamics of the problem and find better negotiated solutions. Explicitly managing the framing aspects of MSTSE can serve to enable this goal by reducing opportunities for the social breakdown of negotiation caused by poor communication or degenerate bargaining tactics, which can occur at the stakeholder-stakeholder level or at the stakeholder-data level. The framing elements called out in this paper represent a first pass at collecting some of the most important features of the MSTSE technique; future research will seek to expand on this list and provide more actionable recommendations for practitioners. Additionally, future research will expand the validation efforts of previous experimental results (Fitzgerald and Ross, 2015) by incorporating the insights of case studies, both by considering the impact that the framing of issues has had on negotiations and by testing the ability of the MSTSE framework to identify "good" and "fair" solutions under a variety of potential macro and micro frames held by the participants.

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Biography

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