Capturing Design Knowledge for Engineering Trade Studies

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Abstract. Currently, much of the information regarding decision alternatives and trade-offs made in the course of a major program development effort is not represented or retained in a way that permits computer-based reasoning over the life cycle of the program. The loss of this information results in problems in tracing design alternatives to requirements, in assessing the impact of change in requirements, and in configuration management.

To address these problems, we are studying the problem of building an intelligent, active *corporate memory facility* which would provide for the capture of the requirements and standards of a program, analyze the design alternatives and trade-offs made over the program's lifetime, and examine relationships between requirements and design trade-offs. Early phases of the work have concentrated on design knowledge capture for the Space Station Freedom. We have demonstrated and are extending tools that help automate and document engineering trade studies (the topic of this paper), and we are developing another tool to help designers interactively explore design alternatives and constraints.

1.0 Overall Problem

Under NASA contract NAS2-12108, the Boeing Advanced Technology Center is conducting research leading to a corporate memory facility (CMF). A corporate memory facility would provide facilities for capturing and using decision history and rationale throughout a major program's life cycle. This effort is jointly funded by OAST's AI Program and the Space Station Freedom Advanced Development Program.

Currently, much of the information regarding alternatives considered and trade-offs made in the course of a major program development effort is not represented or retained in a way that permits computer-based reasoning over the life cycle of the program. The loss of this information results in problems in tracing alternatives to requirements, in assessing the impact of change in requirements, and in configuration management (Boeing Computer Services, 1989a,b).

There is not an integrated set of capabilities to assist in generating and evaluating or reevaluating program alternatives. The lack of this capability results in such problems as belated reaction to changes in requirements and inability to consider a reasonable number of alternatives.

2.0 A Corporate Memory Facility

To address these problems, we are studying the problem of building an intelligent, active corporate memory facility which would provide for the capture of the requirements and standards of a program, alternatives considered and trade-offs made over its lifetime, and relationships between these. The corporate memory facility would provide for requirements traceability, impact assessment, automation and/or assistance in the generation and evaluation of alternatives, and configuration management.

The corporate memory facility would support interactive problem solving across diverse areas such as the aerospace engineering disciplines (propulsion, weights, and aerodynamics). In operational use, a corporate memory facility would reduce life-cycle flow time and cost and improve the quality of program deliverables. Similar benefits could be realized by applying information accumulated in the corporate memory facility for one program to other related programs.

In initial phases of this work, the Advanced Technology Center is studying core corporate memory facility ideas, preparing corporate memory facility technical reports detailing study results, and building feasibility demonstrations. In conjunction with NASA, the Space Station Freedom Program was selected as a testbed; within this test bed we are concentrating on design knowledge capture. In 1989 the Advanced Technology Center examined aspects of the Power subsystem and the Environmental Control and Life Support (ECLS) subsystem. We also used our tools in a portion of the 1989 Space Station Freedom technical audit to investigate the rationale for a previous design decision.

Through the series of demonstrations, we are showing a novel integration and extension of design knowledge capture ideas by:

a. Tailoring knowledge acquisition and process control tools for *engineering trade studies*, a significant and feasible part of design knowledge capture.
b. Digitally recording speech as an unobtrusive method of capturing design rationale at the trade study workstation.
c. Developing an interactive design alternative generation aid.

3.0 Design Knowledge Capture

The Space Station Freedom was selected as the focus of research efforts toward a corporate memory facility since it is a large NASA project in a relatively early stage of design, and much of the design rationale could be captured or retrieved before it was lost. Many organizations in NASA and their subcontractors are interested in design knowledge capture, especially as it applies to the Space Station Freedom.

NASA's goal is to provide for a maximum of ease in the evolution of the Space Station Freedom and its adaptation to new requirements, new technologies, and advanced forms of machine intelligence. One facet of this is the Design Knowledge Capture Plan (NASA, 1988b). It is recognized that this goal must be pursued not only in the design of the Space Station Freedom, but also in the requirements for the documentation of the design, its features, and its rationale.

Following are objectives for design knowledge capture for the Space Station Freedom (Anon., 1988):

a. Establish design and development history for the Space Station Freedom Program.
b. Establish design and development traceability for the Space Station Freedom Program.
c. Maintain viable and effective risk management (e.g. failure modes and contingencies).
d. Capture and retain Space Station Freedom Program experience and expertise.

Design knowledge is defined as all physical descriptions of a system and its components; rationale for design decisions; functional flow diagrams; documentation of design objects or processes they perform along with the results; and interrelationships among design knowledge elements (such as part numbers and descriptions). Design knowledge embodies design objects and their attributes, including both designs selected for implementation and those not selected. It includes the rationale for requirements leading to design, methods of verification, exceptions and waivers from requirements, and other design criteria. Design knowledge is generated by engineers, management, technicians, and production teams (NASA, 1988b; Carnes, Olson, and Praharaj, 1988; Lakin et al., 1988; Anon., 1988; Sivard et al., 1989; NASA, undated).

Design knowledge capture encompasses the acquisition, storage, and manipulation of engineering data, information, and knowledge generated during a program (NASA, 1988b; NASA, undated). Design knowledge capture is also defined as the activity of transferring design knowledge from a source to a machine-interpretable form (NASA, 1988a; Wechsler and Crouse, undated).

Several sources have identified potential benefits of design knowledge capture (Purves and Carnes, 1987; NASA, 1988a; Beazley, 1988; Carnes, Olson, and Praharaj, 1988; anon. 1988; Sivard et al., 1989; Wechsler and Crouse, undated). Many of these benefits generalize to other portions of the corporate memory facility. They include:

a. Convergence of requirements and design through developing a rationale during the design process as each requirement is fulfilled.
b. Higher integrity of the design process and the attendant data products.
c. Better traceability of design data.
d. Integration of the Space Station Freedom Program across both logical and physical interfaces.
e. Secondary use of discipline data in the associated areas of failure modes and effects, resource management, integrated logistics support, configuration management and knowledge-based systems.
f. More efficient work efforts and products.
g. On line availability of design and decision data for critical systems.
h. Requirements traceability.
i. Design verification and validation.
j. Manufacturing quality control.
k. Documentation production.
l. Tutorials for the next generation of design engineers.
m. Effective management of engineering change and increased product quality through a common platform for engineering design, analysis, test, manufacturing.
n. An accumulated body of program knowledge that can fuel applications that manage life cycle functions beyond delivery.
o. Reduced sensitivity to personnel volatility.
p. Support for continuing engineering analysis.
q. Support for manufacturing.
r. Support for future applications.

There are also potential uses of captured design rationale in program management applications (Carnes, Olson, and Praharaj,1988). These include:

a. The influence of individual requirements can be traced.
b. The requirements source and reasoning process behind each design feature can be traced.
c. The influence of proposed requirements changes on the design can be assessed.
d. The effects of changes in assumptions can be assessed.
e. The overall reasoning process can be reviewed for possible future improvements.

4.0 Automating Engineering Trade Studies

We are focusing on trade studies in the design knowledge capture area because -

a. They exhibit a microcosmic path through the full cycle of design information, including requirements linkage, generation and comparison of alternatives, and decision documentation.
b. Many design engineers are familiar with trade studies and are comfortable using them to compare alternatives in quantitative terms.
c. Even though different methodologies for trade studies are available, little has been done to automate them.
d. A trade study tool would be immediately useful in a variety of domains, regardless of the success of the overall design knowledge capture or corporate memory facility effort.
e. Existing Advanced Technology Center tools could be extended to help perform portions of trade studies.

Trade studies are performed, in part, to avoid a designer's tendency to go directly to a design based on past experience, rather than trying to find a design that may better satisfy overall program requirements. Trade studies are often performed to help establish overall system configurations, study the detailed design of individual configuration items to provide the most cost-effective solution, and evaluate alternate solutions when the need for change occurs.

There are two general types of trade study criteria: limits which must be satisfied by any candidate system go/no go criteria (or *hard constraints*), and attributes upon which a ranking can be based (*soft constraints*).

Candidates are usually filtered using hard constraints and then ranked for comparison using soft constraints. Trade trees are used to decompose large numbers of candidates into groups for tractability. Paths through the tree show total configurations. Typical trade study criteria include accuracy, lifetime, power output, stability, sensitivity, bandwidth, low weight, low power, minimum dimensions, operational simplicity, electromagnetic compatibility, reliability, survivability, schedule, cost, safety, and risk. Criteria are usually weighted. The results are usually shown in a *trade study matrix* - a table showing the alternatives, criteria, ratings, and weights.

After candidates are rated and scored, a sensitivity analysis can be performed. This shows the sensitivity of the decision to changes in the value of attributes, weights, costs, and subjective estimates.

In our early work on the corporate memory facility we demonstrated the capture of trade study information and rationale (Figure 1). In the future, this information will be available through the Technical and Management Information System (TMIS). This system is available to anyone working on Space Station Freedom. We are examining several report formats based on current trade study practices and TMIS requirements. The information necessary for these reports is providing the foundation for the knowledge capture process.

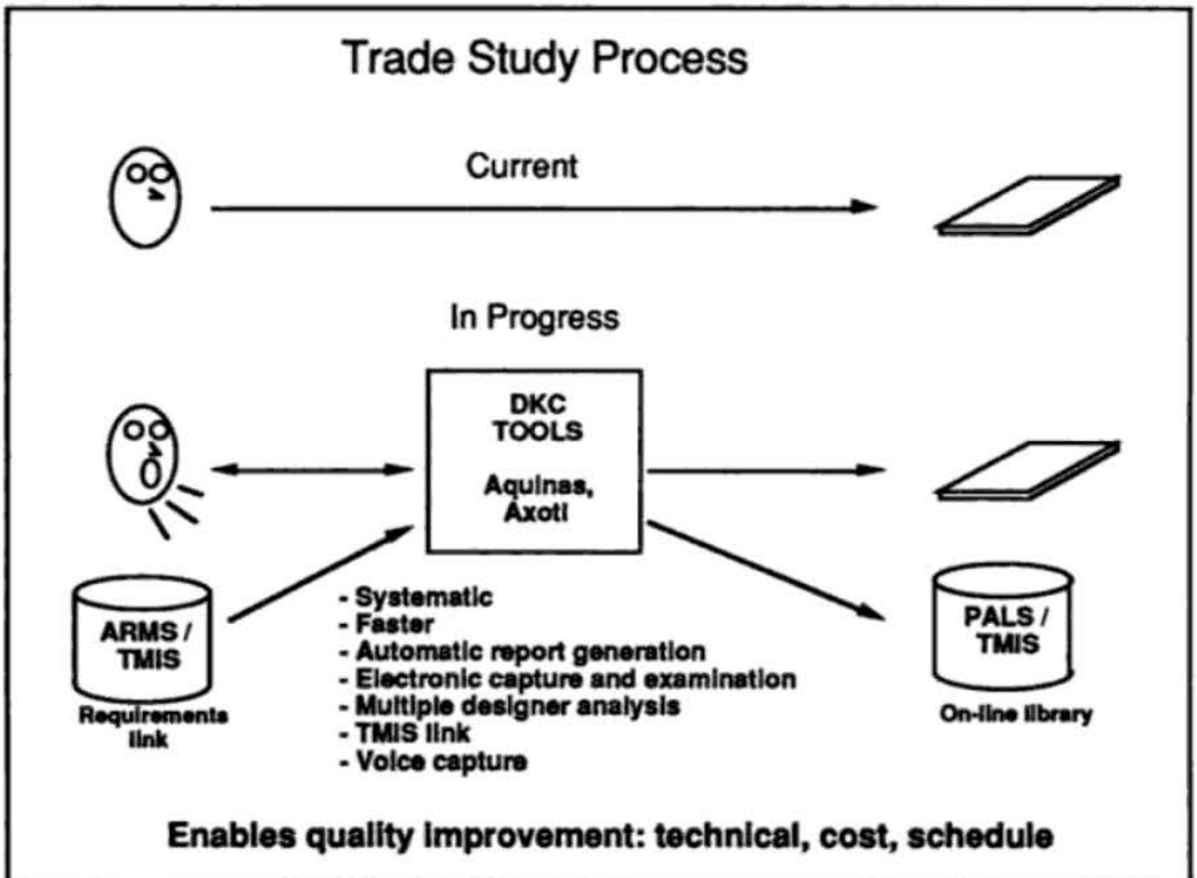

Figure 1. Automating the trade study process.

5.0 Design Knowledge Capture Tools

Two tools, Aquinas and Axotl, were used to build the first demonstration. An additional set of tools (MANIAC, HyperCard, and MacRecorder) was used to capture voice rationale and associate it with the Aquinas knowledge base for interactive playback.

5.1 Aquinas: Capturing Trade Study Design Rationale

Aquinas interviewed experts in several trade study domains and captured candidate and criteria information leading to rank-ordered candidate selections. In the power domain, additional rationale was captured as voice input. In the ECLSS domain, conflicting opinions from multiple designers were captured, analyzed, and documented.

Power subsystem - Chuck Olson, a design engineer in Boeing Aerospace, used Aquinas to build two separate trade studies for the interface between a computer and automatic circuit breakers. Brian Smith, another Boeing Aerospace design engineer, offered advice on building an electronic trade study process assistant.

Environmental Control and Life Support subsystem - Jim Knox, a NASA design engineer at Marshall Space Flight Center, used Aquinas to build a trade study for carbon dioxide removal on Space Station Freedom in the year 2000. Allen Basckay, another NASA design engineer at Marshall Space Flight Center, added additional information to this trade study.

Technical Audit Item #85 - John Palmer, O'Keefe Sullivan, and Carl Case, Boeing Aerospace, used Aquinas to document a 1986 decision about the placement of the pressurized logistics module.

Aquinas is a workbench developed by the Boeing Advanced Technology Center for acquiring and analyzing expert knowledge for solving diagnostic, structured selection, classification, and other problems (Figure 2). In the corporate memory facility context, Aquinas is used to acquire knowledge about requirements and alternatives from individuals or groups of experts, and then assists in merging that knowledge into a single knowledge base. Weights may be assigned to both requirements and their refinements. This knowledge may be merged automatically by Aquinas or by consensus of the program staff using Aquinas as an assistant. Aquinas supports similar capabilities for acquiring compound alternatives.

Dialog Manager							
Repertory Grid Tools	Hierarchical Structure Tools	Uncertainty Tools	Internal Reasoning Engine	Multiple Scale Type Tools	Induction/ Learning Tools	Multiple Expert Tools	Constraints
Common knowledge representation and user interface							

Figure 2. Aquinas consists of several tool sets that assist different knowledge acquisition tasks. General advantages of Aquinas include integration of multiple methods and techniques, rapid prototyping and feasibility analysis, generation of expert enthusiasm, multiple mediating representations, embedded testing, and life cycle support for verification, delivery, and maintenance.

Aquinas, an expanded version of the Expertise Transfer System (ETS; Boose, 1984, 1985, 1986a,b), combines ideas from psychology and knowledge-based systems to support knowledge acquisition tasks. These tasks include eliciting distinctions, decomposing problems, combining uncertain information, incremental testing, integration of data types, automatic expansion and refinement of the knowledge base, use of multiple sources of knowledge, use of constraints during inference, and providing process guidance (Boose and Bradshaw, 1987; Boose, Bradshaw, and Shema, 1989). Aquinas interviews experts and helps them analyze, test, and refine knowledge. Expertise from multiple experts or other knowledge sources can be represented and used separately or combined. Results from user consultations are derived from information propagated through hierarchies.

Using Aquinas, rapid prototypes of knowledge-based systems can be built in as little as one hour, even when the expert has little understanding of knowledge-based systems or has no prior training in the use of the tool. The interviewing methods in Aquinas are derived from George Kelly's Personal Construct Theory and related work (Kelly, 1955; Shaw and Gaines, 1987;

Boose, 1988). Kelly's methods and theory provide a rich framework for modeling the qualitative and quantitative distinctions inherent in an expert's problem-solving knowledge.

Aquinas tools mentioned here are explained more fully elsewhere (Boose and Bradshaw, 1987; Boose, 1988; Kitto and Boose, 1988; Shema and Boose, 1988; Bradshaw and Boose, 1990).

Extended repertory grids in Aquinas are a compact and easily understood form of expertise representation for many types of knowledge. Repertory grids can be analyzed, refined, tested, and maintained more easily than a corresponding, larger rule or frame knowledge base. In Aquinas, we have augmented repertory grid structures to include hierarchies, constraints, structures for eliciting and reasoning about knowledge from multiple experts, multiple variable types, and accommodate forms of machine learning. Generally, these analysis capabilities and compact, higher-level *mediating representations* of expert knowledge make knowledge bases easier to inspect, analyze, maintain, test, and improve. We use a test case-based approach within Aquinas for performance measurement, verification, and maintenance, and automatic knowledge base improvement. This method helps find holes and weaknesses in the knowledge base, and provides facilities for verifying knowledge consistency, accuracy, and sanity range.

Refinement methods in Aquinas include implication and similarity analyses, completeness checking, hole filling, cluster analyses, generalization, automatic rule production, internal testing and debugging aids, and graphic representation transformation. Expertise from multiple experts or other knowledge sources can be represented and used separately or combined, giving consensus and dissenting opinions among groups of experts. Recent progress on Aquinas has been in the areas of knowledge base performance measurement, knowledge base maintenance, interacting trait constraints, consultation graphics, and eliciting strategic and procedural knowledge. Experiments show how Aquinas can automatically improve knowledge bases and even suggest new problem-solving information. Forms of interactive and automatic machine learning are also employed by Aquinas (Boose, Bradshaw, and Shema, 1989).

Aquinas exists in several "C"-based versions that run on different microprocessor platforms and a fuller development version that runs on Sun workstations and Xerox Lisp Machines.

5.2 The Axotl System: Process Model Capture

In the first demonstration, Chuck Olson used Axotl to elicit an electronically-based model of the trade study process.

Axotl, developed at the Boeing Advanced Technology Center, integrates a set of computer-based decision analysis tools with a knowledge-based system. The decision analysis tools are designed for problems requiring careful consideration of uncertainty and complex tradeoffs. In the context of corporate memory facility, alternatives and requirements generated by Aquinas can be analyzed using decision analysis representations to determine the suitability of various alternatives and to gauge the impact of changes in design requirements or circumstances. Influence diagrams are used to represent information, alternatives, and preferences both graphically and mathematically. Our experience has shown that they are an effective way of communicating important issues among participants. Axotl also employs other forms of knowledge representation that may prove useful as part of a corporate memory facility. For example, Boeing has extended and generalized an AND/OR graph representation for goals and activities ("activity graphs") that can be used to dynamically construct and evaluate cyclic plans for achieving a set of process requirements.

Axotl is written in the ParkPlace Smalltalk-80 development environment on the Apple Macintosh II. Versions of Smalltalk-80 exist for Sun, Apollo, Hewlett-Packard, IBM, and Apple hardware.

5.3 MANIAC, HyperCard, and MacRecorder: Capturing Voice Rationale

Together, MANIAC, HyperCard, and MacRecorder were used to record and play back voice rationale.

In the first demonstration, design decision rationale was captured on a tape recorder during Aquinas sessions. To demonstrate feasibility, parts of these recordings were processed using MacRecorder on a Macintosh and stored in HyperCard. MANIAC, an Advanced Technology Center shell that controls communication between Axotl, Aquinas, HyperCard, and other application programs, receives commands from Aquinas to play back digitally recorded voice based on particular Aquinas knowledge base objects. Designers and others who later examine the trade study decision rationale can optionally play back this recorded voice information.

In future demonstrations we will link MacRecorder and Aquinas more directly so that designers may enter and edit voice input directly while using Aquinas. This will be a relatively unobtrusive way to enter rationale (as opposed to text entry) in a cost effective manner. Digitally recorded voice information could eventually be stored and played back as design decision rationale in TMIS in a manner similar to many digital phone message systems.

MANIAC is described more fully in (Bradshaw, Covington, Russo, and Boose, 1990).

5.4 CANARD: Exploratory Design Alternative Generation

As part of the design process, competing alternatives are generated and evaluated for suitability. The best alternative emerges as the result. Unfortunately, constraints, tradeoffs, and other considerations made during the exploration of the design are usually lost, making it impossible to review or easily modify them at a later time. If a modification to the design is required, the designers may have to redo the entire task.

We started development of CANARD, an automated tool which uses possibility tables, constraints, and knowledge bases to capture significant portions of the design process and assist in the generation of alternative solutions consistent with design goals and design constraints (Shema, Bradshaw, Covington, and Boose, 1990). Using a possibility table, a designer identifies the components of an acceptable design, specifies possibilities for each component, develops criteria reflecting preferences among possibilities, and supplies constraints governing compatibility between components and overall design considerations. The designer next interactively explores design alternatives by selecting possibilities for each component, modifying and/or adding components and possibilities as insight into the solution is gained. He then analyzes and stores the many alternative solutions for later retrieval.

For large problems, an iterative search procedure hypothesizes new constraints based on examples of previously-defined design alternatives, and proposes new design alternatives based on permutations of the constraint space. The tool keeps track of what has been tried and assists the designer in covering important aspects of the possible solution space.

CANARD is written in the ParkPlace Smalltalk-80 development environment on the Apple Macintosh II. Versions of Smalltalk-80 exist for Sun, Apollo, Hewlett-Packard, IBM, and Apple hardware.

6.0 Example Trade Study - Technical Audit Item #85

In 1989 a technical audit was performed on the Space Station Freedom for the program's content and implementation planning in relationship to performance, design, and validation requirements. One concern raised during the technical audit was a 1986 decision about the placement of the pressurized logistics module (PLM). Using Aquinas, we hoped to develop a process for capturing the decision rationale on this topic and similar ones.

First we described our problem and proposed process to a group of designers at Boeing in Huntsville, Alabama, who were or who are involved with the placement of the PLM. We then used Aquinas in two sessions with two teams of designers. One session lasted 1-1/4 hours, one session lasted 1-1/2 hours. We elicited trade study matrices from each team and combined the results, using Aquinas to show the combined rank-ordering. The decisions developed using Aquinas agreed with and documented the current placement of the PLM.

Here we describe the steps that were performed with Aquinas for the technical audit.

Step 1. Aquinas elicited nine alternative PLM locations from Team 1 (Node 1 Zenith, Node 1 Nadir, etc.).

Step 2. Aquinas elicited a preliminary set of decision criteria by using triadic comparison. Groups of three solutions were compared and designers were asked to give discriminating criteria:

> Think of an important new criterion that two of NODE.1.ZENITH, NODE.1.NADIR, and NODE .2.ZENITH share, but that the other one does not. What is that trait? (Enter a CR to skip over.)
> NEW TRAIT (EXTREME)** BETTER MSC REACH

What is that criterion's opposite as it applies in this case?
NEW TRAIT (OPPOSITE)** WORSE MSC REACH

What is the name of a scale or concept that describes BETTER.MSC.REACH / WORSE.MSC.REACH?
NEW TRAIT (CONCEPT)** MSC REACH

Think of an important new criterion that two of NODE.1.NADIR, NODE.2.ZENITH, and NODE.2.NADIR share, but that the other one does not. What is that characteristic? (Enter a CR to skip over.)
NEW TRAIT (EXTREME)** CLOSE TO HAB MODULE

What is that criterion's opposite as it applies in this case?
NEW TRAIT (OPPOSITE)** FARTHER FROM HAB MODULE

What is the name of a scale or concept that describes CLOSE.TO.HAB.MODULE / FARTHER.FROM.HAB.MODULE?
NEW TRAIT (CONCEPT)** HAB MODULE PROXIMITY

Step 3. The designers rated each alternative on each criterion. By default, Aquinas supplies ordinal scales from 1 to 5. Designers may change the scale type (to nominal, interval, or ratio) or range for convenience or more precision.

Step 4. The designers assigned a relative weight to each criterion. At this point an initial trade study matrix was complete (Figure 3).

1	2	3	4	5	6	7	8	9	TEAM.1. SOLUTION TRAIT
4	1	4	1	2	3	2	2	1	1. (5) MSC.REACH: BETTER.MSC.REACH(1)/ WORSE.MSC.REACH(5) [ORDINAL 1]
4	4	1	1	1	4	3	2	2	2. (1) HAB.MODULE.PROXIMITY: CLOSE.TO.HAB.MODULE(1) / FARTHER.FROM.HAB.M
1	1	1	1	2	4	4	4	4	3. (3) CG.SHIFT.IMPACT: LESS.CG.SHIFT(1) / GREATER.CG.SHIFT(5) [ORDINAL 1]
4	4	1	1	1	5	5	4	4	4. (1) JAPANESE.MODULE.PROXIMITY: CLOSER.TO.JAPANESE.MODULE(1) / FARTHER
2	1	2	1	5	4	4	5	4	5. (2) GROWTH./PATH: BETTER.FOR.GROWTH.PATH(1) / WORSE.FOR.GROWTH.PATH(
5	5	5	5	5	3	3	3	1	6. (5) PAYLOAD.BAY.BLOCKING: BLOCKING.PAYLOAD.BAY(1) / NOT.BLOCKING.PAYL
1	5	1	5	3	1	3	3	5	7. (4) EXPOSURE.TO.MICRO.METEOROIDS: MORE.EXPOSURE.TO.MICRMETEOROIDS(

1. NODE.1.ZENITH
2. NODE.1.NADIR
3. NODE.2.ZENITH
4. NODE.2.NADIR
5. NODE.2.PORT
6. NODE.3.ZENITH
7. NODE.3.STARBOARD
8. NODE.4.PORT
9. NODE.4.NADIR

TEAM.1.SOLUTION

Figure 3. Initial technical audit trade study matrix from Team 1.

Step 5. The designers used several of Aquinas' analysis tools to discover patterns in the collected information. Implication analysis showed logical generalizations that, for this application, provided a sanity check. A cluster analysis and similarity analysis showed the degree of similarity and redundancy between alternatives and between criteria.

Step 6. Aquinas scored the alternatives by eliciting preferred criteria values from the designers. For example, the designers said they would prefer alternatives that were *better for the station growth path* and had *less effect on the station center of gravity*. For Team 1, Aquinas produced the following results:

1 : NODE.2.NADIR	(1.00)
2 : NODE.1.NADIR	(0.93)
3 : NODE.2.PORT	(0.71)
4 : NODE.2.ZENITH	(0.61)
5 : NODE.4.NADIR	(0.54)
6 : NODE.1.ZENITH	(0.54)
7 : NODE.4.PORT	(0.48)
8 : NODE.3.STARBOARD	(0.48)
9 : NODE.3.ZENITH	(0.31)

Step 7. The second team used Aquinas to independently develop and analyze their own trade study matrix.

Step 8. Both matrices were combined and Aquinas again scored the alternatives, this time showing the *consensus* scores as well as the contributions from both individual teams. The teams are weighted in this example for purposes of illustration (Team 1 has received a weight of 40%, Team 2 a weight of 60%). Teams or individuals may be weighted for technical or other reasons.

Combined results:

1	NODE_2_NADIR	0.89	TEAM_1	1.00	40%	TEAM_2	0.82	60%
2	NODE_1_NADIR	0.81	TEAM_1	0.93	40%	TEAM_2	0.73	60%
3	NODE_2_PORT	0.71	TEAM_1	0.71	40%	TEAM_2	0.70	60%
4	NODE_2_ZENITH	0.64	TEAM_1	0.61	40%	TEAM_2	0.65	60%
5	NODE_1_ZENITH	0.55	TEAM_1	0.54	40%	TEAM_2	0.56	60%
6	NODE_4_NADIR	0.48	TEAM_1	0.54	40%	TEAM_2	0.44	60%
7	NODE_4_PORT	0.43	TEAM_1	0.48	40%	TEAM_2	0.39	60%
8	NODE_3_ZENITH	0.40	TEAM_1	0.31	40%	TEAM_2	0.46	60%
9	NODE_3_STARBOARD	0.28	TEAM_1	0.48	40%	TEAM_2	0.15	60%

Given this information, Aquinas displayed the most dissenting opinion beside the consensus. The dissenting opinion is found by computing a correlation score between each team and the consensus; the team with the lowest correlation score is listed as the dissenting opinion. Dissenting opinions show the user the range of opinion about a decision, not just the top rated list. In this case, both teams showed a high correlation - both teams were in substantial agreement. This can give the user confidence that the top rated alternatives were sound choices.

Correlation scores for all experts:

TEAM_2	.96
TEAM_1	.90

TEAM_1 has the most dissenting opinion.

TEAM_1	/	Consensus
1 : NODE_2_NADIR 0.81	/	NODE_2_NADIR 0.89
2 : NODE_1_NADIR 0.72	/	NODE_1_NADIR 0.81
3 : NODE_2_PORT 0.71	/	NODE_2_PORT 0.71
4 : NODE_2_ZENITH 0.66	/	NODE_2_ZENITH 0.64
5 : NODE_4_NADIR 0.62	/	NODE_1_ZENITH 0.55
6 : NODE_1_ZENITH 0.42	/	NODE_4_NADIR 0.48
7 : NODE_3_STARBOARD 0.41	/	NODE_4_PORT 0.43
8 : NODE_4_PORT 0.34	/	NODE_3_ZENITH 0.40
9 : NODE_3_ZENITH 0.21	/	NODE_3_STARBOARD 0.28

Voice capture. Decision rationale was captured as voice input for both teams. Decision rationale included descriptions of the overall problem, rationale for narrowing the alternatives to those appearing in the matrix, assumptions underlying decisions, definitions of alternatives and criteria, reasons for assigning particular ratings and criteria weights, and realistic assumptions concerning constraints and tradeoffs. Of particular interest were situations where members of the same team initially disagreed and eventually reached consensus. These discussions, when played back, are particularly illuminating for decision makers and others who may need to update trade studies when requirements change.

Near-future capability. We will be building a TMIS-based menu query mechanism that would be able to answer several types of questions about a trade study:

Q. Why did NODE.2.ZENITH do better than NODE.1.ZENITH?
A. It rated higher on CLOSE.TO.HAB.MODULE (1 vs. 4 on a scale of 1 to 5) and CLOSE.TO.LAB. MODULE (1 vs. 4 on a scale of 1 to 5)

Q. Why did NODE.1.NADIR and NODE.2.NADIR do better than NODE.1.ZENITH and NODE.2.ZENITH?
A. They always rated higher on BETTER.MSC.REACH, BETTER.FOR.GROWTH, and LESS.EXPOSURE.TO.MICROMETEOROIDS.
They sometimes rated higher on CLOSE.TO.HAB.MODULE and CLOSER.TO.JAPANESE.MODULE.

Q. If LESS.EXPOSURE.TO.MICROMETEOROIDS were the only criterion, how would the alternatives be ranked?
A. 5: NODE.1.NADIR, NODE.2.NADIR, NODE.4.NADIR
4: -
3: NODE.3.STARBOARD, NODE.4.PORT
2: NODE.2.PORT
1: NODE.1.ZENITH, NODE.2.ZENITH, NODE.3.ZENITH

Q. What criteria most discriminate between the alternatives?
A. GROWTH.PATH, MSC.REACH (TEAM_1), SUPPLY.ROUTE , TRAFFIC.PATTERN (TEAM_2)

7.0 Discussion

7.1 Project Benefits

NASA concluded that "the Aquinas-based methodology was appropriate for effecting most of the rationale capture required for the Space Station Freedom Program, and was especially well suited to trade studies" (Freeman, 1989). They felt that "the captured rationale will be an invaluable resource for the Space Station Freedom Program over its entire lifetime by providing immediate, reliable access to how and why important decisions were made." Benefits of rationale capture were listed as:

a. Better, more reliable design
  - More comprehensive identification of alternatives
  - Explicit rationale can be analyzed, discussed, and agreed upon
  - Design is less "scenario dependent"
b. Reduced development cost
  - Design review will be greatly enhanced, resulting in fewer costly and risky "fixes" late in the program
  - Reduced reliance on inefficient and less effective paper-based methods
  - Less need to pull people in for a meeting to reach an understanding of design elements
c. Reduced cost for operations and maintenance
  - Immediate, full access is provided to the designer's rationale in considering repairs or procedures which deviate from "standard"
d. Reduced cost for follow-on design efforts of the Space Station Freedom Program
  - Evolutionary design and augmentations do not have to "reinvent the wheel" by reconstructing the original design rationale, even if the designers have been unavailable for ten, twenty, or thirty years.
e. Reduced cost for design of similar artifacts
  - Mars mission, lunar colony

Based on this work, NASA is sponsoring the development of a Design Alternatives Rationale Tool (DART) for use on the Space Station Freedom Program. It will be based on extended repertory grids and other methods and will be specialized design for rationale capture. NASA plans to use DART during the preliminary design review for the Space Station Freedom. Like Aquinas, DART could also find use as a general decision aid, a group decision tool, a feasibility assessment aid, and as a knowledge engineering tool. Eventually, NASA would like to use captured rationale to support knowledge-based systems including an Intelligent Design Assistant for Evolutionary Design (Freeman, 1989).

We are continuing to study and model the trade study process. This should lead to further improvements in quality and efficiency. In particular we will (1) recommend a process for making voice playback available over TMIS, (2) help NASA establish guidelines and standards for criteria weights and alternative ratings, and (3) help NASA develop standard criteria templates and checklists to make trade studies more complete and consistent across the Space Station Freedom Program.

7.2 Summary

The Boeing Advanced Technology Center is conducting research leading to a corporate memory facility. A corporate memory facility would provide facilities for capturing and using decision history and rationale throughout a major program's life cycle.

Initially the Advanced Technology Center is preparing corporate memory facility technical reports and building feasibility demonstrations. In conjunction with NASA, The Space Station Freedom Program was selected as an application; within this domain we are concentrating on design knowledge capture. We examined aspects of the Power subsystem and the Environmental Control and Life Support (ECLS) subsystem. We also participated in one aspect of the Space Station Freedom technical audit.

Significant progress was made in helping automate the process of performing engineering trade studies. Other steps in the design knowledge cycle - alternative generation, comparison, evaluation, and documentation - were also demonstrated. In the next phase we will continue to extend our tools to further automate trade studies, strengthen our links to TMIS, and continue work on CANARD.

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