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Guiding Cooperative Stakeholders to Compromise Solutions Using an Interactive Tradespace Exploration Process

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Abstract

Engineering projects frequently involve the cooperation of multiple stakeholders with varying objectives and preferences for the resulting system. Finding a mutually agreeable solution is of paramount importance in order to assure the successful completion of these projects, particularly when different stakeholders are splitting the costs because none can afford to finance the project on their own. This paper proposes a process for uncovering potential mutually agreeable solutions between conflicting stakeholders, without relying on hypothetical aggregate or super-stakeholder preferences, by using guided individual preference compromises and efficiency tradeoffs. Opportunities for experimentally testing the process, with results investigating its usability and solution quality, are discussed. Further directions to improve and expand the process are also discussed, with attention paid to the design of the process as it relates to promoting an implied concept of “goodness” or “fairness” of compromise along with the ability of the process to incorporate advanced interactive technology to improve knowledge retention and understanding of the participating stakeholders.

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1. Introduction and Background

As modern engineering projects increase in size and complexity, they have also tended to increase the number of people affected, thus expanding the set of involved stakeholders. Reinforcing this effect is a similar increase in cost, which has driven many projects to include multiple direct stakeholders in order to spread out the expenses, allowing individuals and organizations with smaller budgets to participate in the design process and experience benefits of systems they would otherwise not be able to afford. However, when more than one party is involved in the decision-making process (frequently by paying a portion of the system cost, but occasionally as an influential group separate from the costs of the system) the selection of a single design to build becomes intrinsically more challenging as the preferences of the different stakeholders must be suitably satisfied, even if they are of conflicting interests. As an example, consider the USAF's attempts to build a space-based radar system, which was cancelled in 2005 due to the inability of stakeholder to agree upon a fixed CONOPs for the system. Techniques for achieving compromise between stakeholders with disparate preferences are therefore of significant importance for modern systems engineering.

1.1. Multiple Stakeholders

The presence of multiple active, participating parties is a recognized part of the modern engineering process, largely supported by the emerging field of “collaborative engineering”. As phrased by Lu et al. [1], the goal of collaborative engineering is to “enable engineers and engineering companies to work more effectively with all stakeholders in achieving rational agreements” with the goal of accomplishing more together than would be possible apart. The benefits of adoption of collaborative engineering practices are seen both in the process (e.g. number of development iterations) and the result (e.g. product quality), and thus represent an avenue for potential improvements in both the costs and benefits of engineering projects. Readers interested in the general state of practice for collaborative engineering are referred to [1].

Collaboration, however, is only one potential level of interaction between participants in a group engineering effort, one that implies a high degree of similar goals. Again, we refer to Lu et al. [1] and use their set of definitions for various degrees of collective behavior, particularly *coordination*, *cooperation*, and *collaboration*. The most striking difference between these three types of behavior lies in the nature of the goals of the participating stakeholders. Collaboration requires a shared goal, while cooperation entails different goals, and coordination has (potentially competing) hidden goals. Collaborative engineering focuses (naturally) on collaboration, but this is only a subset of the potential interactions between stakeholders. Moreover, collaboration is not a *superior* form of behavior, as one might assume due to its higher degree of interaction and alignment of goals, but is rather an artifact of the nature of the project and the relationship of the participating stakeholders. The research discussed in this paper concentrates on cooperation between stakeholders with unaligned goals working together because it is more common in the large-scale group systems of interest to us; it thus falls within the purview of collaborative engineering as a field, but will borrow from other areas as well in order to capture features related to the disagreement between stakeholder preferences.

One such area of interest is that of game theory and mechanism design, another discipline dealing with the interactions of multiple participants. Traditional game theory, as discussed in the seminal work by Von Neumann and Morgenstern [2], concerns itself with competitive, fully self-interested behavior, which at first seems to put it at odds with collaborative engineering. However, there will frequently be aspects of this adversarial behavior in cases of multiple stakeholders with varying preferences, as they try to “game” the group solution to favor their own preferences as much as possible even while they cooperate with the other stakeholders. Mechanism design is then the field of crafting the system, or game, that participants must interact within in order to promote some externally-enforced good [3,4]. Thus, this research also falls broadly under the general scope of mechanism design, as its goal is to create a system within which cooperative stakeholders can interact while promoting the identification of mutually satisfactory and “fair” solutions, ideally one that minimizes the ability of the participants to “game” the system in their favor.

1.2. Tradespace Exploration

Tradespace exploration is a modern engineering practice that explores a design space by enumerating and evaluating a large number of potential designs, including apparently sub-optimal designs (however “optimality” may be defined), with the understanding that certain valuable behaviors may not be captured by a particular stated value metric [5]. The “tradespace” itself is the set of designs considered during this process, and is typically viewed with a two-dimensional plot of benefits and costs, which offers a concise visualization of the two main decision-driving features of the design process. Tradespace exploration has been found to be particularly useful for the design of complex engineering systems with multiple dimensions of benefit, as they are difficult to optimize and rarely intuitive. In Multi-Attribute Tradespace Exploration (MATE), the often chosen benefit metric is a multi-attribute utility function, created as a combination of different performance attributes which are rated from zero, defined as minimally acceptable, to one, at which point no benefit is gained from performing better [6]. The different attributes represent the different ways in which a system delivers benefit to the stakeholder. For example, a car might have attributes for top speed, acceleration, and turning radius; each attribute delivers some independent utility and can be combined into an overall utility for a design. MATE has been effectively used to investigate the preferences of stakeholders and to find attractive designs in line or superior to those found using traditional point-design engineering techniques, without the cost of algorithmic optimization [7].

1.3. Multiple Stakeholders in MATE

Tradespace exploration is an attractive technique for problems in which there are multiple decision makers or stakeholders with different value propositions or “preferences” defining their utility functions. This is because, while a point-design study would result in a single preferred design for each stakeholder, the tradespace allows each stakeholder to find desirable designs and compare with each other across a common set. The presence of designs that are evaluated for all stakeholders also assists in the finding of mutually satisfactory designs, those designs that perform well for each set of preferences but may not be the optimal point choice for any one. This also reduces the likelihood of settling on an inferior hybrid type of solution, which merely combines aspects of each stakeholder’s individually preferred designs without detailed analysis of the resulting system’s performance. For these reasons, tradespace exploration will be used as the framework for design analysis on which the research of this paper is based.

Previous methods for compromising between stakeholders using a tradespace exploration study have been in line with the basic analysis: exploratory. For example, careful consideration of the tradespace may reveal that Stakeholder A has dramatically fewer acceptable designs because his requirement on a single attribute is very restrictive. Upon relaxing this requirement, new mutually attractive options between Stakeholder A and the other stakeholders may appear [8]. This practice was conducted on a case-by-case basis, but an attempt to formalize the steps involved into a coherent process has the potential to unlock more consistent success in finding solutions that are desirable to all participating stakeholders.

Note that one commonly suggested approach for finding compromises between stakeholders using multi-attribute utility is to simply combine their utility functions into a single “aggregate” decision maker utility. However, it is wise to exercise extreme caution in using this technique, as the standard Keeney-Raiffa utility function is not cardinal (an absolute measure of value), placing the direct addition of separately defined utilities on decidedly shaky mathematical grounds. It is also worth remembering Arrow’s paradox, which, roughly worded, states that there is no system for combining multiple rank-orderings into an aggregate ordering without violating at least one commonly accepted rational restriction on group decisions, including transitivity and non-dictatorship among others [9]. Without a clear hierarchical relationship amongst the stakeholders, this result provides a compelling argument in favor of avoiding any attempts at achieving compromise by combining their various preferences in a super-preference set [10].

1.4. Buy-In and Visual Analytics

A serious concern for any proposed method for achieving compromise between stakeholders is that of the buy-in of the stakeholders themselves: if they do not believe or have faith in the process, why should they be compromising their value? The unintuitive nature of multi-dimensional value analysis and the common presence of unanticipated and emergent behavior can prevent users from understanding and believing the results. Visual analytics are therefore of great interest to this research, as a well-constructed presentation of data has the potential to illustrate the complicated logic and the benefits of an otherwise black-box process [11]. Visual analytics also dovetails nicely with the use of tradespace exploration, which generates extremely large quantities of data, for which visualization is already of great interest [12].

2. Types of Compromise in Tradespace Exploration

The intent of this research is to create a process utilizing features and ideas from tradespace exploration, game theory, collaborative engineering, and visual analytics that will promote the identification of designs which compromise the desires of multiple stakeholders as well as possible. A key question is, “Where does compromise occur when multiple definitions of stakeholder value must cooperate?” In this case, there are two distinct types of compromises occurring: preference compromising and design compromising.

Preference compromising occurs when a stakeholder modifies their utility function in order to promote agreement with the other stakeholders. The eliciting of utility functions is an imprecise process, and stakeholders may modify their stated preferences when presented with additional information. Frequently, this has been observed when stakeholders see the “optimal” solution from a tradespace study, and then realize that they misrepresented

their preferences, perhaps putting too much or too little emphasis on a particular performance attribute [8]. However, the presence of *other* utility functions is also potentially a driving force behind the modification of preferences, this time in the name of compromise. For example, if two stakeholders both value the top speed of a car as a performance attribute but Stakeholder A says that 100 mph is minimally acceptable while Stakeholder B says 130 mph, Stakeholder B may reevaluate his decision when confronted with that information and be willing to reduce his requirement to come in line with that of A, particularly if it can be demonstrated that such a switch would reveal additional designs that are attractive to both of them.

Design compromising occurs when a design selection is made, and there are no designs that are individually optimal for all stakeholders. Some design must be chosen, but this will require a compromise on value from at least one of the stakeholders in order for a mutually satisfactory solution to be reached. This type of compromise occurs after preference compromises have been performed. Preference compromises align stakeholders' value statements to create a set of potential attractive solutions, and then design compromises select from amongst that set.

It is this paper's hypothesis that a process which automatically identifies opportunities for preference compromises and offers them to the stakeholders iteratively will gradually converge to the point where either there is a single solution optimal for all stakeholders or the final design compromise requires a smaller value sacrifice by one or more stakeholders than was necessary before the attempts at preference compromise. Of course, not all cases will have a mutually agreeable solution; for example, a two-person zero-sum game would never resolve, because the interests of each stakeholder are directly opposed and thus it is impossible for both to extract benefit from any single solution. Because of the potential for this type of problem, the process is only generally applicable if it contains some sort of termination criterion that ends further attempts at compromise and, ideally, can illustrate why this is the case.

3. The Compromise Process

As previously discussed, the effectiveness of the compromise process is dependent on the buy-in of the stakeholders being asked to compromise, implying that employing descriptive data visualization techniques are likely to improve our overall results. With this in mind, the process was modeled around a framework reflecting the visual analytics paradigm of Keim et al. [13]: analyze first, show the important, zoom/filter and analyze further, and details on demand. Since the process is designed to use data and humans together it is of course well suited to visual analytics, and this framework puts the process in a good position for further integration with visualization tools and advanced technology and automation down the road. The discussion section of this paper has more details on the topic of employing technology in the compromise process.

The main input for the process is the data present in a typical MATE study: the design space with performance evaluated by an underlying model and the utility functions for all of the participating stakeholders. Additionally, advanced tradespace metrics can be useful both for screening for potential compromise opportunities and for justifying and explaining decisions to the stakeholders. For descriptions of some useful tradespace metrics, readers are encouraged to consult the references for this paper, particularly [5,7,14,15]. The steps of the process are:

1. Identify dimension for productive preference compromise
2. Allow relevant stakeholder to select a compromise
3. Repeat 1 and 2 until termination
4. Final design compromise and selection

3.1. Identify dimension for productive preference compromise

The first step corresponds to the "analyze" aspect of the visual analytics paradigm. The input tradespace data is processed in order to find a preference to target for the initial preference compromise. Identifying critical areas to target is paramount for achieving an agreeable compromise. This step will rely on heuristic metrics that are believed to promote agreement between different stakeholders, such as the single-attribute utility yield example that was already discussed: finding the attribute that is eliminating the largest fraction of the tradespace from consideration and flagging it as a potentially beneficial compromise opportunity. As this process is extremely new, it is anticipated that the list of heuristics for identifying compromise opportunities will grow over time, allowing for deeper and more thorough investigation of the differences in each stakeholder's preferences. Advanced tradespace

metrics will also likely be of significant use for this task. A working list of potentially useful identification heuristics is included in Table 1.

Table 1. Potential Metrics for Identifying Preference Compromise Opportunities

Metric	Reasoning	Potential Compromise
Single Attribute Utility Yield	If the yield for a single attribute is significantly lower than the others, it is possible that the requirement is stricter than necessary, especially if other stakeholders use the same attribute but with a less restrictive preference	Relax the preference (minimum acceptable level)
Multi-Attribute Utility Aggregation Weight	If the weight for a particular attribute is significantly lower than the other attributes in that stakeholders MAU function, and no other stakeholder utilize that attribute, it likely represents a “nice to have” rather than a requirement	Remove the attribute
Design Variable Main Effects	A particular design variable’s main effects on each single attribute utility (or cost) can be calculated: if an attribute displays the opposite positive/negative tendency of the other attributes for a single design variable, it is likely proving deleterious to compromise for the stakeholder using it by promoting designs that are unproductive for other stakeholders	Reduce attribute weight, potentially reduce the design space to eliminate designs with the level of variable most in favor of the odd attribute

Also note that the compilation of these heuristic methods into an automated (computerized) process will have a very desirable effect on the nature of multi-stakeholder compromises in tradespace studies: it will dramatically reduce the burden on tradespace “experts” by eliminating the need for them to manually search through the data to look for avenues for potential compromise. In addition to freeing up these people for other tasks, this also reduces the level of expertise required to use the process, suggesting that it could be possible for non-technical stakeholders to reach compromises between themselves using only the computerized tool. The automatic nature should also promote consistency in results between cases and personnel.

3.2. Allow relevant stakeholder to select a compromise

With the most promising avenue for compromise identified, the next step is to present it to the appropriate stakeholder, corresponding with the “show the important” aspect of visual analytics. It should be demonstrated to the stakeholder with relevant graphs and data why they are being asked to change this dimension of their preferences. A small set of compromise options (2-4) can be made available to the stakeholder in order to provide a few alternatives for ways to mitigate the negative effects caught by the metrics in the analyze step. For example, returning to the car’s top speed illustration, Stakeholder B could have the option to do nothing, reduce the lower limit to 115 mph, or reduce to 100 mph. Each option can be presented with a preview of the effects of accepting it, in this case likely involving the increase in the number of valid designs for each choice.

Note that “do nothing” should always be a choice. The goal of this process is not to *force* stakeholders to compromise, but instead to challenge them about their preferences and see if they can better align them with the other participants. For example, if aligning an attribute requirement with the other stakeholders violates a non-negotiable feature of their mission (such as reducing the fuel on board a satellite to below the amount needed to reach the orbit necessary for one stakeholder’s operation) then the ability to not accept the compromise must be present or the results of the process will potentially include physically infeasible designs. Obviously, stakeholders who are unable to accept any of the suggested preference compromises will either have to accept a larger design compromise or fail to find a mutually agreeable solution at all: this is behavior that is desired out of the process.

3.3. Repeat 1 and 2 until termination

This is the iterative aspect of the process: we apply the compromise option selected by the stakeholder in the previous step, identify a new potential compromise dimension, and repeat. This gradual refinement of preferences is analogous to “zoom, filter and analyze further.” Like the heuristics for identifying compromise opportunities, the

termination criteria is also expected to be refined over time, or possibly varied depending on the particular case. One such option for termination criteria could be to stop when the heuristics are unable to identify any further potential compromises. Alternatively, the stakeholders themselves could be allowed to judge when to stop, either because they are uncomfortable modifying their preferences further or because they believe that a mutual agreement can be reached at the current level. The effects of different termination criteria can be tested experimentally, as discussed in the following section of this paper.

3.4. Final design compromise and selection

With the preference compromises complete and the loop terminated, a design must be selected. If a Pareto efficient design (nondominated in cost and utility) is considered "optimal" for an individual stakeholder, any "joint" Pareto efficient designs (optimal for every stakeholder) are obvious potential design selections, as they do not require a design compromise for any stakeholder [16]. If no joint solutions are present, then a set of efficient design compromises can be assembled by considering the Fuzzy Pareto Number (FPN) of each design in the design space for each user [15].

FPN is a metric for cost-utility efficiency adapted from Smaling’s work on fuzzy Pareto sets [17]. The distance from the Pareto front is calculated as a percentage of the range of the cost/utility data; for example, all 1% fuzzy Pareto efficient designs will be less than or equal to 1% of the range of costs more and 1% of the range of utilities less than a truly (0%) Pareto efficient design. The FPN of a design is the smallest percentage K for which the design is in the fuzzy Pareto set P_K , as shown in Figure 1.

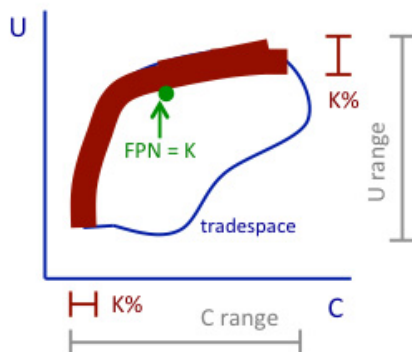


Fig. 1. Notional tradespace on utility (U) and cost (C) axes, with K% fuzzy Pareto set, P_K , and design point with FPN = K

FPN is used as a cost-efficiency metric because it can concisely describe the removal of a point from true Pareto efficiency with a single number that is comparable between tradespaces of different shapes and sizes. It is then possible to find the designs that are Pareto efficient in FPN for each user: these designs will be, in some sense, the "efficient trades in stakeholder efficiency", and thus are an excellent starting point for finding compromises between stakeholders, allowing the stakeholders to focus on a small set of designs and discuss which is the most appropriate selection. Figure 2 shows the tradespaces of two notional stakeholders and the set of designs that are the most efficient trades of FPN between them.

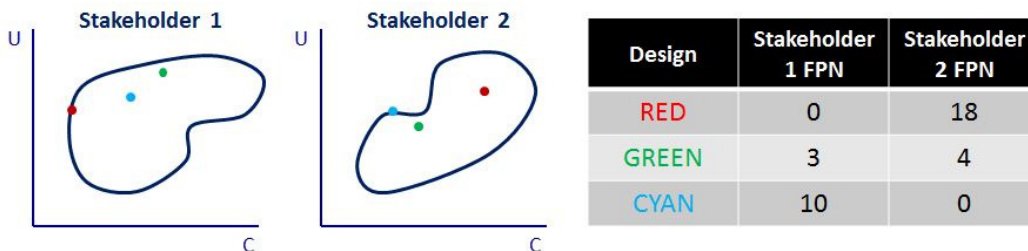


Fig. 2. (a) Stakeholder 1 tradespace, (b) Stakeholder 2 tradespace, (c) Three designs highlighted as FPN-tradeoff efficient between them

This step, in its current form, is largely open-ended: a set of designs that represent good compromises (found using tradespace metrics) is shown to the stakeholders in order to focus their attention on specific potential solutions for them to select between as they see fit, using whatever metrics or bargaining tools they might usually use to decide between various possible options. The open-endedness serves the purpose of allowing the stakeholders to control their own final selection, increasing the likelihood that they will be satisfied with the end result of the process. Thus, the ultimate contribution of the previous steps is one of making the final step easier by helping to identify preference differences and align them as much as possible, reducing tension in the design compromise. Other means of generating a set of potentially interesting compromise designs could be considered, for example, using the multi-dimensional Pareto set of all stakeholders' utilities and costs to seed the set of compromise designs. Prescriptive methods for selecting from among a generated set of potential compromise designs (i.e., automating the final design compromise using a prescriptive judgement on fairness) are also a primary topic for further research explored in the discussion section of this paper.

4. Refining the Process Experimentally

As described in the previous section, there are many aspects of the compromise process that are either currently open-ended or that are potentially beneficial to tailor on an application-by-application basis. A thorough set of experiments is likely to provide significant insights towards further refinement of the process, particularly for the preference compromise steps. This section will describe some of the experiments that are planned to be conducted in the near future in order to investigate the effects of some of these changes on the stakeholders' experiences and the quality of the resulting compromise set.

First, the amount of information available to the participating stakeholders can be varied to affect their decision making. Presenting complete information to every stakeholder allows them to make the most educated decisions, but the act of limiting information could be used to influence them away from destructive tendencies or biases, or to reduce their ability to "game" the compromises in their favor. The types of information that can be controlled include information about other stakeholder preferences or compromises and information about the design space itself, perhaps restricting them from viewing the tradespace in order to prevent attachment to a particular design early on in the process. These techniques can be evaluated by performing trials of the process with different levels of information sharing, or potentially by facing stakeholders with a decision and little information and seeing how they gradually revise that decision when offered more information.

Because there is no "right" answer, the order in which compromise opportunities are found and executed is likely to have an impact on the final design selection, as will the selection of termination criteria. As each compromise is made, the tradespace is altered and identification heuristics are recalculated, which creates the possibility that any coupled heuristics could resolve each other with a single compromise that varies depending upon which is initiated first. Even if the heuristics are not coupled, any termination criterion that takes effect before all heuristics are exhausted will result in different subsets of heuristics being used in each case, depending on their ordering. Ideally, heuristics would be utilized in some sort of "effectiveness" order, allowing the most useful heuristics to be used first with the understanding that they will have the biggest impact: the effectiveness of each heuristic can be compared effectively by evaluating them on different tradespaces before and after the associated compromise is made. Alternatively, it may be of interest to enforce other orderings, such as one that requires each stakeholder to make an even number of compromises in order to roughly balance the accommodation performed by each. The choices offered for each identified compromise can also influence the direction in which the compromise moves. Additionally, termination could be controlled by the stakeholders rather than automatically, giving them the power to stop the preference compromising loop when they are comfortable reaching an agreement at the current level. All of these "rules of engagement" can be tested for their effects on the solution, and then offered to the stakeholders to select upon beginning the process in order to promote whatever behavior they desire.

User feedback is a key output of experimentation and testing of a tool or method; of particular interest to this process is the satisfaction of the stakeholder, as they must be satisfied in order to generate buy-in. One way in which satisfaction can be measured is in the inverse using regret [18]. A questionnaire or other feedback method could be used to quantify the perceived regret of a stakeholder as they are encouraged to accept compromises to their original preferences. This data could then be used to identify patterns of stakeholder response to different aspects of the process, including types of compromises that inspire particularly negative reactions. Some mapping

of regret to compromise type could then inform additional “rules of engagement” designed to equalize the regret of each stakeholder’s preference compromises. Similarly, the stress that a complete set of preference compromises exerts on a stakeholder’s tradespace could be evaluated using either qualitative (e.g. Likert-type scale) or quantitative (some average distance metric between original and final design point locations) means, and this information could be used to equalize imbalances of regret in the preference compromises through an oppositely unequal sharing of regret in the design compromise. Thus, an integrated user-feedback channel will provide additional benefits for this research, as the qualitative experience of each stakeholder is useful not only to verify usability but also to further inform and refine the process.

5. Discussion of Research Extensions

This paper has outlined a process for finding compromises between cooperative stakeholders with differing goals by using a Multi-Attribute Tradespace Exploration to identify opportunities to realign their stated preferences, with identified near-term goals of experimentation within the process steps. This section will cover the other goals for furthering this compromise process, improving its usability and the quality of its results.

5.1. Preference Compromise Identification Heuristics

It is clear that the success of the method is strongly dependent upon the ability for preference compromise opportunities to be identified. With the end goal of having the process be fully automated outside of the compromise choice selections by the stakeholders at the end of step 2, it is especially important then to create an expansive set of identification heuristics for this purpose, as it will diminish the need for oversight from a tradespace or negotiation expert. Of course, these heuristics will likely be created by distilling knowledge from these experts. A working list of ideas for heuristics was included in the description of the process in Table 1. Future work is intended to expand upon this list, including the use of more advanced tradespace- and utility-related metrics. Other possible avenues for the discovery of new metrics include careful observation and data recording of experiments with the process and interviews with personnel involved with historical case studies to gain insight into their experience with the drivers of stakeholder disagreement and eventual compromise.

5.2. Achieving Prescriptive “Fair” Design Compromises

If the final goal of the process is to find a single desirable compromise design, a prescriptive means of selecting from amongst a set of viable compromises would be useful. In the description of the process in this paper, the idea of efficiently trading stakeholder efficiency with designs that are Pareto optimal in FPN for each stakeholder was introduced as a means of generating an interesting set of viable compromises for stakeholder to discuss and decide amongst. A purely egalitarian concept of “fairness” would suggest that the best compromise design in this set would be the one for which all stakeholders have as-close-to-equal FPN as possible; if the stakeholders agree that this is fair, the solution could be mandated before revealing other options. However, this may not prove to be the most realistic suggestion, as it is certainly possible that all of the stakeholders could prefer to select an “unfair” compromise using a different rationale: perhaps choosing to select a design with higher utility for each stakeholder yet not equally efficient, or a utilitarian approach where they choose to minimize the sum of all their FPN’s. Alternatively, the idea of “fairness” could also be associated with the actual stake, as in supplied funds, of each stakeholder. If costs will be unequally distributed, it could be appealing to consider a solution in which the desires of the stakeholder paying the most money (be they for efficiency via FPN or pure utility) are given a higher weight than those of the other stakeholders, or allowing the stakeholders to bargain “outside of the system” (e.g., “side payments”), making offers and concessions that involve other ways in which they interact not captured by the modeling of the specific project they are discussing. All of these ideas merit further investigation, as the prescriptive design compromise process can potentially be designed with any specification of “fairness” agreed upon by the participating stakeholders.

The prescriptive selection of compromise designs is also a promising part of the process for the insertion of mechanism design theory. Because the final system will belong to the stakeholders, the ability to let them select the final design is desirable: but how can their various preferences and rationales for selecting designs be combined

together? Arrow's paradox again suggests that we cannot aggregate their preferences rankings of designs into a coherent superset, but the possibility of designing some type of bargaining or auction technique is appealing. Game theory and mechanism design theory could be utilized to design the auction to promote a supplied fairness criteria (perhaps agreed upon by the stakeholders) and limit the ability of stakeholders to "game" the system in their favor. Additionally, the recording of FPN compromise sets for each iteration of the preference compromises in the main process could allow stakeholders to bid on previously-identified compromises, potentially enabling the discovery of coalition behavior between stakeholders, where a subset of the stakeholders find that breaking off on their own will allow for more attractive compromises than working with the complete group. Future research will look into the design of this step for potential improvements of this nature.

Regardless of the means by which prescription is inserted into the process, the stakeholders should agree upon any and all prescriptive judgements *before the process begins*, which prevents self-serving biases by removing the temptation to ascribe to a concept of fairness that results in a design selection that favors one's own interest. This is similar to the idea of the "veil of ignorance" central to Rawls' *Theory of Justice* [19] because, without knowledge of his own realized benefit under various potential definitions of fairness (as he would have if performed at the end of the process), it is likely that a stakeholder will report his true conception of fairness to ensure that he finds the final solution acceptable. In fact, the philosophical implications of the prescriptive elements of the process should be explored in more detail in the future, as any prescriptive judgement *implies* a philosophy (whether intended or not), and it is likely beneficial to stakeholders' satisfaction that the underlying philosophy of the method aligns with their own as much as possible. The customizability of the process is of additional benefit when considering this angle of the problem.

5.3. Technology

Automation via technology has been mentioned as an important goal of this research, as it will reduce the "expertise burden" of the process and increase consistency of the results. Designing a highly usable interface for calculating the metrics, presenting the data, and allowing for stakeholder interaction by modifying preferences or selecting designs is a nontrivial task. Previous research at MIT in the area of interactive tradespace exploration resulted in a set of software tools coded in MATLAB® designed to allow people of wide ranges of familiarity to interact with tradespace data in a meaningful and educational way [7,8]. This software reads stored data from a case study database, and allows users to interrogate the information multi-dimensionally with the assistance of a large number of "widgets" that offer different views and data types. Furthermore, the database is capable of being modified on the fly, allowing users to do things such as update user preferences and save the results, which is of direct interest to this work.

Because the software was intentionally built on a flexible architecture to allow the gradual inclusion of additional widgets, it is well-suited for modification to new tasks. It is likely that further efforts will be able to leverage the built-in capabilities for tradespace data visualization within a widget that guides an iterative process between stakeholders as they gradually modify their preferences as stored in the linked database. This also opens up the interesting possibility of performing the compromise process remotely, thus negating the need for stakeholders to be co-located. Additionally, by allowing the stakeholders to use the complete set of widgets and other data tools, the process will also have a compelling amount of "data on demand", completing the set of four aspects of the "visual analytics paradigm".

5.4. Other research extensions

If the compromise process can be refined and employed with success as outlined in this paper, extensions into analyses beyond the basic MATE framework have the potential to vastly increase the amount of information able to be considered and bargained between the stakeholders. MATE operates with a single static tradespace, but large engineering systems with multiple stakeholders are typically subject to significant exogenous uncertainty. The Epoch-Era Analysis (EEA) framework accounts for this by defining short-run periods of fixed context (epochs), creating a multitude of potential static tradespaces that can then be assembled into dynamic long-run futures (eras) [20]. Integrating the compromise process with EEA would allow the stakeholders to considered alternative futures for the system in question and could be accomplished by either considering the complete epoch space within the

compromise process, or by performing the process independently on each epoch's tradespace and creating a new means of compromising between the selections of each epoch.

It is also desirable to allow the stakeholders to compromise using more subtle value-creating properties than direct utility and cost. Many of these properties are referred to as "ilities" from their frequently shared suffix, and include such terms as changeability, flexibility, robustness, and survivability. These represent temporal sources of value that are not easily captured for a static context or in a static tradespace, and a significant amount of research has been devoted to exploring methods and metrics for quantifying their value [14,15,21]. Incorporating these metrics into the compromise process would allow for more nuanced understandings of stakeholder preferences, such as favoring actively changeable versus passively robust systems.

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