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STUDY OF ARGUMENTATIVE NEGOTIATION IN COLLABORATIVE DESIGN

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ABSTRACT

Engineering of complex systems often involves teamwork. The team members must work together to identify requirements, explore design spaces, generate design alternatives, and make both interactive and joint design decisions. Due to the latency of information and the disciplinary differences, it is often a difficult process for the team members to reach agreements when needed. Negotiation has been studied as a method for facilitating information exchange, mutual understanding, and joint decision-making. In our previous work, we introduced an argumentation-based negotiation framework to support collaborative design. In this paper, we present an experiment study that was conducted to assess the impact of this negotiation support approach on the process and the outcome of collaborative design. The results of the experiment have shown both the positive effects and limitations of the approach.

Keywords: Collaborative design, negotiation, argumentation, experiment study.

1 INTRODUCTION

Engineering design is a multi-faceted activity of which a key component is to achieve tradeoffs between competing criteria in order to deliver quality products to a demanding market. In automotive engineering, for example, the market's demand for new vehicles of more comfort and convenience onboard pulls the weight of cars upwards while skyrocketing gasoline prices make the fuel economy a new priority. Engineers must constantly explore new avenues to keep their products up to date with the expectations of the fast-paced market. To do so, the effective teamwork is essential.

Engineering teams composed of experts in different technical areas are working together to identify requirements, generate design alternatives, make both interactive and joint design decisions, and eventually arrive at a final design. Such a process requires not only flawless communications but also proper means to facilitate mutual understanding, agreement making, and generation of new ideas.

Collaborative engineering support systems have been developed with the primary goal of achieving seamless information flows among designers and engineering systems. Database systems, various communication and workflow tools have been developed to support information sharing, design change propagation, and process management. Few systems provide means for engineers to negotiate their decisions for the benefit of the overall design, and little work has been done to quantitatively assess how different negotiation methods may impact on the collaborative design process and results.

In our research, we take an argumentation-based negotiation [1] approach to supporting collaborative design. Our research goal is to develop a negotiation framework that links designers and engineering systems together at the decision-level, facilitates understandings among them, and helps designers expand their search space and subsequently generate better alternatives. In our previous work [2,3], we developed an Argumentative Negotiation framework for Engineering Design, called ANED. ANED is composed of an argumentation model, a negotiation protocol, and a design context model. It has been implemented as a computer tool to support engineering negotiation. As the second step of this research, we conducted an experiment study to assess the impact of the ANED approach on the process and results of collaborative design.

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Negotiation is a process in which a joint decision is made by two or more parties [4]. The parties first verbalize contradictory demands and then move towards an agreement through tradeoffs and searching for new alternatives. For collaborative design, negotiation can be a way for multiple designers to exchange information, learn about other designers' perspectives and intents, and identify new opportunities based on the learned information and knowledge. Therefore, negotiation in collaborative design should not be merely a way for designers to reach agreements through simple give-and-take interactions. It should facilitate designers' exploration of a wider range of solution space through influencing each others' understanding of the problem, knowledge, perspective and judgments.

Negotiation processes can be analyzed from two different perspectives. The *value analysis* views negotiation as a multi-party joint decision making process [5] and attempts to comprehend the negotiation situation in more numerical terms such as buyer's/seller's true and revealed prices, preferences, and zone of possible agreements (ZOPA). In this analysis, it is often the case that the -"propose-reject/accept" negotiation structure is assumed and the choice space for each party is relatively clear. By translating the contents of negotiation into numerical values, the analysis can uncover potential win-win directions, the efficient frontier (or Pareto frontier) and how compromising or modifying one's preference can lead to more desirable agreements.

On the other hand, the negotiation process can be analyzed from a *linguistic* perspective. This analysis focuses on the structure and process, and attempts to understand how the use of the different *communication language* and *domain language* may impact the process and outcome of negotiation. The communication language is composed of locutions or speech-acts [6] that the parties can use for their negotiation. It defines the structure of interaction and determines what intentions and information can or cannot be communicated. For example, if only the locutions of *propose*, *reject*, and *accept* are allowed for negotiation, then one will not be able to *request* the other party to provide justification for a given proposal. The domain language for negotiation determines what concepts and information of the domain can be communicated and negotiated. In case of engineering design, the domain language may cover only the *design parameters* and their *values*, or it may further includes *constraints* and *functional requirements*.

To support engineering collaboration through negotiation, we need to understand what negotiation structures and processes are most effective in encouraging designers explore their design spaces and generating good design alternatives. In this research, we follow the *linguistic analysis* and attempt to clarify the roles that our argumentation-based negotiation framework may play in supporting collaborative design. Our research question hence is "*how will the application of ANED negotiation protocol (enforced by the ANED tool) impact the collaborative design process and outcomes comparing with the cases where such protocol is absent?*"

To address this question, we have conducted a design experiment study in which human subjects are engaged in solving collaborative design problems with and without using our ANED tool. The results have shown both the positive effects and limitations of the ANED approach. In the following sections, we first review the related work in Section 2 and then provide a brief overview of the key concepts of the ANED framework in Section 3. After that the experiment design and the performance measures are described in Section 4. The experiment results are presented and discussed in Section 5 and conclusion remarks drawn in Section 6.

2 RELATED WORK

Extensive research on negotiation has been done in diverse areas from social psychology and social sciences where the focus is on human interaction [4,7,8,9], to distributed artificial intelligence whose goal is to achieve collaborative work between computer systems [10,11,1,12]. Decision theorists proposed normative models of negotiation based on decision and game theories [5].

Gulliver [7] proposed an eight-phase model of negotiation process that describes the progress of negotiation from the initial recognition of the dispute to some kind of outcome. The eight phases are: search for arena, agenda setting, exploring the field, narrowing the difference, preliminaries to final bargaining, final bargaining, ritual affirmation, and execution. Pruitt [4] proposed a strategic choice model of negotiation, stating that parties involved in negotiation must make strategic choices at every point in time. The choices include conceding unilaterally, standing firm, or collaborating with other parties in search of a mutually acceptable solution. Toulmin [8] introduced a simple model of argument structure for negotiation based on the exchange of "claims", "data" and "warrant" amongst the participants to assert and justify their negotiation stance.

Researchers in the distributed artificial intelligence community have investigated the issue of negotiation by creating agent-based support system that collect data from the participants and reconcile their disparities to achieve optimal decisions. Sycara [11] proposed a negotiation process that uses case-based reasoning mechanism together with a restricted protocol to support agents resolving their goal conflicts. Jennings et al [13] proposed argumentation-based negotiation to support negotiation among distributed agents. Through argumentation, the parties can exchange various information pertaining to the negotiation situation, explore mutual option spaces and eventual arrive at an acceptable solution [1].

Raiffa et al [5] proposed taxonomy of group decision-making and suggested negotiation as a way to make joint decisions. Extending the multi-objective decision theory and game theory, he examined the dynamics of win-lose, win-win and multi-party negotiations and proposed novel approaches for successful negotiation.

While the advances of the above-mentioned negotiation research have been applied in business management activities

and networked computer systems, few have been introduced to the field of engineering design. Researchers in the field of engineering design attempted to facilitate engineering negotiation by providing information and technology supports. Some treated the problem of negotiation in design as an issue of information imprecision and developed formal mathematical models to incorporate the imprecision into design computations [14,15]. Others formulated collaborative design problems as games and treated negotiation as a process of playing various types of games, e.g., collaborative, non-collaborative [16]. Viewing negotiation as a conflict resolution process and devising ways to support conflict identification and resolution is another direction of engineering negotiation research [17]. CONVINCER [18] is a computer program that facilitates the negotiation process in large-scale infrastructure projects by integrating the concepts of game theory and negotiation forms and guiding negotiations toward sustainable outcomes. One common feature of the existing approaches to negotiation in engineering is that they treat negotiation as a process of single level information exchange and conflict resolution and attempt to *reduce* the negotiation problem into a multi-objective optimization problem so that a convergent solution can be found. Because these approaches usually require prior knowledge of evaluation criteria and available alternatives, they have only limited use for the early stage of engineering design where defining problems and exploring alternative spaces should be part of the negotiation process.

There have been experiment studies of negotiation in the literature but few of them are specific to the engineering design field. Some experiments conducted in the fields of social and management sciences study the impact of personality on the negotiation outcome [19] and others explore the difference between individual vs. group negotiators [20]. In the field of engineering design, Kirshmann et al [22] tested the influence of groupware on a design project. Their approach is similar to ours in its implementation but the two differ in the focus of study. They investigate the impact of video and audio connectivity and the sharing of various applications, whereas our research is focused on the impact of ANED negotiation protocol.

3 ANED: ARGUMENTATIVE NEGOTIATION

ANED was developed based on the argumentation-based approach to negotiation [1,13]. The basic idea is that negotiation should not be reduced to a mere give-and-take/reject process. Instead it should be viewed as an opportunity for the participants to argue about their respective positions and expectations, influence each other, and eventually achieve mutually beneficial agreements. To ensure that negotiation is efficient and moving toward a right direction, designers should do more than simply “agreeing” or “rejecting” a proposal. They must provide “arguments” for others to understand “what do you want” and “why.” Our ANED protocol is composed of three key components: 1) an *argumentation model*, 2) a *communication language* composed

of specific speech-acts, and 3) a *design context model* consisting of the concepts of engineering design and serving as domain language for negotiation. In the following we briefly describe the three components. The details can be found in [3].

3.1 Argumentation Model

Following Toulmin [8], we model argument as a structure depicted in Figure 1.

In this model, negotiation starts when a designer makes a “Claim”, e.g., “Hinge position h_g should be $20\text{cm} < h_g < 25\text{cm}$.” If the claim is challenged by another designer, then the designer is required to provide “Data”, e.g., “Door size $D_s=60\text{cm}$ ”, to defend it. If the challenger is still not satisfied with the data, then a “Warrant”, e.g., “If sports car, then $h_g < 0.5 D_s$ ”, can be supplied by the designer, either voluntarily or at the request of the challenger.

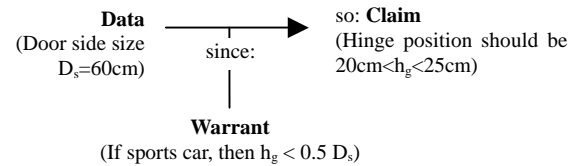


Figure 1: ANED Argumentation Model (Adapted from [8])

A “Warrant” can be a rule that states the relation between the “claim” and “data”, as shown in Figure 1, or a related higher-level concept, such as a function requirement. In the latter case, if the challenger starts to challenge the “warrant”, i.e., the higher-level concept, the negotiation moves to a higher-level in which the “warrant” becomes a “claim” and negotiation continues.

3.2 Communication Language

The communication language determines the structure of negotiation in terms of what actions can be taken in the process. The speech-acts of ANED were chosen from Ballmer and Brennenstuhl’s speech-act dictionary [22] based on our analysis of engineering negotiation needs [3]. Following is a brief description of the speech-acts used in the ANED protocol.

- *Propose <claim>*: introduce an initial <claim> and initiate negotiation process.
- *Counter-Propose <claim>*: introduce a new <claim> going against another claim proposed by the other party earlier.
- *Compromise <claim>*: proposed a <claim> that is a compromised version of the previous one.
- *Critique NOT <claim> AS <data> (or SINCE <warrant>)*: introduce a negated <claim> followed by <data> and possibly a <warrant> to justify the negation.
- *Defend <claim> AS <data> (or SINCE <warrant>)*: introduce <data> and/or <warrant> to defend the <claim> challenged by the other party.

- *Agree <claim>*: declare that an agreement is reached on the <claim> and the party is committed to the agreement.
- *Refine <claim1> WITH <claim2>*: introduce a new <claim2> whose contents build upon the last <claim1> passed on by the other party.

Figure 2 illustrates the ANED negotiation protocol based on the argumentation model and communication language described above [2,3].

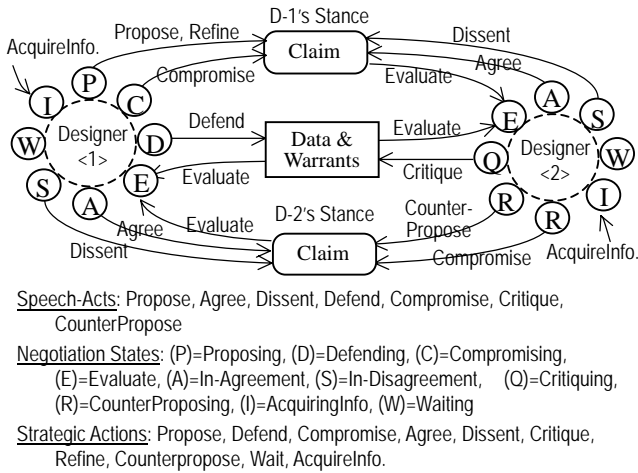


Figure 2: ANED Negotiation Protocol

3.3 Design Context Model

The *design context model* in ANED is an information model that captures design product and process concepts and sub-concepts for designers and computers to describe the design situations and compose negotiation arguments. Following are the concepts included in the model.

- *Design Entity (DE)*: Refers to the elements generated during the design process to satisfy certain functional requirements, e.g., *solution concepts*, *components*, *assemblies*, and *parts*. A design entity is usually characterized by a number of *design parameters*.
- *Design Constraints (DC)*: Specifies relations and bounds of certain design parameters of the overall system or design entities.
- *Functional Requirements (FR)*: Refers to the functional specific requirements that can be fulfilled by design entities that characterize a physical embodiment.
- *Design Objectives (DO)*: Is defined as a statement of some aspect associated with the design product that the designer desires to achieve.

4 RESEARCH METHOD

Our objective of this experiment study is to evaluate the effectiveness of ANED negotiation protocol and investigate how the protocol influences the negotiation process and design results. More specifically, we intend to compare how using and

not using the ANED protocol lead to different collaborative design processes and outcomes and identify what needs to be done to further improve ANED. Prior to the experiment, we formulated the following hypotheses:

- *Hypothesis 1*: The ANED negotiation protocol can help designers generate more design alternatives, because the better understanding of others through argumentation and the attempt to maintaining one's own stance may lead to searching for more alternatives.
- *Hypothesis 2*: The ANED protocol can improve the performance of collaborative design, since more design alternatives lead to better design results.
- *Hypothesis 3*: The restrictive ANED protocol can impact on the collaboration process in two ways: (1) *collaboration is more efficient*, due to more focused exchange of information, and (2) *more exchanges are needed for a solution*, since each party tries to argue about and maintain its positions.

To achieve the research objective and validate the hypotheses, we need a proper experiment design, a suitable collaborative design problem for testing, and adequate design process and outcome measures.

4.1 Experiment Design

The experiment involved 16 subjects who were divided into 2 treatment groups: a control group (CG) and a protocol group (PG). Each group had 4 teams, and each team had 2 participants working together to solve a common design problem. All teams in both groups worked on the same design problem and were given the same information and directions for design.

To make sure that all communications between the two subjects of a team are correctly monitored and there is no unmonitored communication, such as those through voice volume, body language and gestures, we divide the two subjects into two rooms, and they can communicate only through a keyboard-and-text based computer connection that we provide. All communication logs are saved and used for analysis.

The CG group and PG group were different in the following ways.

- *Control Group (CG)*: The CG teams are given an ordinary *chat tool* so that they can chat freely using any communication language and design information as they collaborate on solving the common design problem.
- *Protocol Group (PG)*: The PG teams are asked to use the ANED tool so that they are forced to use the ANED communication language and design context model for communicating and describing their design situations.

The 16 subjects who participated in this study were recruited amongst the students attending a senior level design class AME410 (*Engineering design theory and methodology*) offered at the University of Southern California. Participation

was strictly on a voluntary basis, and no coercive process was used. The eight 2-person teams were created randomly, and the different treatments administered to each of them were also the product of a random process. The students were all undergraduates in their senior year, and majoring either in mechanical engineering or aerospace engineering. Prior to conducting the experiment, the authors went through several testing sessions with the help of a group of graduate students majoring in mechanical engineering.

Each experiment sample lasted about an hour and proceeded as follows:

- **t = 0–15 min:** The subjects sit through an automated PowerPoint slideshow of the design exercise that explains the subject’s tasks and responsibilities.
- **t = 15–25 min:** Brief practice time for the subjects to familiarize with the problem, the data, the use of ANED tool for design and communication.
- **t = 25 min – 1h:** The subjects work collaboratively to solve the design problem.

4.2 Design Problem

The design problem for the experiment should be simple enough so that the subjects can comprehend and solve it within the allowed time frame. On the other hand, the problem should also be rich or complex enough so that the effect of applying the ANED protocol is observable. We created a problem of designing a *manufacturing line* for the production of a *water filter* composed of a *grid* and a *filter body*, as shown in Figure 3. Each subject is responsible for a part of the process: Designer 1 is in charge of the fabrication of the filter body, while Designer 2 is in charge of the grid production and assembly processes.

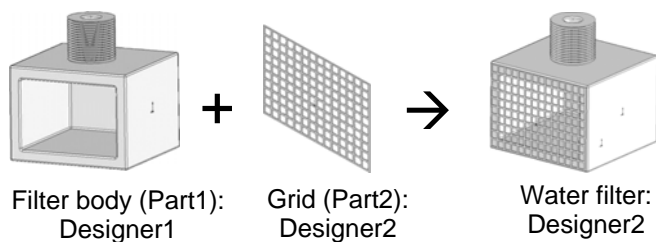


Figure 3: Water Filter to Be Manufactured

The task of each subject is to select (1) the required operations for fabricating the water filter and (2) the needed machines to carry out the selected operations. All the possible operations for producing and assembling Part1 and Part2 are predefined. Each operation has 3 alternative corresponding machines. Each machine has two attributes: the *cost* (\$) of using the machine and the *space* (m^2) the machine occupies. Table 1 summarizes the design objectives, tasks, and the design information for each designer.

To add needed complexity to the manufacturing line design problem, we framed the following concepts as part of the problem definition.

Table 1: Design Tasks, Objectives and Information

| | Design Objectives | Design Tasks | Information Provided |
|------------|--|--|---|
| Designer 1 | <ul style="list-style-type: none"> > Ensure full compatibility of machines selected > Minimize the cost of use of machines | <ul style="list-style-type: none"> > Select operations and machines to produce Part 1 > Lay out machines according to the rules | <ul style="list-style-type: none"> > Drawing of Part 1 > Table of operations for Part 1 > Partial table operations for Part 2 (no cost & space info) > Compatibility, issue, option list > A list of rules |
| Designer 2 | <ul style="list-style-type: none"> > Minimize the space occupied by machines | <ul style="list-style-type: none"> > Select machines to produce Part 2 & assemble it w/ Part 1 > Lay out machines according to the rules | <ul style="list-style-type: none"> > Drawing of the Part 2 > A table of operations for Part 2 > A partial table of operations for Part 1 (no cost & space info) > Compatibility, issue, option list > A list of rules |

- **Local incompatibility:** Two machines may be locally incompatible so that they cannot be applied simultaneously by one designer in one manufacturing process. For example, M_{32} and M_{41} are locally incompatible, so Designer 1 cannot select both in his solution set.
- **Global incompatibility:** Two machines may be globally incompatible so that they cannot be applied by the two designers in a team simultaneously in the overall process. For example, M_{11} and M_{61} are globally incompatible; Designer 1 cannot select M_{11} in his solution set if Designer 2 selects M_{61} , and vice-versa
- **Issue:** Two machines may have a shared issue. In this case, they can be simultaneously applied only if the issue is addressed by selecting an option. For example, M_{22} and M_{61} have an issue (#2): “Cut grid must be checked dimensionally to match NC high quality”
- **Option:** An option is an item that can be selected from the option list to resolve an issue encountered by the subjects during their machine selection task. For example, Option #11 in Designer 2’s options list “Dimensional Control Station”, which costs \$3 and takes up two blocks of space addresses the aforementioned issue #2.

The incompatibilities and issues were arbitrarily chosen to prevent the subjects from selecting the cheapest or the most compact set of machines. This way, the subjects are forced to make decisions over local and global tradeoffs. Each of the two team members had different list of options. The lists were designed to provide the subject with some of the solutions to his/her own issues and some of the solutions to the issues of his/her teammate. Therefore, the only way to properly resolve some of the issues was to discuss them, and collaboratively search for suitable solutions.

A machine layout tool, illustrated in Figure 4, is given to each of the subjects during the design session. Besides the computer based communication tool, each subject can also see the other team member’s machine layout screen. The following guidelines were given to the subject:

- The space is shared between the two sets of machines selected by each designer and machines cannot overlap.
- Machines must be laid out from left to right following the order of operations.
- Designer 1 must position machines in the top half of the factory, and Designer 2 in the bottom half.

These guidelines were enforced to give the subjects another opportunity to collaborate about the layout, explore possibilities and possibly create some win-win situations.

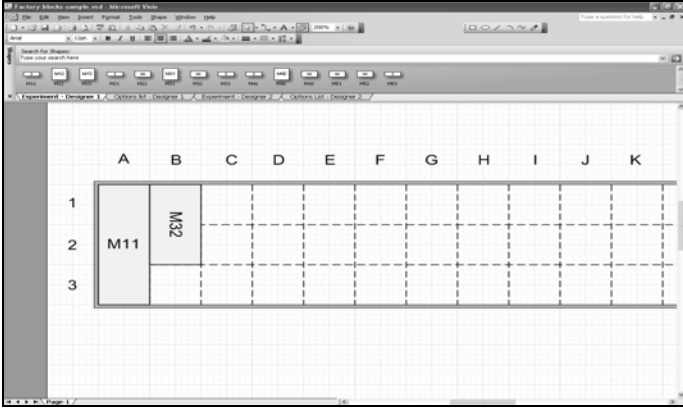


Figure 4: The Machine Layout Tool Interface

4.3 Performance Measures

One major task of this research is to develop meaningful performance measures to assess the effectiveness and efficiency of the collaborative design process. Following indices are introduced as design performance measures.

Score-based Design Performance Index (SDP): This index is computed using two metrics: cost performance S_c and space performance S_s . The maximal score $S_c=100\%$ was assigned to the cheapest design observed (m_c), while the score of $S_c=0\%$ was assigned to the design with the highest possible cost (M_c). A linear grading scheme was used. The score S_c can be represented as:

$$S_c = 1 - \frac{A_c - m_c}{M_c - m_c}$$

where A_c is the cost of the machine set selected by the team.

The space is measured along the horizontal direction. The space score is computed as:

$$S_s = 1 - \frac{A_s - m_s}{M_s - m_s}$$

where M_s : maximum number of cells used; m_s : minimum number of cells used; A_s : number of cells used in the experiment evaluated.

The SDP index is computed using weighting factors:

$$SDP = 0.8 \times S_c + 0.2 \times S_s$$

Design Space Exploration Index (DSE): When there is an issue associated with an incompatibility, resolving the issue may need new solutions or options. DSE index measures the “exploration” quality of the design process and is computed by counting the number of *issues* discussed (A_I) and the number of *options* considered (A_O) to resolve these issues. For each of these two measures the highest number recorded throughout the experiment (M_I and M_O , respectively) are considered as full scores and scaled to 100%. The lowest values for each were both 0. We have:

$$DSE = \frac{(I + O)}{2}; \text{ where } I = \frac{A_I}{M_I} \text{ and } O = \frac{A_O}{M_O}$$

Negotiation Content Distribution (NCD): This term refers to the occurrence of each *speech-act* (Figure 2) in a given experiment. For each team, the numbers of occurrence of the following utterances are collected: (1) plan proposals (propose/counter-propose), (2) solution proposals (propose/counter-propose), (3) arguments (critique, defend, dissent) and (4) information requests (acquire-info).

Tracking the speech-acts used provides an overview of the negotiation contents that can be used to assess dominant communication activities in each team.

Negotiation Process Distribution (NPD): In this study, a collaborative design process is divided into 3 consecutive phases. They are:

- **Planning:** During the strategic planning phase the subjects strategize about how to address the design problem.
- **Resolution:** During the design resolution phase the subjects generate solutions for the common design problem.
- **Optimization:** During the design optimization phase, the subjects try to improve their design.

For each team sample, the NPD index measures the ratio of the number of utterances devoted to each of the phases. For example, for the planning phase, we have:

$$NPD_{Planning} = \frac{\sum_{Planning} \text{Utterances}}{\sum_{Experiment} \text{Utterances}}$$

Similarly, we can calculate $NPD_{Resolution}$ and $NPD_{Optimization}$.

5 EXPERIMENT RESULTS AND DISCUSSION

With 2 treatment groups, i.e., the Control Group and the Protocol Group, and 4 sample teams in each group, our experiment yielded 8 samples. One way analysis of variance (ANOVA), equivalent to a t-test in this case, was performed with the negotiation type, two levels: *Ad-hoc* (-1) for CG and *ANED-supported* (+1) for PG, as the independent variable for four dependent variables described in Section 4.3. The level of significance was chosen at $p = 0.05$ as a matter of convention. The ANOVA assumptions (i.e., normal distribution of data,

same variance for different treatments, randomness of samples, and independence of samples) were validated for all ANOVAs performed in this research by performing residual analyses. Pearson's correlation coefficient was also used to support a number of observations.

In the following subsections, we first introduce the data encoding scheme and then, based on the experiment results, discuss the impact of our ANED protocol on the design process and outcomes.

5.1 Communication Data Encoding

After each experiment session, the following design materials were collected:

- Final machines and options selected;
- Final layout of the machines; and
- Transcript of the communication between the two subjects.

Table 2: Locution Definitions and Coding Examples

| Utterance type | Description | Example |
|---------------------------------|---|--|
| Proposal (Strategic) | Utterance introducing a proposal related to a strategic approach to the problem | <i>"So why don't we start with your machines?"</i> |
| Proposal – Local | Utterance introducing a proposal for a decision the utterer is responsible for | Des.1: <i>"I think M₄₁ is out for F₄"</i> |
| Proposal – On other party | Utterance introducing a proposal for a decision the addressee is responsible for | Des. 2 <i>"Why don't you use the 2-block machine for F₄ because we are not saving any space"</i> |
| Critique | Utterance introducing a criticism of an incoming proposal | Des.1: <i>"you shouldn't use M₁₂ because it creates a conflict on my side"</i> |
| Counter-Proposal | Utterance introducing a proposal following a previously rebutted proposal | Des.2 responding the above critique: <i>"we could use M₉₃ then"</i> |
| Defense | Utterance introducing a previously criticized proposal along with additional data backing it up | Des.1: <i>"...but it conflicts with M₁₁..."</i> Des.2: <i>"it's ok because M₁₁ won't be used in all likelihood"</i> |
| Agreement | Short utterance signifying acceptance of the last uttered proposal | <i>"yes, this choice is fine"</i> |
| Dissent | Categorical rebuttal of a proposal | <i>"...so no M₁₁"</i> |
| Information request | Utterance formulating an inquiry from the utterer regarding information known by the addressee | Des.1: <i>"Is there a 2-block machine for F₆ that is cheaper?"</i> |
| Information passing solicited | Utterance introducing information previously requested from the utterer | Des.2: <i>"yes there is a cheaper one for F₆"</i> |
| Information passing voluntarily | Utterance introducing information willfully transmitted to the addressee without prior request. | <i>"I don't see any conflict on my side"</i> |

The communication logs collected from the design sessions were encoded using the communication language described in Section 3.2. Since the ANED tool was employed by the PG teams, the encoding of their communications was straightforward. For the CG teams, we developed standard definitions for each locution in the communication language and coded their transcripts by mapping the communication transcripts to the definitions of the locutions. The encoding was performed by one coder but was spot checked by the second

coder to ensure the consistency. Table 2 shows the definitions and some examples of the coding.

Based on the selected machines, options, and the encoded communication transcripts, the values of the four performance measures described above can be obtained. The results and their implications are discussed in the following subsections.

5.2 Impact on Design Performance

From the data shown in Table 3, the average SDP of the Control Group is 81.38% versus 85.66% for the Protocol Group. While the difference is subtle, the tendency of improvement from using Protocol can be seen. Because the standard deviation is relatively large in both groups, the one-way ANOVA with the experiment type (CG vs. PG) as factor and the SDP as response did not yield a significant result ($F_{1,6} = 1.05$, $p = 0.344$), hence could not conclusively validate our Hypothesis #2.

Table 3: Score Based Design Performance

| | Control Group (CG) | | | | Protocol Group (PG) | | | |
|----------------|--------------------|------|------|------|---------------------|------|------|------|
| | T1 | T2 | T2 | T4 | T1 | T2 | T3 | T4 |
| SDP (%): | 73.9 | 83.4 | 79.3 | 89.0 | 87.6 | 86.6 | 90.4 | 78.0 |
| Score-cost (%) | 77.9 | 79.3 | 77.6 | 86.2 | 84.5 | 100 | 96.5 | 81.0 |
| Score-space(%) | 66 | 100 | 66 | 100 | 100 | 33 | 66 | 66 |

The insignificance might be due to the definition of the design problem. Further analysis of the design problem revealed that the problem was created such that the score differences between the good solutions and the bad ones are small comparing with the total scores. Therefore the chance for the subjects to achieve significantly better scores by uncovering win-win situations was relatively low. To verify this measurement shortcoming, we examined the design space exploration aspect of the design process.

5.3 Impact on Design Space Exploration

An effective negotiation process should lead to exploration of a larger design space, since the final agreement is only as good as the best of the agreements explored during the negotiation. Using DSE as the response and the CG/PG as the factor, the experiment results are shown in Table 4. The ANOVA result shows that the ANED protocol has a significant effect on design space exploration ($F_{1,6} = 38.21$, $p = 0.001$), supporting our Hypothesis #1. Another interesting analysis can be done by looking at the correlation between the experiment type (with or without protocol) and the number of issues discussed. Pearson's coefficient value computed is $r = 0.961$ ($p = 0.000$), indicating a very strong correlation.

Table 4: Design Space Exploration Index

| | Control Group (CG) | | | | Protocol Group (PG) | | | |
|------------------|--------------------|----|----|----|---------------------|------|----|------|
| | T1 | T2 | T2 | T4 | T1 | T2 | T3 | T4 |
| DSE (%): | 37.5 | 0 | 0 | 0 | 87.5 | 87.5 | 75 | 62.5 |
| Issue-discussed | 1 | 0 | 0 | 0 | 4 | 3 | 4 | 3 |
| Option-discussed | 2 | 0 | 0 | 0 | 3 | 4 | 2 | 2 |

When ANED was developed, one of the initial postulates was that negotiation is not merely a communicative process but also a stimulating and hence creative one, during which the parties not only exchange information but also argue with, and attempt to influence, each other. Conflicts between two parties are not only the problems to deal with but also the opportunities that the parties can take to explore new solutions. This basic principle is adopted by TRIZ [23]. In ANED, the argumentative protocol allows the parties to preserve and then explore the conflicts once they are identified. In addition, the negotiation tendency of “maintaining one’s own position” embedded in the protocol leads the parties to strive for more alternatives for resolving their conflicts. As shown in Table 4, unlike the teams in the Control Group who tended to agree on the solutions they found in the first place, the teams in the Protocol Group kept their conflicts longer and reached agreements only after exploring more alternatives through discussing issues and deciding on options. Our results indicate that the ANED approach has the potential to enhance designers’ behavior of generating more alternatives.

5.4 Impact on Negotiation Content Distribution

One objective of this experiment was to observe the impact of ANED protocol on the collaboration process in engineering design. By analyzing the *negotiation content distribution* (NCD) data shown in Table 5, we notice a significant difference between the two treatment groups in the type of activities that dominate the negotiation process.

The one-way ANOVA for the total number of non-planning proposals (i.e., “Proposal-other” in Table 5) shows that the protocol *has a significant impact on subjects’ proposal making behavior* ($F_{1,6} = 8.21, p = 0.029$). Using ANED protocol leads the subjects to generating more *resolution* and *optimization* related proposals. This result was expected because proposals and counter-proposals are the locations introducing possible agreement points: generating more proposals expands the range of the possible agreements. This supports our *Hypothesis #1*.

Table 5: Negotiation Content Distribution Index

| | Control Group (CG) | | | | Protocol Group (PG) | | | |
|-----------------|--------------------|----|----|----|---------------------|----|----|----|
| | T1 | T2 | T2 | T4 | T1 | T2 | T3 | T4 |
| NCD: | | | | | | | | |
| Proposals-plan | 8 | 4 | 15 | 11 | 6 | 0 | 0 | 2 |
| Proposals-other | 6 | 2 | 10 | 9 | 14 | 12 | 21 | 12 |
| Arguments | 14 | 3 | 15 | 13 | 25 | 14 | 19 | 9 |
| Info-request | 21 | 5 | 37 | 29 | 6 | 5 | 9 | 5 |
| Issue-discussed | 1 | 0 | 0 | 0 | 4 | 3 | 4 | 3 |

The analysis of the numbers of information request utterances indicates that the protocol *reduces the need for information request* ($F_{1,6} = 5.90, p = 0.051$). This can be explained as the result of two combined effects. First, the higher number of proposals is balanced by a lower number of information request/passing loops since proposing and arguing

assume the information passing function in the form of *data* and *warrants* (see Figure 1). Second, the efficiency of argumentative negotiation enhances mutual understanding of their stances and reduces the need for information requests.

The analysis of the number of *planning* related proposals shows a conclusive result ($F_{1,6} = 7.58, p = 0.033$): the *ad-hoc group* does more planning related exchanges than the *protocol supported group*. We will discuss this interesting result in the following subsection.

The average amount of utterances used by each group validates our *Hypothesis #3(1)*, i.e., the protocol improves collaboration efficiency, as the teams in Protocol Group used an average of only 69 utterances to complete the design task whereas the Control Group teams needed an average of 118.

5.5 Impact on Negotiation Process Distribution

Besides negotiation content distribution, we assessed the impact of the protocol on negotiation process distribution (NPD) by counting the numbers of utterances used in each of the three phases, *planning*, *resolution*, and *optimization*. The experiment results are shown in Table 6. We have:

- For the *planning* phase, the Control Group used 23% of the utterances, whereas the Protocol Group used nearly 0%.
- For the *resolution* phase, 42% are used by the Control Group versus 87% by the Protocol Group.
- For the *optimization* phase, the Control Group had 35% while the Protocol Group had 12%.

A statistical analysis supports the observations. Although the significance is not as strong for the resolution phase ($F_{1,6} = 4.25, p = 0.085$), the data leads to significant results for planning ($F_{1,6} = 13.33, p = 0.011$) and optimization ($F_{1,6} = 6.45, p = 0.044$).

Table 6: Negotiation Process Distribution Index

| | Control Group (CG) | | | | Protocol Group (PG) | | | |
|-----------------------------------|--------------------|------|------|------|---------------------|------|------|------|
| | T1 | T2 | T2 | T4 | T1 | T2 | T3 | T4 |
| NPD (Number of utterances) | | | | | | | | |
| Planning | 68 | 5 | 20 | 8 | 2 | 2 | 0 | 0 |
| Resolution | 26 | 5 | 149 | 57 | 93 | 93 | 49 | 57 |
| Optimization | 28 | 15 | 64 | 27 | 7 | 7 | 10 | 9 |
| NPD (Ratio of utterances) | | | | | | | | |
| Planning | 0.56 | 0.20 | 0.09 | 0.09 | 0.02 | 0.00 | 0.00 | 0.00 |
| Resolution | 0.21 | 0.2 | 0.64 | 0.62 | 0.91 | 0.83 | 0.86 | 0.88 |
| Optimization | 0.23 | 0.60 | 0.27 | 0.29 | 0.07 | 0.17 | 0.14 | 0.12 |

The data and analysis revealed two interesting results. First, the teams in the Protocol Group spend little effort of their communication on *planning*, while the Control Group teams devote almost a quarter of their effort in *planning*. Planning related communications are needed when two designers try to decide on the strategy and process to solve a problem. The ANED protocol was designed with a focus on the argument exchange, and the exchange process is predefined. This restriction to some extent relegates the need for planning. Using the protocol, the subjects first identify their stances and

go directly into the argumentation process. In the ad-hoc Control Group teams, however, after the subjects get together, they spend a long time on deciding what needs to be done and how to do it. In other words, they try to “optimize” the way to solve the problem. This planning “optimization” often leads to an “easy way out” to solve the problem. As a result, the solutions found from the “easy ways” are considered as *the* solutions. Few more explorations are pursued. The discussion in the following paragraph further supports this observation.

The second interesting result is that the Protocol Group had twice the *resolution* related communications than the Control Group, supporting our *Hypothesis #3(1)*. Without the guidance and restriction of the protocol, the ad-hoc teams tend to find solutions and then stick to the found solutions, rather than try to argue for and maintain their own stances. As a result “any solutions are good solutions”, leading to less effort in resolution phase. On the other hand, The Protocol Group dedicated most of their communication exchange to problem resolution. The argumentative negotiation protocol contributes to a richer communication contents amongst the subjects and let them spend more time arguing about their positions, exploring new alternatives, and proposing compromises during the problem resolution phase. This more thorough design space exploration often results in a convergence to desirable solutions, reducing the need for post-resolution *optimization*, as visible in the data shown in Table 6.

6 CONCLUDING REMARKS

This experiment study yielded several results backing up our initial hypotheses and showed that negotiation outcomes in a collaborative design process can be positively affected by a negotiation support system. The use of the ANED protocol denoting clear argumentative positions and promoting mutual challenge of arguments proved to have a positive effect on the dynamics of the negotiation process and have the potential of improving collaborative design results. By imposing argumentative interaction, the protocol leads the subjects to making more efforts on design space exploration and alternative generation, avoiding general human tendency of “plan, quick solution, and finish.” Furthermore, the restrictive exchange of information makes the overall collaboration process more efficient.

While the use of ANED protocol can prevent designers from quickly committing to the solutions found after initial strategic planning, the fact that little planning occurred in Protocol Group teams implies that the designers should have a good understanding about the design problem and the design process when they come to work together. Otherwise, they may not have a chance to develop such shared understandings since the protocol may prevent them from doing so. This observation suggests that it is judicious to provide the protocol users with the *speech-acts* tailored to strategic planning. Furthermore, the experiment study described above was not set up to address the issue of multi-disciplinary collaboration. Although it can be speculated that being able to enhance design space exploration

can be positively linked to being able to facilitate better understanding between the designers of different disciplines, further study is needed to verify this link.

It should be mentioned that the results obtained thus far are limited to the types of the design problem tested. Future experiment research is needed to test various types of design problems and to include professional designers as subjects. Another future research direction is to introduce design guidelines, in addition to the protocol, to help designers maneuver more efficiently in the design space. Our current research addresses these issues.

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