Roles of Negotiation Protocol and Strategy in Collaborative Design

Yan Jin
University of Southern California, USA

Mathieu Geslin
Honda R & D Americas, Inc, USA

In collaborative design, designers work together to identify requirements, explore design spaces, generate design alternatives, and make agreements. Due to information latency and disciplinary differences, it is often a difficult task for designers to reach agreements when needed. Negotiation has been a method for facilitating information exchange, mutual understanding, and joint decision-making. Our research attempts to understand how negotiation protocols and strategies may influence collaborative design behavior. In this paper, an experimental study is presented that indicates the roles of an argumentative negotiation protocol and a multi-level negotiation strategy in collaborative design. The results of the experiment have shown both positive effects and limitations of the protocol and strategy.

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. Designers 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. Designers from different technical areas work 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

J.S. Gero and A.K. Goel (eds.), *Design Computing and Cognition '08,*

flawless communications but also proper means to facilitate mutual understanding, agreement making, and generation of new ideas.

Most collaborative design support systems are 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 help designers negotiate decisions for the benefit of the overall design, and little work has been done to quantitatively assess how negotiation protocols and strategies may influence collaborative behaviors and design results.

In our research, we take an argumentation-based negotiation approach [1] to supporting collaborative design. Our 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 number of multi-level negotiation strategies. 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 roles of ANED negotiation protocol and strategy on the process and results of collaborative design.

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/or searching for new alternatives. For collaborative design, negotiation can be a way for designers to exchange information, learn about others' 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.

Another way to understand the negotiation process is *linguistic analysis*. This analysis focuses on the structure and process, and attempts to reveal how the use of the different *communication language* and *domain language* may vary the process and outcome of negotiation. The communication language can be modeled as locutions or speech-acts [6] that the parties 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 used 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 design, the domain language may cover only the *design parameters* and their *values*, or it may further include *constraints* and *functional requirements*.

In order to support collaborative design 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: *What are the roles of the ANED protocol & strategy (enforced by ANED tool) in influencing collaborative design processes and outcomes?*

To address this question, we conducted a design experiment study in which human subjects were engaged in solving collaborative design problems with and without using our ANED tool. In the following sections, we first review the related work in Section 2 and then provide a brief overview of the protocol, strategy, and other key concepts of the ANED framework in Section 3. After that the method of experiment study and the performance measures are described in Section 4. The experiment results are presented and discussed in Section 5 & 6, and conclusion remarks drawn in Section 7.

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.

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. Some researchers 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 conflict resolution [16] or playing various types of games [17][18]. 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 are 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]. Kirshmann et al [21] tested the influence of groupware on a design project.

Overview of ANED

ANED was developed based on the argumentation-based approach to negotiation [13]. It is composed of three key components: 1) an *argumentation model*, 2) a *communication language* composed of specific speech-acts, and 3) a number of multi-level *negotiation strategies*.

Argumentation Model

Following Toulmin [8] we model argument as a structure depicted in Fig. 1. In this model, negotiation starts when a designer makes a "Claim", e.g., "Hinge position h_g should be 20cm < h_g < 25cm." If the claim is challenged by another designer, then the designer is required to provide "Data", e.g., "Door size D_s=60cm", 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. A "Warrant" can be a rule that states the relation between a "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", the negotiation moves to a higher-level in which the "warrant" becomes a "claim" and negotiation continues.

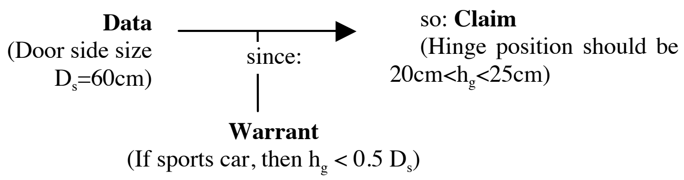

Fig. 1. ANED Argumentation Model (Adapted from Toulmin [8])

Communication Language

Communication language determines the structure of negotiation in terms of what actions can be taken in the process. The speech-acts of ANED, shown below, were chosen from Ballmer and Brennenstuhl's speech-act dictionary [22] based on our analysis of engineering negotiation needs [3].

- *Propose <claim>*: introduce *<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 *<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 to the other party.

Multi-Level Issues and Negotiation Strategies

In collaborative design, negotiation usually starts from identification of conflicts. The conflicts can be task related, such as entity conflicts and constraint conflicts, or they can be value judgment related, such as objective conflicts and preference conflicts. Conventional negotiation begins from identifying ZOPA (Zone Of Possible Agreements). If there is no ZOPA between the two participants, then the negotiation can be deadlocked. In our research, we propose a *multi-level argumentation* approach, as shown in Figure 2. The basic idea is that, most issues being negotiated belong to a hierarchy of related issues. Usually, a "super issue" governs the "range" and "behavior" of its "sub issues". If two participants cannot agree at the level of certain "sub issues", then they should be able to move to a "higher level" and negotiate about the related "super issues". The agreement at the level of "super issues" may lead to an innovative and unforeseeable agreement at the "sub issue" level. We call this process multi-level integrative negotiation.

Given the model of argument and communication language, the efficacy of negotiation depends on how the participants decide on strategic actions, proposals and arguments. The question is related to negotiation strategy:

whether to explore the solution space of the current issue, or identify new issues at the same level, or to move to a higher level of relevant issues. In ANED, four generic strategies are devised based (Figure 2).

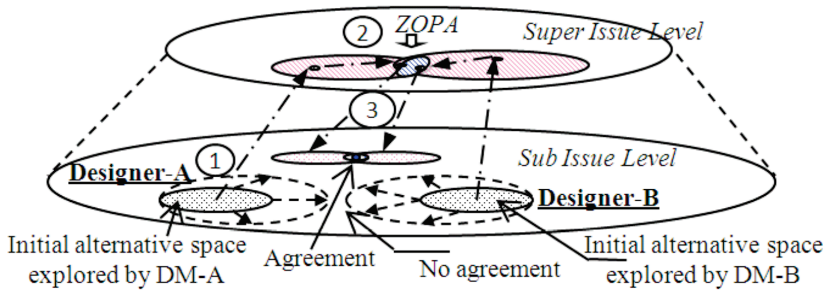

Fig. 2. A Model of Multi-Level Issues & Negotiation

- *Solution exploration*: Try to stick to the current issue and explore its solution space extensively.
- *Issue exploration*: Try to move to, or create, new issues at the same level in order to avoid conflicts.
- *Hierarchy exploration*: Try to move to a higher level of the design entity hierarchy in order to resolve conflicts. The hierarchy includes (from lower to higher level): *parameter-value* → *parameter* → *parameter constraints* → *functional requirements* → *design objectives (evaluation criteria)*.

Method

The objective of this experiment study is to investigate how ANED protocol and strategy influence the collaborative design process and results. In this section, we describe the experiment design, the test problem, and the measures devised to evaluate the outcome of design results and processes.

Experiment Design

The experiment involved 24 subjects who were divided into 3 treatment groups: a control group (CG), a protocol group (PG), and a protocol plus strategy group (PSG). Each group had 4 teams, and each team had 2 participants working together to solve a common design problem. All 12 teams worked on the same design problem and were given the same information.

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, PG and PSG groups 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 language and design information.
- *Protocol Group (PG)*: The PG teams are asked to use the ANED tool so that they are forced to use the ANED communication protocol.
- *Protocol and Strategy Group (PSG)*: The PSG teams use the ANED tool and apply the "*Hierarchy Exploration*" strategy described above.

The 24 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. The twelve 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, majoring either in mechanical or aerospace engineering.

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

- **t = 0–15 min:** Subjects sit through an automated PowerPoint slideshow of the design exercise that explains the their tasks and responsibilities.
- **t = 15–25 min:** Brief practice time for the subjects to familiarize with the problem, data, use of ANED tool for design and communication.
- **t = 25 min – 1h:** The subjects collaborate to solve the design problem.

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*., 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.

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 possible operations for producing and assembling Part1 and Part2 are predefined. Each operation has 3 alternative corresponding machines. Each machine as 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.

Table 1 Design Tasks, Objectives and Information

	Design Objectives	**Design Tasks**	**Information Provided**
Designer 1	> Ensure full compatibility of machines selected > Minimize the cost of use of machines > Minimize the space occupied by machines	> Select operations and machines to produce Part 1 > Lay out machines according to the rules	> 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		> Select machines to produce Part 2 & assemble it w/ Part 1 > Lay out machines according to the rules	> 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

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

- ***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 op-

tion. 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 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 left to right following 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.

Performance Measures

One 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 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. We have cost score:

$$\boldsymbol{S}_C = 1 - \frac{A_C - \boldsymbol{m}_C}{\boldsymbol{M}_C - \boldsymbol{m}_C} \tag{1}$$

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

Similarly, the space score is computed as:

$$S_S = 1 - \frac{A_S - m_S}{M_S - m_S} \qquad (2)$$

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:

$$SDP = 0.8 \times S_C + 0.2 \times S_S \qquad (3)$$

***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:

$$DSE = \frac{(I + O)}{2} \;\; \text{; where} \;\; I = \frac{A_I}{M_I} \;\; \text{and} \;\; O = \frac{A_O}{M_O} \qquad (4)$$

***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.

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

$$NPD_{Planning} = \frac{\sum_{Planning} Utterances}{\sum_{Experiment} Utterances} \tag{5}$$

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

Roles of Argumentative Negotiation Protocol

In the course of this research we developed the following hypotheses regarding how our argumentative negotiation protocol may influence collaborative design results and processes.

- *Hypothesis #1*: *ANED protocol can help designers generate more design alternatives,* because better understanding of others through argumentation and insisting on one's own stance may lead to searching for more alternatives.
- Hypothesis #2: ANED protocol can improve design results, since more design alternatives lead to better design.
- Hypothesis #3: ANED protocol can increase the efficiency of collaboration, since the communication is more focused and targeted.

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) and ANED-protocol (+1)) as the independent variable and performance measures as dependent variables. Level of significance was set to $p = 0.05$. Pearson's correlation coefficient was also used to support a number of observations. Table 2 summarizes the experiment results

Protocol and Design Performance

From the data shown in Table 2, 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 analysis did not yield a significant result ($F_{1,6} = 1.05$, $p = 0.344$), hence could not conclusively validate our *Hypothesis #2*.

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.

Table 2 Summary of Experiment Results (CG vs. PG)

	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*
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*
NCD:								
Proposals-plan	*8*	*4*	*15*	*11*	*6*	*0*	*0*	*2*
Proposals-other	*6*	*2*	*10*	*9*	*14*	*12*	*21*	*12*
Agreements	*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*
NPD:								
Planning	*0.56*	*0.20*	*0.09*	*0.09*	*0.02*	*0.00*	*0.00*	*0.00*
Resolution	*0.21*	*0.20*	*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*

Protocol and Design Space Exploration

Using DSE as the response and the CG/PG as the factor, 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.

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 problems to deal with but opportunities of finding new solutions. This principle is adopted by TRIZ [23]. Our results indicate the potential to apply the principle to collaborative design.

Protocol and Negotiation Content Distribution

By analyzing the *negotiation content distribution* (NCD) data shown in Table 2, we notice a significant difference between the two treatment groups in the type of activities dominating the negotiation process.

The one-way ANOVA for the total number of non-planning proposals ("Proposal-other" in Table 2) 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 locutions introducing possible agreement points: generating more proposals expands the range of the possible agreements. This supports our *Hypothesis #1*.

The analysis of the number 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, 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 Section 3.2). 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*, 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 Control Group teams needed an average of 118.

Protocol and 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 2.

The statistical analysis supports the observation from Table 2. 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).

The data analysis revealed two interesting results. First, the teams in the PG teams spent little effort of their communication on *planning,* while the CG teams devoted almost a quarter of their effort in *planning*. Planning related communications are needed when two designers try to decide on their 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: the subjects first identify their stances and then go directly into the argumentation process. In the ad-hoc CG 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 *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. 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* solution is a *good* solution, leading to less effort in resolution phase.

Roles of Multi-Level Negotiation Strategy

The PSG treatment group was exposed to the "hierarchical exploration strategy" described in Section 3.3. Prior to the test, the subjects were given a number of case examples of how to apply the strategy. Our intent was to assess how effective this exposure to the strategy can be. Two hypotheses are postulated:

- Hypothesis #4: Following the "hierarchical exploration strategy" can improve the thoroughness of design space exploration, since moving to a higher level provides a better view of sub-issues in the lower level.
- *Hypothesis #5: The strategy support leads to more proposals and agreements*, since having the options of moving into higher levels provides more opportunities to find proposals

The experiment results of PG vs. PSG teams are shown in Table 3.

Strategy and Score-based design performance

We can draw a number of conclusions based on the raw costs and space results from Table 3. First, the average cost scores vary (PG-90.52% vs. PSG-97.03%) between the two treatment groups. Furthermore, the teams from the PSG did not get as high space scores (average 49.5%) as the teams of the PSG (average 66.25%) which reveals a more thought-out process focusing on high cost score and compromising on the space score (consistent with *Hypothesis #4*). The strategic support has thus been instrumental in keeping the design effort in line with the design requirement shown in Eq (3).

Table 3 Summary of Experiment Results (PG vs. PSG)

	Control Group (PG)				**Protocol & Strategy Group (PSG)**			
	T1	***T2***	***T2***	***T4***	***T1***	***T2***	***T3***	***T4***
SDP (%):	*87.6*	*86.6*	*90.4*	*78.0*	*83.8*	*90.4*	*83.8*	*91.8*
Score-cost (%)	*84.5*	*100*	*96.6*	*81.0*	*96.6*	*96.6*	*96.6*	*98.3*
Score-space (%)	*100*	*33*	*66*	*66*	*33*	*66*	*33*	*66*
DSE (%):	*46.4*	*47.3*	*39.3*	*33.0*	*52.7*	*19.6*	*80.4*	*100*
Issue-discussed	*4*	*3*	*4*	*3*	*5*	*2*	*6*	*8*
Option-discussed	*3*	*4*	*2*	*2*	*3*	*1*	*6*	*7*
NCD:								
Proposals-plan	*6*	*0*	*0*	*2*	*6*	*5*	*5*	*10*
Proposals-other	*14*	*12*	*21*	*12*	*32*	*16*	*27*	*29*
Agreements	*9*	*10*	*16*	*8*	*17*	*11*	*18*	*17*
Info-request	*6*	*5*	*9*	*5*	*16*	*8*	*17*	*43*
Issue-discussed	*4*	*3*	*4*	*3*	*5*	*2*	*6*	*8*
NPD:								
Planning	*0.02*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Resolution	*0.91*	*0.83*	*0.86*	*0.88*	*0.51*	*0.77*	*0.66*	*0.70*
Optimization	*0.07*	*0.17*	*0.14*	*0.12*	*0.49*	*0.23*	*0.34*	*0.30*

The analysis indicates, however, that the cost difference shown in Table 3 is not statistically significant (F=1.97, p=0.21), fending off any conclusion. Nevertheless, the standard deviation drops from σ_2 =2.66 to σ_3 = 0.25, denoting a higher consistency of the design results among the PSG teams. This observation corroborates the average number of issues selected by teams of each group in their final design (2.25 for PSG vs 0.75 for PG).

The SDP values follow comparable trends, as they are based on the scores along the cost and space performance measures. The average SDP shows a progression from PG to PSG. However, the statistical significance is not clearly established. Therefore, the contribution of the strategy on the design outcome quality is important but not as far-reaching as expected according to this experiment. The reasons can be the limited exposure to the strategy received by the subjects of PSG. It can also be the limitation of the problem definition. Further research is needed.

Strategy and Design space exploration performance

For design space exploration, Table 3 shows a progression in the average numbers of issues and options discussed from PG to PSG teams (consistent with *Hypothesis #4*), even though the statistical significance is not reached due to large standard deviation values ($F_{1,6}$ =1.49, p = 0.269).

A careful examination of the date indicates that although T2 of PSG did not exhibit significant efforts to explore the design space thoroughly, they achieved a high scoring design. This "singularity" may be due to the design problem's insufficient intricacy to require extensive and thorough design space exploration to achieve a good design. In a real-world design task, the complexity stems from the fact that the solution space is continuous and not discrete as in the problem used in this experiment. There are virtually thousands of solutions for each task leading towards a design solution, and the likelihood of achieving a good design by chance is essentially annihilated. Further study is needed to include more real and complex design problems.

Strategy and Negotiation content distribution

The analysis of the negotiation content distribution data of the PG and PSG teams in Table 3 reveals conclusive results of the impact of the negotiation strategy. PSG teams generated a significantly higher number of strategic proposals ($F_{1,6}$ = 5.93, p = 0.051) and the total number of other proposals ($F_{1,6}$ = 8.40, p = 0.027). In addition, the increased number of proposals is echoed by a direct increase in the number of agreements reached as visible in Table 3 ($F_{1,6}$= 6.79, p = 0.040).

The results are consistent with our *Hypothesis #5*. The implication can be drawn that the hierarchical exploration strategy has a distinct effect on the types of utterances employed by the subjects. The density of the total argumentative content does not change; however, more proposals are exchanged. The subjects are conscious that the discussion should not be limited to the machine selection and machine layout, but should spread over the higher levels of machine issues and incompatibilities. This way, they can generate proposals over a larger scope, leading to more proposals and agreements.

Strategy and Negotiation Process Distribution

The NPD data in Table 3 indicate that PSG teams share the same behavior in strategic planning with those in the PG teams: the *planning* phase is totally missing for the same reasons described in Section 5.4. Nonetheless, the distribution over the other two phases, i.e., *resolution* and *optimization* is appreciably different. One-way ANOVAs over the ratio of utterances used for *resolution* and *optimization* yield both $F_{1,6} = 13.37$ and $p = 0.011$. The PSG teams spent an average of 66% of their communication efforts over the design problem *resolution* phase and the remainder 34% *optimizing* the design solution. This redistribution of the two activities is synonymous of a more effective problem resolution phase, since the total amount of utterances used is comparable in the two groups. This observation agrees with the higher efficiency of collaboration for PSG teams observed through the number of agreements reached. The team members, who adhere to the same strategy, achieved better understanding of each other's intentions and negotiation stances.

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 significantly affected by the ANED negotiation protocol and strategies. The findings can be summarized as follows:

- The use of ANED's *argumentative negotiation protocol* and *hierarchy exploration strategy* affects the dynamics of the negotiation/ collaboration process positively and has the potential of improving the results of collaborative design. Future research is needed to link the process benefits to the improvement of the 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 of the argumentative negotiation protocol makes the overall collaboration process more efficient because the communication is more focused and well guided.
- Little planning occurred in protocol- & strategy-supported teams implies that the designers should have a good understanding about the design problem and the design process when they come to work together. Future research is needed to verify if adding more speech-acts may help planning interactions.
- The *hierarchical exploration strategy* propels the designer to explore a wider range of design space more thoroughly, both vertically over different issue levels and horizontally across each issue level.
- The *hierarchical exploration strategy* provides a larger space and more opportunities for designers to generate more proposals and thus more agreements. As a result, the number of arguments exchanged being equal, the strategy-supported teams are able to reach a final design faster and spend more time optimizing their results.

The experiment study described above has two major limitations. First, the experiment study 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. Second, the results obtained thus far are limited to the type of the design problem tested. Future experiment research is needed to test various types of design problems and to include professional designers as subjects.

References

1. Parsons S, C Sierra, Jennings NR (1998) Agents that reason and negotiate by arguing. J. of Logic and Computation 8(3): 261-292
2. Jin Y, S Lu (2004) Agent-based negotiation for collaborative design decision making. Annals of the CIRP 53(1): 122-125
3. Geslin M, Y Jin (2005) A context based approach to engineering design negotiation. Proc. of 17th ASME Intl Conf. on Design Theory and Methodology, DETC2005/DTM-85183 Long Beach, CA, September 24-28
4. Pruitt DG (1981) Negotiation behaviour - organizational and occupational psychology. Academic Press, New York

5. Raiffa H, J Richardson, D Metcalfe (2002) Negotiation analysis: the science and art of collaborative decision making. The Belknap Press of Harvard University Press
6. Searle J (1969) Speech acts: an essay in the philosophy of language. Cambridge University Press, Cambridge
7. Gulliver PH (1979) Disputes and negotiations: a cross-cultural perspective. Academic Press, New York
8. Toulmin SE (1969) The uses of argument. Cambridge University Press, Cambridge
9. Rahim MA (1986) Managing conflict in organizations. Praeger, New York
10. Bond AH, L Gasser (1988) An analysis of problems and research in DAI. In AH Bond and L Gasser (eds), Readings in Distributed Artificial Intelligence, Morgan Kaufmann, San Mateo, CA: 3-35
11. Sycara KP (1989) Multiagent compromise via negotiation. In Gasser, L and Huhns M (eds), Distributed Artificial Intelligence Vol 2, Pitman Publishing, London: 119-137
12. Ronsenschein J, G Zlotkin (1994) Rules of encounter: designing conventions for automated negotiation among computers. MIT Press, Cambridge, MA
13. Jennings NR, S Parsons, P Noriega, C Sierra (1998) On argumentation-based negotiation. Proc. of the Intl Workshop on Multi-Agent Systems: 1-7
14. Antonsson E, KN Otto (1995) Imprecision in engineering design. ASME Journal of Mechanical Design 117(B): 25-32
15. Scott M (1997) Formalizing negotiation in engineering design. Ph.D. Thesis, California Institute of Technology
16. Klein M (2000) Towards a systematic repository of knowledge about managing collaborative design conflicts. In Gero, JS (ed), Artificial Intelligence in Design'00, Kluwer, Dordrecht
17. Lewis K, F Mistree (1998) Collaborative, sequential and isolated decisions in design. ASME Journal of Mechanical Design 120: 643-652
18. Peña-Mora F, Wang CY (1998) Computer-supported collaborative negotiation methodology. Journal of Computing in Civil Engineering 12(2): 64-81
19. Evan WM, McDougall JA (1967) Inter-organizational conflict: a labor-management bargaining experiment. Journal of Conflict Resolution 6(4): 398-413
20. Polzer JT (1996) Intergroup negotiations the effects of negotiating teams J. of Conflict Resolution 40(4): 678-698
21. Kirschman JS, Greenstein JS (2002) The use of groupware for collaboration in distributed student engineering design teams. Journal of Engineering Education 91(4): 403-407
22. Ballmer T, Brennenstuhl W (1981) Speech act classification: a study in the lexical analysis of English speech activity verbs. Springer-Verlag, Berlin
23. Altshuller GS (1998) 40 principles: TRIZ keys to technical innovation. Technical Innovation Center, Inc, Worcester, MA