Team Engineering Analysis and Modeling: Toward a Normative Model of Team Interaction

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ABSTRACT **The TEAM (Team Engineering Analysis and Modeling) research project advocates a competence-centered approach to modeling the interaction among members of engineering design teams. This paper describes the first phase of research: empirical analysis of team member Interactions. Comments and responses from an electronic design review system were analyzed to describe message design and participants' interaction. This modeling effort will form the basis for knowledge-based tools to support consensus management in engineering design teams.**

I. INTRODUCTION

The Team Engineering Analysis and Design (TEAM) project is a collaboration between engineers and social scientists that seeks a principled, model-driven approach to the design of consensus management systems for engineering designers. TEAM proposes a *competence-centered* approach to modeling interaction that incorporates both analysis of engineering designers' current practices (a user-centered perspective that is situated and empirical) and a specification of normative models of design and team member interactions (a normative task-centered perspective). The notion of competence encompasses both technical competence in design and social competence in interaction. This paper focuses on the latter.

The ultimate goal of the TEAM project is to develop knowledge-based support tools to facilitate the collaborative design process. To do so, the first step **is to analyze** interactions among engineering design teams and identify the functions of, and interactions between, the messages that are created and passed between them. This paper describes a specific engineering design context from which a data set was derived, proposes a coding scheme to capture the function of messages, presents empirical results. and discusses future plans for research.

II. BACKGROUND

The specific engineering design context for this research is the design and construction of a facility requested by the Air Force and carried out by the Army Corps of Engineers. The following sections elaborate on the participants, the design process, and the electronic review management system that mediated interactions between designers, quality assurance teams, and the Air Force "customer."

A. Participants in the Design Process

An Air Force base (the end-user AFB) initiates a design project by making a request to the Air Force Strategic Air Command (SAC). As is the case for many construction projects, SAC contacts an Army Corps of Engineers design project manager. This project manager is responsible for the design phase of a project and oversees a number of groups, including engineering design, cost estimation, and design quality assurance. And as is often the case, the actual design is done by an outside contracting fii referred to as the Architect/Engineer (A/E). Figure 1 provides an overview of the organization involved in this particular project. Participants involved in the design process are from SAC itself, from the Air Force Base (AFB) "end-user" community, from Corps geotechnical, landscaping, cost estimating, design quality assurance, and construction quality assurance groups, and from the A/E firm. The construction project manager assumes responsibility in the subsequent construction phase.

B. Design Process

The design process itself, which is carried out by the A/E and monitored by the design project manager, SAC, and the end

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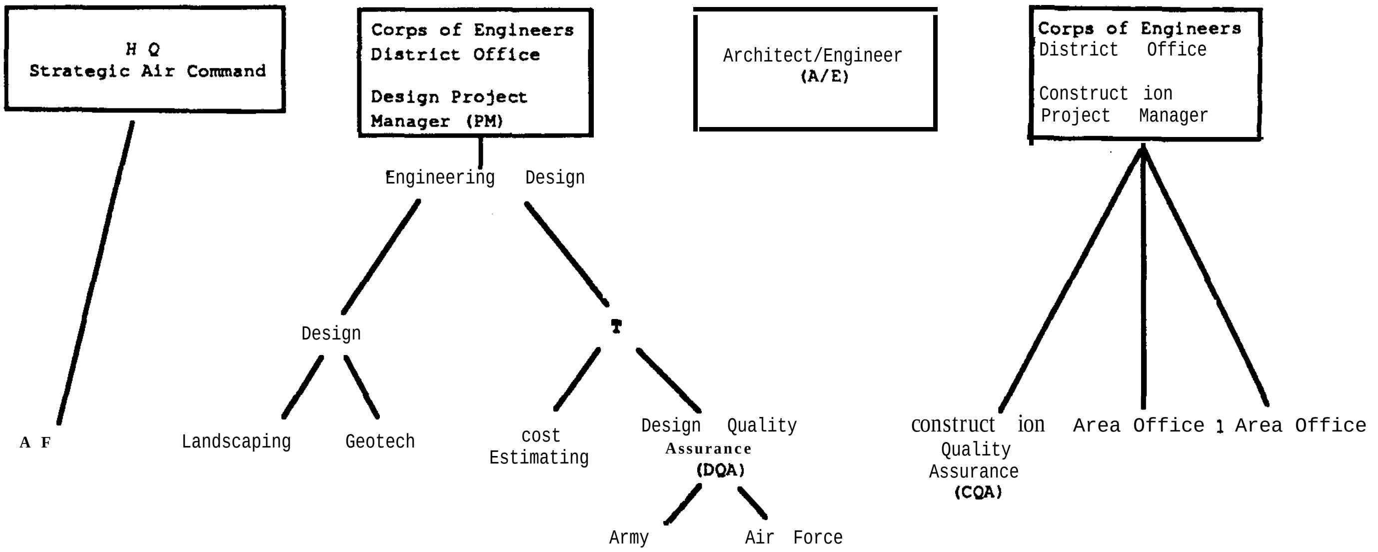

Figure 1. Air Force/Army Corps of Engineers organization relevant to engineering design.

user, is structured as a series of sequential phases that are not necessarily **continguous.**

For this construction project, the following phases occurred: project book (2 weeks), project definition (3 weeks), initial submittal review (2 weeks), 60% **onboard** review (2 weeks), final design (3 weeks), final design late (3 **1/2** weeks), first backcheck (1 **1/2** weeks), and second backcheck (1 week).

C. The ARMS System

The Automated Review Management System (ARMS) is a software package that manages design review comments and responses for the Army Corps of Engineers [1]. Reviewers, from the Corps, SAC, or the end-user facility, make comments on aspects of the A/E's design. Typically, someone from one of the design project manager's groups will originate such a comment, and SAC and the end-user Air Force Base facility will state their opinions of the remark using a standard response protocol. The comments are forwarded to the A/E via the design project manager. Also through ARMS, the **A/E** responds to each comment, also with a standard response protocol.

Although the use of ARMS is a required part of design in many Corps of Engineers projects, it is important to realize that its use reflects only portions of the design process. ARMS focuses on "macro" consensus management issues between fairly large "sender units" such as SAC and Design Quality Assurance; the "micro" negotiations within a sender unit are unknown. No data are available on faceto-face meetings or review conferences. Nevertheless, ARMS provides a complete picture of the interactions that it does support, and is thus quite useful as a starting point for analysis.

III. METHOD

An entire set of ARMS comments and responses from a facility construction project (867 comments and associated responses) served as the data set. Each ARMS sequence was segmented into: (1) comment; (2) responses (with possible elaboration) by the A/E, SAC, and Corps; and (3) first and second backchecks (see Table 1).

Table 1. Sample sequence from ARMS.

Sequence	**Component Segment**
Desk chairs need to be dual purpose for both leisure and desk seating.	**Comment**
>SAC: CONCUR	**SAC response**
>CORPS: CONCUR	**Corps response**
>A/E Response: DONE	**A/E response**
SEE LOCATION CODE C8XD UPHOLSTERED DESK ARMCHAIR	**A/E elaboration**
>BACKCHECKED for 1st Backcheck (approved) by XXX on Wed Mar 4 19xx	First backcheck

A. Normative Model

Comments and responses were coded using a message coding system based on a model of competent feedback in the revision process **[2, 3].** Repair and revision are central processes involved in the design and production of messages in any medium; they are processes through which message producers seek, receive, and respond to feedback about the adequacy of their messages. There are extensive literatures concerned with the various practical and theoretical questions involved in the study of revision: questions such as how recipients provide information about the need for revision, how message producers interpret such information, what kinds of revisions are made in response to feedback, and the like [4, 5, 6, 7].

From this literature we have abstracted a general model of competent feedback against which we can evaluate actual feedback messages and their effects [11, 12, 13]. According to this model. competent feedback must address recipient needs for direction and motivation. The recipient's need for direction is derived from the fact that a clear understanding of necessary revision is a prerequisite for performing that revision. The recipient's need for motivation (or "backing") follows from the assumption that the recipient is a free agent and may choose not to comply with a revision request unless appropriate motivation is invoked.

The comment component of this sequence is the revision message supplied by the agent assigned to evaluate the project. Because these comments must function effectively in guiding revision of the design, they should contain, in their fully elaborated form, identification of problems with the plan and suggested solutions to the identified problems. Moreover, because the authority or basis for a complaint or suggestion may not be clear, comments may also include some explicit mention of the backing for the revision message.

B. Coding Comments

Based on the above normative model, comments were classified along three dimensions: (1) specification of problem; (2) specification of solution; and (3) specification of backing.

Each comment was evaluated in terms of the degree to which it specified what was problematic about the project or plans. A comment received a score of 1 if it lacked any specification of a problem, a score of 2 if it contained a general reference to a problem or mentioned a hypothetical problem, and a score of 3 if it contained a specific and detailed characterization of the problem.

Each comment was also evaluated in terms of the degree to which it specified a solution to a problem. A comment received a score of 1 if it failed to offer a solution, a score of 2 if it made a general suggestion or asked a general question, and a score of 3 if it made a specific suggestion or asked a specific question.

Finally, each comment was also evaluated in terms of the degree to which specific authority (i.e., backing) for the comment was given. A comment received a score of 1 if no backing was mentioned, a score of 2 if the comment contained an explanation of the reasoning on which it was based, and a score of 3 if it contained references to specific rules, procedures, or other authoritative basis for the comment.

To evaluate the reliability of the proposed coding scheme, two coders, working independently, evaluated 25 randomly selected comments in terms of problem specification, solution specification, and backing. The coders achieved 80% exact agreement on assignment of comments to levels of problem specification (Cohen's κ = .668), 80% exact agreement on assignment of comments to levels of solution specification (Cohen's κ = .651), and 92% exact agreement on assignment of comments to levels of backing specification (Cohen's κ = .821)[1].

C. Coding *Responses*

The response component of the sequence was the response given to a comment by the architect/engineer, SAC, and Corps. Thus, each comment could receive up to three responses, one from each agency. These responses were selected from a menu provided by ARMS (see Table 2). Because the possible responses were specified by the conventions of the ARMS system, the type of response supplied by each agency was simply recorded.

Table 2. Response Menu Items from ARMS.

Response Menu Item	Description
Withdrawn	Withdrawn by maker. A/E to take no action.
Concur	Concur. A/E to comply
Added Scope	Added construction scope and wst. Technically acceptable. PM to decide on incorporation.
changed Scope	Changed construction scope. No construction cost impact. Technically acceptable. PM to decide on incorporation.
Info	For A/E's information
Denied	Comment denied. A/E to take no action.
Duplicate	Duplicate comment. A/B to take action per other similar comment.

'Cohen's κ produces a reliability estimate that corrects for chance agreement. According to Cohen, κ's from A to .6 are fair, from .6 to .7 are good, and over .75 are excellent. For a detailed discussion, see [15].

Frequently, however, the agency would incorporate elaborating material into its response to a comment. To code these elaborating statements, we developed a system for classifying response annotations as shown in Table 3.

Table 3. Classification of Response Annotations

Code	Description (Based on ARMS documentation)
0	No elaboration
1	Reference: Specific reference to design specifications or drawings
2	Agreement: Either a statement of agreement with the comment or a statement of commitment to do an act suggested by the comment
3	Explanation of the agency's response or action
4	Denied or disagreed with a comment
5	Labeled comment as duplicate
6	Other

Two coders, working independently, classified the response annotations made by each agency to the 25 randomly selected comments (a total of 75 responses). The two coders achieved 88% exact agreement (Cohen's κ = .81). These coding procedures produced a quantitative representation of the nature of the originating comment and the nature of the SAC, Corps, and A/E responses made to a comment.

IV. Results

The first stage of analysis focuses on a descriptive characterization of the relationships between message function, response, response annotation, design phase, and sender unit.

A. Comments

Overall, the results showed that design phase and sender unit were significantly related to the frequency of comments. The three message functions of problem specification, solution specification, and backing were dependent on phase and sender unit. Furthermore, the three message functions were interrelated.

The Effect of Design Phase. The majority of the comments (52.8%) occurred in the fifth phase (final design). Approximately 20% of the contributions were made during the 60% Onboard Review phase, while 13% of the contributions were made during the Project Definition phase.

The Effect of Sender Unit. SAC and the end-user AFB initiated approximately 10% and 34% of the messages respectively. The Design Quality Assurance units accounted for an additional 34% of the messages. The construction units only contributed 2.5% of the messages.

Effects related to Problem Focus. Overall, problem specification appeared to follow a bimodal distribution: comments either lacked specification or were specific. In particular, 47.8% of the messages did not provide an explicit definition of the problem, while 42.4% provided very specific definition of the problem. Only 9.7% of the messages provided general indications of the problem.

With respect to the variation of problem focus by project phase, the analysis showed that comments made in the Initial Submittal Review and Second Backcheck phases had a substantially greater problem focus. Comments in the Project Book and 60% onboard review were also more likely to have a problem focus.

With respect to the *variation* in problem focus by sender unit, we found that comments made by SAC and the end-user AFB were significantly more likely to have a problem focus. In addition, comments made by the Landscaping and Cost Estimation units of the design team were also more likely to have a problem focus. Comments made by members of the Design Quality Assurance units were less likely to have a problem focus.

Effects related to Solution Specification. Solution specification was also characterized by a bimodal distribution. 34.7% of the messages did not provide any explicit recommendation for the task, while 52.9% provided specific task recommendations. 12.3% provided only general task recommendations.

With respect to the effect of phase, it was found that comments made in the Final Design, Final Design Late, and First backcheck were more likely to provide specific solutions, whereas comments made during the Initial Submittal Review and 60% Onboard Review were significantly less likely to do so.

With respect to the effect of sender unit, the data showed that comments made by SAC, the end user AFB, and Cost Estimation were significantly less likely to provide a specific solution. However, comments made members of the Geotech, Landscaping, and Design Quality Assurance units were significantly more likely to provide specific solutions.

Effects related to Backing. Overall, most comments did not provide backing. In particular, 66.1% of the messages did not include any backing, while 22.3% of the messages provided very specific resources to support their comments. 11.6% provided general reasoning in support of the comments.

Backing did appear to vary somewhat by design phase. Comments made during the Project Definition phase were significantly more likely to have backing statements. Comments made during the Initial Submittal Review were least likely to have backing statements.

Backing was also affected by sending unit. Comments made by SAC, the end user AFB, and Cost Estimation were less likely to include backing statements. However, comments originating in the Design Quality Assurance, Geotech and Landscaping units were significantly more likely to include backing statements.

Interrelationship between Problem Focus, Solution Specification and Backing. Comments that had a high problem focus were less likely to provide specific solutions. Further, comments that had a high problem focus were also more likely to include some backing statements.

B. Responses

Response actions were made by SAC (315 responses), the Corps (510) and the A/E (720). According to the ARMS manual, the A/E was required to provide response actions for all comments. However, the A/E did not participate in the Project Book and Project Definition phases.

Usually (84% of the time), SAC responded by concurring with the comment. They responded by providing more information for 7.3% of the comments, and with a denial for 3.5% of the comments.

The Corps concurred with 77% of the comments. They provided additional information for 4% of the comments, and denied only 1.5% of the comments. They also noted duplication of ideas in 17% of the comments.

As per the rules, the A/E responded by indicating that all comments were acted on, that is, "Done".

The Effect of Phase. In the Initial Submittal Review, SAC was more likely to provide a concur response and also significantly more likely to offer a denied response. They were least likely to concur in the Project Book phase. The Corps was least likely to provide a concur response in the Project Book and Initial Submittal Review phases.

The Effect of Sending Unit. SAC was most likely to offer a concur response to comments made by end users (SAC itself and the AFB). They were significantly less likely to concur with comments made by all other units. Further, they were more likely to deny comments originating at the end-user AFB.

The Corps was most likely to concur with comments originating from SAC. They were also likely to concur with comments originating from Geotech and Landscaping. However, they were least likely to concur in response to comments originating from Cost Estimation and Design Quality Assurance.

Relationship to Problem Focus, Solution Specification, and Backing. SAC was more likely to concur with comments that had a high problem focus and less likely to concur with comments that had a high solution specification or provided backing. The Corps was more likely to deny comments that had a high problem focus.

C. Response Annotations

Overall, SAC and the Corps usually did not elaborate upon their response actions, but the A/E, as required, usually did. In particular, the A/E provided response elaborations to 83% of the comments. Of these, 53% were offering references, 16% provided explanations, and 15% indicated agreement.

The Effect of Phase. The A/E was more likely to include references in the latter stages of design: Final Design, First Backcheck and Second Backcheck, and less likely to do so in Initial Submittal Review. The A/E was more likely to provide explanations in the Initial Submittal Review phase and was less likely to do so in the First and Second Backcheck phases. Also, the A/E was more likely to indicate agreement in the Initial Submittal Review phase.

The Effect of Sender Unit. The A/E was more likely to include references in response to comments made by Geotech. Design Quality Assurance, Construction Quality Assurance, and SAC. Furthermore, the A/E was more likely to provide explanations in response to comments by Landscaping and Construction Quality Assurance units and less likely to do so with comments made by Cost Estimation. Finally, the A/E was more likely to indicate agreement with the Construction unit (Area Office 2) and with Cost Estimation .

Relationship with Problem Focus, Solution Specification, and Backing. The A/E was more likely to offer explanations, but not references, in response to comments with a high problem focus. In response to comments with a high solution specification, the A/E was more likely to include references and offer explanations but was less likely to indicate agreement. The A/E was less likely to include references and indicate agreement with comments that provided backing statements.

V. Discussion

The descriptive analysis above is the first step towards the specification of a model of team interaction. The results of the present study provide an initial description of the ARMS review process and suggest areas for further study. We interpret these results in light of practices advocated by concurrent engineering (e.g., [11]).

With respect to design phase, the results showed that most comments were elicited during the late rather than the early stages of the design process, even though early resolution of problems is more efficient and effective.

Results also showed an imbalance in the distribution of comments across sender units. In particular, the end user and Design Quality Assurance units were the most active, and Construction units the least. This reflects the current traditional engineering design practice of sequential phases; in contrast to the proposed desirability of "simultaneous engineering". Furthermore, an imbalance in the distribution of responses (e.g., SAC concurred with itself and its subordinate most of all) may indicate a lack of consensus across units.

Revision comments did not usually offer general outlines of problems or solutions but instead either provided detailed specification or none at all. Moreover, comments tended to contain either problem or solution specifications but not both, and this effect was dependent upon project phase.

Perhaps the most curious and interesting finding was that specification of backing was associated with a greater likelihood of a denial response. If backing is seen as an indication that commenter feels the need to justify what may be an untenable position, the presence of backing in a comment may lead it to be disregarded. On the other hand, if backing as seen as a means of providing documentation, it may be viewed positively as acceptable elaboration. Thus, rather than judging that a particular communicative practice is "good" or "bad", we must carefully examine how such framing occurs and how it is manifested and managed in interaction.

The interaction between technical and social competence deserves to be examined in greater detail. The engineering design community has traditionally focused on technical competence, while communication scientists focus on social competence independently of how communicative practices influence performance on substantive tasks. The TEAM project aims to bridge this gap by using the results from the ARMS study to characterize current practices and refine the normative model. Such a model must represent roles, responsibilities, authority, the structure of the communication network, and mechanisms and resources for repair. Concepts such as footing and ratified participation [12], operative languages [13], and self-organizing systems theory [14] are expected to be relevant in the modeling effort. The model in turn will form the basis for knowledge-based support tools for engineering design teams. Some implications from the current research are that design support systems should facilitate early, effective feedback and should actively solicit contributions from relevant participants (i.e., engage in a proactive ratification process that allows personnel from diverse parts of the organization to interact).

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