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An Empirical Evaluation of Graphical Interfaces to Support Flight Planning

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Abstract

Whether optimization techniques or expert systems technologies are used, the underlying inference processes and the model or knowledge base for a computerized problem-solving system are likely to be incomplete for any given complex, real-world task. To deal with the resultant brittleness, it has been suggested that "cooperative" rather than "automated" problem-solving systems be designed. Such cooperative systems are proposed to explicitly enhance the collaboration of people and the computer system when working in partnership to solve problems.

This study evaluates the impact of alternative design concepts on the performance of airline pilots interacting with such a cooperative system designed to support enroute flight planning. Thirty pilots were studied using three different versions of the system. The results clearly demonstrate that different system design concepts can strongly influence the cognitive processes of users. Indeed, one of the designs studied caused four times as many pilots to accept a poor flight amendment. Based on think-aloud protocols, cognitive models are proposed to account for how features of the computer system interacted with specific types of scenarios to influence exploration and decision-making by the pilots. The results are then used to develop recommendations for guiding the design of cooperative systems.

Introduction

In this study, three alternative designs for a cooperative problem-solving system (Robertson, Zachery and Black, 1990) were empirically evaluated. All three designs provided support for the task of enroute planning for commercial aviation flights. They differed in terms of the timing and degree of assistance provided by the computer.

The goals of the study were three-fold:

1. To gain a better understanding of how people perform adaptive planning tasks;
2. To increase our understanding of how alternative system designs influence the cognitive processes of users during such planning tasks;
3. To develop recommendations to guide in the design of advanced tools to support pilots and dispatchers in their flight planning activities.

The Context

Enroute flight planning involves the modification of the flight plan of an airborne aircraft in response to problems with weather, air traffic, medical emergencies, mechanical failures, etc. The flight crew, air traffic controllers and airline company dispatchers all play important roles in this planning process.

Figure 1 shows the relationships between the various components of the planning environment, with the flight plan as the central unifying element of the components. The flight plan stipulates what altitude and heading the plane will fly during various phases of the flight and what routes the plane will take. The route in turn determines the weather that will be encountered along the way. Similarly, the weather affects the speed, safety, and efficiency of the plane, as well as passenger comfort. The capabilities of the plane partially determine what weather must be avoided and what routes may be flown. There are several more relationships that could be pointed out, but they are not central to our discussion.

Insert Figure 1 about here

The planner, then, is concerned with getting from a given origin to a given destination in a timely fashion and with a minimum of fuel consumed, while maintaining flight safety and passenger comfort. The planner must consider what routes to take (these routes consist of waypoints, or navigational points, and jet routes, the so-called 'highways in the sky' that connect the waypoints), what altitudes to fly, what weather to avoid (including winds, thunderstorms, freezing rain, and turbulence), and he/she must consider the ever changing capabilities of the plane (for example, the weight of the plane decreases as more fuel is consumed; the lighter the plane, the higher it can fly).

The initial flight plan is rarely followed exactly, due to unforeseen events occurring while enroute. Indeed, minor changes in flight plans are frequently made and major changes are fairly common.

These amendments to the original plan are due to the dynamic, unpredictable nature of the "world" in which the plans are carried out. Weather patterns do not always develop as predicted, resulting in unexpected areas of turbulence, less favorable tail winds or storms that must be avoided. Air traffic congestion may delay take-off or restrict the plane to lower than planned altitudes.

Airport or runway closures can cause major disruptions, not just for one aircraft, but for everyone planning on landing at that airport. Mechanical failures, medical emergencies or other critical problems may force the plane to divert to a nearby airport.

Enroute flight planning can be represented as search through a hierarchy of problem spaces (Laird, Newell, and Rosenbloom, 1987). When a problem arises, as described above, the flight crew must come up with a revised flight plan. To select this revised plan, a variety of alternative solution paths may be considered.

A state description for one possible problem space representation consists of:

1. The plane's current location (a point along its route and an altitude), airspeed, and attitude (direction of travel);
2. The flight's currently approved plan;
3. Static and dynamic characteristics of the plane, such as its weight, its maximum altitude capabilities, its fuel consumption characteristics, etc. Characteristics that are normally considered static may in some cases change because of a problem such as engine failure;
4. Actual and forecast weather along the plane's current route and any possible alternate routes. The state description needs to include measures of uncertainty about weather forecasts, as well as the best "guess" of what the weather will be;
5. Information on passenger connections and flight crew availabilities;
6. Static and dynamic characteristics of airports that could be used for landing (runway lengths, visibility, air traffic congestion, etc.);

7. Similar information for any other planes whose paths could interact with possible alternative paths for the plane of concern.

(This is a simplified summary of a state description.)

Major operators include:

1. changing altitude;
2. changing airspeed;
3. changing the route;
4. changing the destination (a special, but important, case of changing the route).

Each of these operators can be applied to either the plane of concern, or to another plane with which its plan interacts. Furthermore, the first three operators can be applied to different segments of the flight. For example, the plane may fly at 33,000 feet from Milwaukee to Chicago, but at 25,000 feet from Chicago to St. Louis.

There are also a number of constraints. Planes must maintain a certain separation distance between both each other and thunderstorm cells (according to the Federal Air Regulations). Planes often fly along the jet routes and are also constrained to fly at certain altitudes. Over the continental U.S., for instance, 33,000 feet is an "eastbound only" altitude. There are also physical limitations. The plane can't fly if it is out of fuel and it can't land at an airport with runways that are too short.

Some of these constraints are actually "soft", in that they may be violated in some circumstances. If, for instance, there is no eastbound traffic, Air Traffic Control (ATC) may allow a plane to fly west at an "eastbound only" altitude. Similarly, ATC may approve a vector that deviates from the jet routes in order to avoid a storm or save fuel.

Description of the state spaces, operators, and constraints is difficult because there are so many possibilities to consider. Definition of the evaluation function for selecting among operators is even more challenging, however. It is clear that multiple competing and complementary goals are considered (Wilensky, 1983) in evaluating preferences among alternative operators (or operator sequences). Safety, fuel consumption, time, and passenger comfort are all important considerations. It is not as clear, though, exactly how human planners currently deal with tradeoffs among these goals.

In short, the full problem space for enroute flight planning is very large and complex. Multiple goals must be considered in a highly stochastic environment where multiple plans must be coordinated.

Background

There are several areas of research which have a bearing on the current effort. Among these are computational approaches to planning, models of human planning, human-human cooperative problem solving, group problem solving, and human-machine cooperative problem solving (including decision support systems). Some of the pertinent literature for each of these areas is discussed below.

In the following, the terms 'plan' and 'subplan' are used interchangeably; technically, a subplan is subordinate to a plan, but because the scale is relative, it is often easier to simply use the term 'plan'. It should be understood that all plan units can be viewed as subordinate to a larger plan.

Models of Planning

A common belief is that it is necessary to plan activities in order to make the most efficient use of one's time. It is therefore common to see planning supports such as the Day-Timer® and the Franklin Day Planner®. Indeed, the rationality of human behavior is often judged by whether or not that behavior fits in a logical plan. Furthermore, planning has been of interest to artificial intelligence (AI) researchers because of the challenges it presents and because of its close association with problem solving in general.

But how can planning be modeled by computational methods and what do these models have in common with human planning? Below we discuss some of the efforts to address these questions.

First, models developed by Miller, Galanter and Pribrum (1960), Sacerdoti (1974), Hayes-Roth and Hayes-Roth (1979), Suchman (1987), and Wilensky (1983) are discussed. Two simple operational definitions taken from Cohen and Feigenbaum (1982) will help in this discussion. A plan is "a representation of a course of action" and planning is "deciding on a course of action before acting" (p. 515).

Miller, Galanter, and Pribram. In 1960, Miller, Galanter, and Pribram began to lay a foundation for understanding human planning activities. The authors viewed humans as information processors, and their definition of a plan was "any hierarchical process in the organism which can control the order in which a sequence of operations is to be performed," (p. 16). This definition is slightly more restrictive than the one previously stated in that it stipulates a particular process for controlling action.

According to Miller, et al., a plan may range from an outline of activities to a sequence of operations. The outline of activities was termed the 'strategy', while the exact operations were called 'tactics'. Plan 'execution' referred to the control of operations by the plan. A final aspect of the Miller, et al., view of planning was the 'image', which was defined as "all the accumulated, organized knowledge that the organism has about itself and its world" (although the knowledge wasn't necessarily 'imaginal' in the sense of representing visual information).

Miller, et al., were concerned with how plans controlled behavior and with how plans interacted with images. The authors postulated a basic plan unit, called the "Test-Operate-Test-Exit (TOTE) unit", which could serve both as a representation for plan knowledge and as a controller of behavior. The 'Test' phase checks for congruity between the desired state and the current state, while the 'Operate' phase constitutes the execution of an action to achieve the desired state. The action is repeated until the desired state is achieved.

According to Miller, et al., the power of such a representation lies in the ability to put other TOTE units in the operate phase of higher order units, thus nesting the TOTE units. Their representation for driving a nail is shown in Figure 2.

Insert Figure 2 about here

Miller, Galanter, and Pribram (1960) raised some interesting issues in planning, such as competition between plans, processing/memory limitations, plan flexibility in the face of uncertainty, planning among multiple agents, meta-planning (reasoning about plans), and adapting stored plans to new situations. Many of these issues were not addressed again until the work of Wilensky (1983).

Although the hierarchical notions put forth by Miller, et al., are appealing, the authors didn't explain how plans are generated, how sequences of actions are determined, or how information in the 'image' can be used to determine when it is necessary to change a plan. The authors also failed to mention goals and their relationship to plans. This relationship was made explicit by the computational approaches to planning that followed.

The ABSTRIPS Model. As psychologists, Miller et al. were concerned with modeling human performance. It is interesting to contrast the emphasis of this type of model with models developed by AI researchers, such as Sacerdoti (1974). ABSTRIPS (Sacerdoti, 1974) is a hierarchical planner that generates a hierarchy of representations for a plan. The highest representation in the hierarchy is an abstraction (simplification) of the plan, and the lowest representation is a detailed list of actions required to solve the problem. Goals, objects, and/or operators may be abstracted. The purpose of such abstractions is to discriminate between items that are crucial to the success of a plan and those items that are details (i.e., tasks that are likely to be taken care of in a number of ways). ABSTRIPS first works at achieving the critical plan elements and then successively incorporates further levels of detail.

ABSTRIPS' planning begins with a complete plan at the highest abstraction, which is then progressively refined until a detailed successful plan is achieved. If a plan fails at one level of abstraction, the planner backs up to higher levels of abstraction until it reaches a choice point and then it takes a different path. Each level of abstraction contains all of the objects and operators given in the initial state (or ground space).

A predetermined (coded) partial ordering of preconditions is supplied to the program by the programmer/knowledge engineer, along with initial criticality (importance) values. ABSTRIPS then adjusts these values. The adjustment procedure is: All preconditions whose truth value cannot be changed by any operator in the domain are assigned a maximum criticality value. For each of the remaining preconditions, if a short plan can be found to achieve it (assuming all previous processed preconditions are true), it is assumed to be a detail and is assigned a criticality equal to its rank in the partial order. If such a plan can not be found, the precondition is given a criticality greater than the highest value in the partial order.

ABSTRIPS - An Example. The ABSTRIPS planner comes from the domain of 'robot navigation', in which one is concerned with moving a robot between adjacent rooms and using the robot to move boxes. Although the following example plan, adapted from Cohen and Feigenbaum (1982), is not of robot navigation, it will help illustrate the ABSTRIPS model:

> "Consider now the problem of getting a cup of coffee. You go to the kitchen and if coffee is made, you pour some. If not, you make some or go out to buy some. If you decide to make some, but there are no coffee beans or ground coffee, you go to the store to get some. If you have no money, you go to the bank first." (p. 523).

The relevant objects to be planned about are presented in Table 1.

Insert Table 1 about here

Some of the operators (methods of action) and their preconditions and postconditions are presented in Table 2.

Insert Table 2 about here

Finally, the initial state is not having brewed coffee, and the goal state is a cup of brewed coffee.

In this example, one might suppose that the most important precondition is that a place exists, since operators that depend on that place can only be used if it exists. Furthermore, one might suppose that having something is the next most important precondition, and finally, that being somewhere is the least important, since it is most easily changed. The initial partial ordering supplied to ABSTRIPS is shown in Table 3.

Insert Table 3 about here

Following this reasoning, *bank exists, coffee-bean store exists, brewed-coffee store exists,* and *kitchen exists* are all assigned a maximum criticality (3 for now) because their truth cannot be changed by any operator (note that *grinder store exists* has not been processed). *Have beans, have boiling water,* and *have money* all can be achieved by a short plan, given that the previous preconditions are true; therefore, they are assigned a criticality of 2 (equal to their rank). However, *have grinder* cannot be achieved by a simple plan because the grinder store does not exist. Therefore, *have grinder* is given a criticality of 4 and the *exists* preconditions are moved up to a value of 5. All of the *be somewhere* preconditions are assigned a value of 1 (equal to their rank in the initial partial order). These values are summarized in Table 4.

Insert Table 4 about here

After assigning all criticality values, ABSTRIPS begins to plan at the highest level of abstraction (criticality 5). It assumes that all preconditions with lesser criticality are true. Thus, for the goal of having brewed coffee, ABSTRIPS finds two possible plans to achieve it: make coffee and buy coffee. ABSTRIPS initially tries to make coffee. Once it has achieved a complete plan at this level, it moves down one level of abstraction and formulates a plan including all higher levels of abstraction, and so on until the goal is achieved or a dead-end is reached. In this case, since the grinder store does not exist, ABSTRIPS backtracks through abstraction levels to the last choice point and pursues the plan of buying brewed coffee and succeeds.

ABSTRIPS - Contributions. The use of hierarchical abstraction spaces can facilitate finding dead-ends early, so that the amount of backtracking may be reduced compared to non-hierarchical planners (which treat all subgoals as having equal import). This fact is important because the less backtracking the planner has to do, the faster a satisfactory plan can be found. If the solution space is very large, such efficiency may be important.

Thus, the introduction of the concept of an abstraction hierarchy was one of the most significant developments of early computational planning work. Indeed, nearly all planners developed since ABSTRIPS have incorporated abstraction hierarchies because of their power in reducing search.

Furthermore, ABSTRIPS was designed to accomplish multiple, non-interacting goals, while a number of previous planners could not handle more than one goal at a time. By pursuing multiple goals, ABSTRIPS takes a step toward being more 'human-like' than previous planners.

Finally, the ABSTRIPS approach is relatively domain independent, so one could use it as a general purpose planning system in a variety of domains (provided one wanted to spend the time to represent the domain appropriately).

ABSTRIPS - Limitations. ABSTRIPS could have trouble with conjunctive goals that interact. Although it is possible to represent the domain such that ABSTRIPS implicitly considers such interactions by setting up one goal as a precondition for another, such ordering may not be possible with all domains. In such cases, the planner would have to be able to abandon or relax some of the goals/constraints.

Additionally, it is unlikely that people plan in the strictly top-down manner used by ABSTRIPS. Exclusive top-down planning can be inefficient in many situations (e.g., in errand running tasks). Such 'non-human' behavior may affect the acceptability of the plans produced by such planning systems or the acceptability of interactions with such systems (e.g., explanations produced to justify the recommended plan).

Unlike top-down planners, people frequently recognize opportunities to achieve multiple goals when planning for a single goal. Thus, people are to some extent 'opportunistic', which leads to the planning model developed by Hayes-Roth and Hayes-Roth.

Hayes-Roth and Hayes-Roth - An Opportunistic Model. Hayes-Roth and Hayes-Roth (1979) studied human planning in a paper-and-pencil simulation of daily activities (running errands) and used the data obtained to develop a planning system that was very different from planners that had previously been developed. In a nutshell, the theory is that humans plan at multiple levels of abstraction simultaneously, and that some planning is in fact bottom up. If the opportunity presents itself to achieve a goal while working toward another goal, that opportunity will be seized (hence the term 'opportunistic planning'). In another typical behavior, 'island driving', the problem solver finds a correct solution to a subplan (island) and then extends problem solving to other subplans.

The system developed by the Hayes-Roths achieved an opportunistic style of planning by using a blackboard architecture with multiple representations of planning knowledge and multiple levels of abstraction within those representations. This architecture has its roots in the Hearsay-II speech understanding system (Erman, Hayes-Roth, Lesser, and Reddy, 1980). Planning therefore had bottom-up and top-down components, with specialists that recognized both opportunities to achieve task-specific subgoals and opportunities to achieve meta-planning goals (such as conserving resources).

Specifically, the authors assumed that many cognitive 'specialists' (a.k.a. 'demons') act independently in making decisions that are incorporated into a plan. Specialists record their decisions on a common blackboard so that these decisions are made available for other specialists to use. The blackboard consists of five 'planes' which represent different conceptual categories of planning:

1. the 'plan' plane consists of actions that the planner intends to take;
2. the 'plan-abstractions' plane contains desired attributes of plan decisions;
3. the 'knowledge-base' plane consists of information about relationships in the world;
4. the 'executive' plane contains decisions about the allocation of planning resources; and,

5. the 'meta-plan' plane consists of decisions about the planning process in use (i.e., the type of problem under consideration, the methods being used, evaluation criteria, etc.).

These planes are further divided into levels of abstraction peculiar to each plane. According to Hayes-Roth and Hayes-Roth, these abstraction levels provide a taxonomy of the decisions made and they restrict the number of prior decisions that must be considered by individual specialists.

The cyclical planning process is controlled by the executive plane, which decides which one of the triggered specialists to fire during each cycle. The process repeats until a complete plan is developed, until a plan satisfies 'important evaluation criteria', or until failure.

Contributions. The more significant contribution of this work was the introduction of the idea of planning at multiple levels of abstraction simultaneously. This allows a planner to capitalize on relationships in the environment when they are noticed. In other words, some components of human planning are no doubt bottom-up; presumably, this yields more efficient planning in some cases.

Another benefit of the Hayes-Roth and Hayes-Roth model is that it uses multiple descriptions of the planning process. Thus, the planner can reason about aspects of the environment or the planning process which aren't directly associated with the plan itself. For example, the planner may notice that there are multiple errands in the southeast corner of the city, or that pursuing a particular aspect of the plan will require too many cognitive resources.

Limitations. From the standpoint of the present work, there are two drawbacks to this model. First, the planning task was very simple: There were no significant constraints on errands. The only factor that typically constrains errand planning, time, was removed from the experiment.

Second, all planning work was undertaken in advance of acting (in fact, the subjects never were required to enact their plans), whereas humans tend to develop loose plan structures and rely on specific environmental feedback during plan execution to guide them in the details. As previously discussed, the act of carrying out one's plans frequently leads to replanning. The 'think then act' problem is endemic to all computational planners, and more will be said about it later. It bears mentioning here because of the claims made by the Hayes-Roths and because it is precisely the issue brought up by Suchman (discussed below).

Suchman - The Situated Action Model. Like the Hayes-Roths, Suchman (1987) has also been involved in analyzing everyday actions. From Suchman's point of view, most activities revolve around direct interaction with the environment and relatively little behavior is extensively planned. Suchman forcefully argues her views in the following paragraphs from the preface of her book:

> "...however planned, purposeful actions are inevitably *situated actions*....actions taken in the context of particular, concrete circumstances...[T]he circumstances of our actions are never fully anticipated and are continuously changing around us. As a consequence our actions, while systematic, are never planned in the strong sense that cognitive science would have it. Rather, plans are best viewed as a weak resource for what is primarily *ad hoc* activity. It is only when we are pressed to account for the rationality of our actions...that we invoke the guidance of a plan. Stated in advance, plans are necessarily vague, insofar as they must accommodate the unforeseeable contingencies of particular situations. Reconstructed in retrospect, plans systematically filter out precisely the particularity of detail that characterizes situated actions, in

favor of those aspects of the actions that can be seen to accord with the plan." (pp. viii-ix).

Contributions and Limitations. Suchman's point that most plans serve primarily as a framework for situated action is well taken. It is certainly true of a lot of behavior, such as in the human-machine interaction studies which she carried out, and there is a tendency for people to ascribe to notions of plans in order to rationalize behavior. But it is precisely this framework that is under consideration. Furthermore, there are domains and activities that require considerable detailed planning before actions can be initiated. Successful businessmen and businesswomen certainly do not decide to introduce a new product on a whim. Rather, they carry out market surveys, determine the cost of production, analyze the actions of their competitors, and determine what effects the sale of the new product will have on profit margins, long term equity, goodwill, etc.

Enroute flight planning makes use of both plans and situated action. Flight planning is a complex activity characterized by multiple interacting goals and constraints. Furthermore, because airplanes travel at a relatively high rate of speed (thus there is sometimes rather little time available for planning), pilots, dispatchers, and ATC must have some relatively detailed contingency plans developed prior to actually using them. Indeed, pilots are *required* to have such contingency plans prior to taking off. However, such planning is a somewhat separate activity from the moment by moment actions required to keep the wings level and keep the aircraft on course. In this view, Suchman's conceptions can be seen to fit nicely within the purview of the Executor in Wilensky's (1983) model: The Executor fills in the necessary details of a plan in carrying it out.

Wilensky. In 1983, Wilensky described a more comprehensive approach to computational planning. He proposed that an efficient planner would have plan frameworks stored in memory that could be retrieved according to the goal which they achieved. The planner would be able to reason about the future and how the future would be affected as a result of planned actions. The planner would also be able to develop new goals based on the situations in which it found itself.

Furthermore, the planner would be able to detect interactions between subgoals and to plan according to those interactions by relaxing or abandoning some of its subgoals or by trying to achieve multiple subgoals at the same time. The planner should also be able to take into account the goals and actions of other agents. Some of the details of a plan would not be able to be decided upon until plan execution. Finally, the planner should be able to reason about the plans themselves, thus performing meta-planning. Meta-planning would be concerned with conserving resources, achieving as many goals as possible at the same time, maximizing the value of the goals achieved, and avoiding impossible goals.

The components of Wilensky's planning system are described as follows:

"1. Goal Detector--This mechanism is responsible for determining that the planner has a goal...[T]he Goal Detector notices situations...that have arisen that are relevant to the planner...

2. Plan Proposer--This component's task is to find stored plans relevant to current goals...The Plan Proposer is also responsible for expanding plans into component plans...for further planning or execution...

3. Projector--The purpose of this component is to test plans by building hypothetical world models...[T]his ability is used to debug current plans by simulating a future that may contain undesirable elements, thus enabling the goal detector to form new goals...

4. Executor--...[T]he Executor tries to carry out the sequence of intended actions...This may require expanding plans to a level of detail at which they can be directly executed and detecting interactions only noticeable at this level." (p. 22).

These components interact as shown in Figure 3.

Insert Figure 3 about here

Contributions. Wilensky is to be commended for his efforts to model many of the components which make up human planning activities. Particularly notable are his efforts to include multiple agents, stored plans, the effects of the planner's actions on the world, subgoal interactions, and the uncertainties involved in plan execution. His model goes beyond studying one major aspect of planning in isolation of others.

Limitations. As a conceptual model, it is hard to find fault with Wilensky's framework. On the other hand it is likely that such a comprehensive approach to planning would be difficult for anyone to implement for significant real-world (as opposed to toy) planning tasks.

Operations Research Models. In contrast to these symbolic reasoning models, the field of operations research has developed quantitative tools to help with planning activities. These may involve the use of linear programming techniques or decision analytic approaches (Holzman, 1989). They require detailed mathematical descriptions of the decision problem, and in one sense or another seek optimal plans or solutions, thus contrasting with AI approaches which generally are satisfied with computational methods that produce "good" rather than optimal solutions.

Models of Planning - Conclusion. Research such as that described above has had a major impact on our understanding of planning. It has served to provide a conceptual framework for understanding the task of planning, as well as to outline different strategies for accomplishing such tasks, including strategies applied by human planners. As will be described later, these insights were of great value in guiding our system development efforts.

Cooperative Problem Solving Systems

Cooperative problem solving is really an extension of past efforts at joint human-machine problem solving, but with a shift in emphasis away from machine-dominated approaches. This shift in emphasis has been fairly recent, so relatively few studies have been conducted on cooperative problem solving systems. However, there have been some conclusions drawn from this and related work which indicate what types of system characteristics may be beneficial to cooperative problem solving.

Decision Support Systems. Decision support systems (DSS) are an outgrowth of management information systems (MIS) in the decision science and business communities. Whereas MISs are typically automated methods for monitoring and summarizing financial data without interpretation, DSSs use these data along with a model of aspects of a given enterprise and of the external environment to provide managers with feedback to hypothetical situations. For example, a company may use a decision support system to help determine the pricing for a new product in a competitive environment. DSSs are typically used for strategic planning (long range planning--over two years) and management control/tactical planning (moderate term planning--approximately six months to two years) in business environments.

There is a wide range of software programs that have been labeled decision support systems. For example, Thierauf (1988) lists report generators, electronic spreadsheets, financial planning languages, and statistical analysis packages as types of decision support systems. A DSS developer may work at a terminal connected to a mainframe and use a shell, called a DSS generator, specifically designed for producing decision support systems, or he/she may work at a personal computer using Lotus 1-2-3. Similarly, the developer may be a manager/end-user of the DSS, or he/she may be a DSS builder/knowledge engineer called in to assist in the project.

The general design principles for such systems tend to be rather vague. Authors tend to use blanket statements such as "use up-to-date information", "the system should respond in a timely manner", and "present information in a concise and appropriate manner" (which often means graphically) (cf. Bidgoli, 1989; Holsapple and Winston, 1987; Davis, 1988; Thierauf, 1988).

As an example, Hall (1988) developed a decision support system and studied its effect on strategic planning. The author found that those subjects who used the system developed much better strategic plans than those who did not (according to independent judges), and that managerial experience did not play a role. Hall did not study *how* behavior changed as a result of using the decision support system.

Human-Machine Cooperative Problem Solving Studies. There are several studies which are particularly relevant to cooperative problem solving. Coombs and Alty (1984), although they didn't study human-computer cooperative problem solving, identified possibly desirable aspects of the approach; Shute and Smith (in press) similarly studied human-human cooperative problem solving, but had results which differ from those of Coombs and Alty; Mitchell and Saisi (1987) studied a cooperative system for satellite information display and control; Suchman (1987, already discussed in the context of computational approaches to planning) studied interactions with an 'expert' copier; Roth, Bennett, and Woods

(1987) studied technicians using an expert system for fault diagnosis and repair; and Lehner and Zirk (1987) studied the effects of mental models of a computer's processing on performance. The first two studies were conducted on systems which were cooperative by design, while the Suchman and Roth, Bennett, and Woods studies were conducted on systems that were authoritarian by design, but became cooperative (actually, uncooperative) in practice.

Coombs and Alty. As mentioned, Coombs and Alty didn't study cases of human-machine cooperative problem solving; rather, they studied human-human interactions and discovered aspects of such interactions which may be of use in building a cooperative human-machine system. The authors suggested that human experts rarely are asked to give solutions to hard problems (which runs counter to the idea behind expert systems); instead, they are asked to provide assistance in promoting the understanding of a problem area. The following activities were said to aid in promoting understanding:

"a. providing relevant contextual information;

b. focusing attention on important topics in the subject area;

c. helping to predict outcomes of given processing circumstances." (p. 22).

In studying advisory interactions at a university computing center, the authors made two observations. First, interactions in which the advisor controlled the conversation were judged unsatisfactory, due in part to a lack of feedback and a lack of description of how information was being used in the reasoning process (or, indeed, what that process was). Second, advisory encounters that were judged as satisfactory were characterized by:

1. both parties sharing the advisor and client roles;
2. the parties keeping assumptions, information, and strategies explicit; and,
3. both parties gaining insights into problems and solution methods.

Shute and Smith. In contrast to Coombs and Alty, Shute and Smith (in press) studied human-human interactions between search intermediaries and information seekers in the domain of information retrieval. In this case, the expert search intermediary guided the interactions with the information seeker in order to better define the information seeker's interests. In particular, the intermediaries, who were experts in the subject matter of interest to the information seekers, devoted much of their time to teaching the information seekers about the subject area. They did so by suggesting related topics that might be of interest. Although the information seekers had control in the sense that they provided feedback to the intermediaries about the relevance of suggested topic refinements, the intermediaries largely controlled the conversations. Contrary to Coombs and Alty's conclusion, the information seekers were quite satisfied with such interactions.

Furthermore, the expert intermediaries automatically handled lower level details such as selecting appropriate commands (e.g.,. display all 1-3 or search water pollution/CV) or choosing appropriate logical operators (e.g.,. AND, WITH), often with little or no explanation to the information seeker. When explanation was provided, it was generally given in the form of tutoring (in case the information seeker had to do such a search on his/her own someday).

Such results suggest that acceptable roles and interaction styles are dependent on the nature of the task and the types of assistance available from the expert consultant.

Mitchell and Saisi. Mitchell and Saisi (1987) compared two different satellite display and control system designs. The first design was one actually used in satellite control and was characterized by a data availability approach to design (data availability designs essentially display raw data organized by data type). The second design centered on the activities of the operator. This system utilized analogical representations and integration of data, as well as adaptive collections of data (these collections were made at the operator's request and were sensitive to the state of the system). They found that operators trained on both systems performed much better overall on the second (activity-oriented) system than on the original system.

Suchman. Suchman (1987) studied interactions with a copier that gave 'expert' guidance for its use. Suchman observed that significant communication difficulties arose for novices. In general, she found communication failures due to ambiguous instructions, rigid procedures (unanticipated variability), a lack of direct access by the person to the machine's 'reasoning' processes, and a similar lack of access by the computer to the misunderstandings held by the person using the copier.

Roth, Bennett, and Woods. Roth, Bennett, and Woods (1987) found similar communication difficulties in a study of technicians using an expert system to trouble-shoot a malfunctioning device. These authors found that the technician's level of expertise and degree of active participation in problem solving greatly affected overall performance and success.

Lehner and Zirk. Lehner and Zirk (1987) studied the extent to which a person's mental model of an expert system's decision processes affected the joint performance of the person and expert system. Lehner and Zirk studied subjects in a simulated stock purchasing task. The authors found that *if* the subjects had a good model of the expert system's problem-solving approach, combined performance was better if the subject and computer used different problem-solving methods than if they used the same approach.

'Groupware'. An emerging field which is related to human-computer cooperative problem solving is the development of 'groupware', wherein a computer system serves as an intermediary between people working together on

problems. Electronic mail is sometimes called groupware, as it certainly does support the activities of multiple agents. However, groupware generally refers to software which is more task oriented than electronic mail. For example, Benson, Ciborra, and Proffitt (1990) developed a system to assist commercial airline pilots in the process of bidding for flights (pilots bid on which flights they wish to fly; flights go to the highest bidder).

Cooperative Systems - Discussion. As summarized earlier, studies of planning have served to identify considerations that should be addressed in developing computerized aids for planning. Studies of human-human and human-computer cooperative problem solving have identified additional questions, including:

1. Who should control the interactions and directions for exploration?
2. What expertise can the "client" bring to the problem solving process?
3. Is it possible to provide the computer with information/knowledge which may be beyond a given person's expertise?
4. Is there an opportunity to teach the human agent useful strategies?
5. What happens when the human agent has information which is not available to the computer?
6. What are the goals of the human user and how can the interface be organized around these?
7. Is the system robust/flexible to different problem solving styles?
8. Is the system robust to unanticipated variability?
9. Is it possible to provide the operator with an appropriate model of the computer's problem solving processes?

A great deal of research remains to be done to answer these questions (and to identify the contexts in which those answers are applicable).

Enroute Flight Planning Research

Additional related research includes an optimization approach to flight profile planning (OPTIM), a stand-alone enroute flight planner (Diverter), and a proposed cooperative system approach to enroute flight planning (Personalized Flight Replanner). These are discussed below.

OPTIM. Most flight planning systems to date have used optimization techniques to develop their plans and they have been concerned with preflight planning, as opposed to enroute planning. In fact there are many commercial systems that will allow a person to see weather information and develop flight plans; these systems will propose flight plans based on the performance characteristics of a given aircraft. Although these systems incorporate data on prevailing winds in such computations, they do not generally consider other weather concerns.)

OPTIM (Sorensen, Waters, & Patmore, 1983) was developed to generate near optimal vertical flight profile for a given aircraft over a given horizontal route (consisting of waypoints and jet routes) and with given winds and temperatures at the waypoints along the route. Specifically, OPTIM minimizes the output value of an algebraic function consisting of factors which specify the cost of fuel, the cost of time, the aircraft's fuel flow rate, the aircraft's ground speed, the aircraft's airspeed, the aircraft's thrust and drag coefficients, and the aircraft's weight; the ground speed is determined by the aircraft's velocity and the wind velocity. OPTIM was not concerned with how someone would come up with the necessary horizontal flight plan for input.

Diverter. Diverter (Rudolph, Homoki, & Sexton, 1990) represents an attempt to provide pilots with a system to develop appropriate plans for diversion to a new destination airport (as opposed to deviating enroute while maintaining the same destination airport). Diverter uses production rules, Air Traffic Control reports, aircraft system status, and a database of airfields and routes to reason about plans to alternative destinations. The production rules contain information on aircraft performance characteristics, Federal Air Regulations, and navigational and weather avoidance heuristics. For each diversion option, Diverter evaluates the runways, airfields, and routes independently based on a variety of factors (e.g., safety, weather, fuel consumption, etc.) and then combines these evaluations for a total diversion 'score'. The diversions are then rank ordered according their scores and the top option is selected by the computer and recommended to the pilot. The major drawbacks to Diverter are that:

1. Control is limited to assigning weights for the various attributes used in search;
2. Important criteria (such as passenger connections) are totally ignored by the system; and,
3. It provides no means for using it as a tool in which the human adds in considerations of additional criteria.

Personalized Flight Replanner. Cohen, Leddo, and Tolcott (1989), investigated a cooperative approach to enroute flight planning. They proposed a system in which, for each situation encountered, the pilot would be responsible for determining what parameters would affect enroute flight planning decisions and for determining the relative importance of those factors. The proposed system consisted of five modules:

1. a plan (bird's eye) view of the route, weather, air traffic, and airports;
2. an altitude (profile) view of weather and traffic;
3. an 'uncertainties' module, which would be used to evaluate conflicting evidence on the efficacy of routes (e.g.,report X indicates the storm will not reach the destination prior to arrival, report Y indicates that it will);

4. an 'evaluation' module for comparing options on the basis of their likelihood of achieving goals (e.g., route A will encounter moderate turbulence, but route B will consume too much fuel); and
5. a 'goals' module, where the pilot would set decision criteria for various flight parameters (e.g., fuel remaining should be greater than 6000 lbs. at the destination).

All of these modules would be cross-referenced and the pilot could request assistance from the computer for evaluating any of the modules or filling in flight parameters. While these are interesting ideas, this flight replanning system exists only as a paper mockup.

Background - Discussion

Above, three literatures were briefly reviewed. As discussed, publications on models of planning (by humans and by computers) provide important insights into the nature of planning as a task and into strategies for accomplishing such tasks. The literature on cooperative systems raises interesting questions that need to be considered when developing an interactive planning system. Finally, the literature on flight planning systems identifies some of the important factors to deal with in designing a system specifically for that task.

Below, we describe the design of a system based on the considerations suggested by these literatures. Then we present the results of an empirical study of three variations on this system design.

The Flight Planning Testbed - Design Features

The Flight Planning Testbed (FPT) was developed to test several cooperative planning system design concepts. This design was developed following an extensive cognitive task analysis (Smith, McCoy, Layton, and Bihari, 1992). The basic flight planning system performs a number of functions in response to input from a human operator. The system allows the person (either a pilot or a dispatcher) to develop and display up to four flight plans in conjunction with weather information and to obtain feedback in terms of flight parameters such as fuel, time, and distance. The weather information consists of both graphic depictions and verbal descriptions and can be displayed at several altitudes. The displays show the entire flight path, thus emphasizing global solutions to problems. In addition, the person can manipulate the display time to see the relationship between the weather information and the plane's position. The system computes the optimal vertical profile to minimize fuel consumption, arrival times at waypoints, and fuel remaining at those waypoints, based on winds components. It also determines these flight parameters given a user-selected vertical profile.

The basic system runs on a Macintosh IIfx with two color monitors. The features and functions on each monitor are discussed in turn.

Left Monitor

The displays and controls on the left monitor are shown in Figures 4 and 5. (In all of the figures which depict system displays, some of the information loses saliency as printed here in black and white instead of color.)

Insert Figures 4 and 5 about here

The primary feature on the left monitor is a map display. This display depicts the continental United States, the aircraft position, and planned routes. Several pieces of information can be overlaid on this map. This information includes:

1. Weather information, which consists of the following:
   a. 'composite clouds'-- which depicts cloud cover, cloud bases and tops, and cloud type (this is similar to a 'U.S. High Level Significant Weather Prognostic Chart' with the information on the jet stream, tropopause heights, and turbulence removed);
   b. 'composite radar'-- which depicts radar returns, cell intensities, cell types, cell direction and speed of movement, and cell tops (this is similar to a color 'Radar Summary Chart');
   c. 'fronts'-- which depicts frontal positions, types of fronts, and high and low pressure areas (this is similar to a 'Surface Analysis Chart' with the isobars removed);
   d. 'clouds at altitude'-- which depicts the cloud cover at an altitude selected by the operator (these altitudes range from 23,000 feet to 33,000 feet);
   e. 'radar at altitude'-- which depicts radar returns, cell intensities, cell types, and cell direction and speed of movement at an altitude selected by the operator (these altitudes range from 23,000 feet to 33,000 feet; this display is similar to airborne radar with the exception that it depicts the entire continental U.S.;
   f. 'winds at altitude'-- which depicts wind direction and speed at an altitude selected by the operator (these altitudes range from 23,000 feet to 33,000 feet; this display is similar to an 'Observed Winds Aloft Chart' without the temperatures associated with the winds);
2. Jet routes and waypoints-- which depicts all of the waypoints (navigational points) and jet routes (the 'highways in the sky' that connect waypoints) which are normally found on the 'IFR Enroute High Altitude Charts' for the continental U.S.; these jet routes and way points are shown in Figure 6.

All weather information is available for two display times: The 'current' time and a one hour forecast. When a forecast is displayed, the aircraft is displayed in its predicted position (on each route) at the forecast time, as well as at its current position. One can also 'zoom in' on a region of the map, which replaces that map of the continental U.S. with a magnification of an area surrounding an operator-selected point. Similarly, the user can 'unzoom' back to the map of the continental U.S.

Insert Figure 6 about here

The last general item of interest on this monitor is a 'notification window' which presents the person with important information regarding the various planned routes (e.g., a warning that the plane will consume all of its fuel before reaching the chosen destination).

Right Monitor

The right monitor displays and controls are shown in Figure 7. It displays a 'flight log' of a route. This flight log is essentially a spreadsheet which depicts each segment of the route (i.e., all of the waypoints and jet routes which make up the route), as well as information pertinent to those segments. This information consists of the arrival time and fuel remaining at each waypoint, the average altitude and speed for each segment, as well as other flight parameters. The flight log also graphically displays the planned altitudes for the route and the least-fuel-consumption altitudes for that route. Finally, the flight log displays weather information which is pertinent to the route. For example, turbulence information is on by default, but the person can also select information on the winds. The turbulence information that is presented is a one-word summary of the maximum turbulence on a given flight segment. The operator can get a more detailed description of that information (available 'pilot reports' or 'pireps') by selecting ('clicking' on) the one-word summary.

Insert Figure 7 about here

The monitor displays four flight segments at a time, but it is not large enough to display longer routes. Therefore, the flight log has to be 'scrolled', so that information which is not currently on the screen will be displayed. Furthermore, the operator can select which route to display in the flight log at any given time (the flight log displays only one route at a time).

The other display on this monitor (at the bottom of the screen) shows the flight parameters for all four alternative routes upon arrival at the destination. These parameters include time of arrival, time enroute, fuel remaining, and total distance. This display allows users to compare the 'bottom line' for each route.

FPT - Important Features

The design principles underlying FPT as a cooperative planning system are discussed in detail in Smith, McCoy, Layton and Bihari (1992). Five of the most significant considerations, however, are:

1. Provide tools that allow cooperative planning at different levels of abstraction (inspired by the work of Sacerdotti; Hayes-Roth and Hayes-Roth; Shute and Smith; and Suchman);
2. Provide the human planner with data displays and representations to support plan generation and evaluation at these different levels of abstraction;

3. Provide cognitive interfaces to the available support tools that allow the person to easily communicate desired tradeoffs among goals;
4. Provide tools that help the person predict the outcomes of various plans (Coombs and Alty, 1987);
5. Incorporate a graphical interface that allows the person to view and explore alternative plans in the context of the relevant data (i.e.,weather displays).

Below we describe an empirical study to assess some of these design considerations.

Methods

In the study described below, FPT was used as a testbed to study the effects of different design features on cooperative problem solving performance. Briefly, each of the thirty subjects (professional airline pilots) was asked to use one of three alternative system designs (ten subjects per condition). Each subject was trained on the use of that version of the system and given four cases to solve.

System Designs

As mentioned above, three different enroute flight planning support systems were designed. In actuality, these three systems represented variations on the levels and timing of support provided by the computer. These variations on the system design represented the independent variable studied in this experiment. The three different versions are discussed below.

The 'Sketching Only' System. The 'sketching only' system allowed the human planner to sketch proposed flight paths on a map display, while the computer filled in lower level details (such as fuel remaining, time of arrival, and recommended altitudes) by using an optimization program that found an altitude profile and speeds that minimized fuel consumption (taking into account wind components). In this version, the person was responsible for proposing the alternate paths, while the computer was responsible for providing computational feedback on those solutions. The computer did not take an active role in planning deviations in this version.

The sketching of routes was carried out by displaying the jet routes and waypoints and selecting ('clicking' on) each waypoint that the pilot wanted the airplane to pass through. Such routes were constrained to paths where there was a jet route connecting the desired waypoints; if there was no jet route connecting two waypoints, then the pilot was not allowed to propose that route. This placed a slight restriction on the pilots' planning abilities because they can normally request vectoring to fly direct routes from one point to another. However, this approached allowed them to plan general solutions with the understanding that these solutions were not necessarily the exact routes that would actually be flown.

The 'Route Constraints and Sketching' System. The 'route constraints and sketching' system retained all of the capabilities of the 'sketching only' system and it added another capability: The person could specify higher level constraints on the type of solution he desired and then ask the computer to find the shortest distance route which satisfied those constraints. If the computer was unable to find a route that met the constraints placed on it, it would so notify the person. The constraints that could be specified were the maximum allowable turbulence, the maximum allowable precipitation, and the destination. (It is easy to see how this interface design concept could be extended to include other constraints such as earliest and latest desired arrival times.) This tool places a substantial burden on the computer to work out the details of the alternative flight plan.

Specifying constraints on a desired solution is a very different "problem space" (Laird, Newell and Rosenbloom, 1987) than the one faced by the person using the 'sketching only' version of the system. In the 'sketching only' version, the person's explanation is grounded in the representation of the physical space (e.g., the waypoints and jet routes) and the relationships of the objects within that space (e.g., aircraft position, storm position, wind velocities at various locations and altitudes, etc.). We hypothesized that the 'route constraints' version would allow the person to abstractly control the computer's search of the physical world, while not being required to search for paths in that space himself.

Both the person and the computer could be actively involved in the planning process with this system. The person could specify constraints on the solution he desired from the computer. The computer would then recommend appropriate alternatives. Furthermore, the person had recourse, through the sketching tool, to plan specific routes himself. Reasons for the person to carry out such detailed planning in spite of the availability of the route constraints tool could include a preference to do the work himself or reservations about a particular solution suggested by the computer.

The 'Automatic Route Constraints, Route Constraints, and Sketching' System. The 'automatic route constraints, route constraints, and sketching' version took the computer's involvement one step further in that the computer automatically suggested a deviation (based on default constraints of no turbulence, no precipitation, and the originally planned destination) as soon as it detected a problem with the original route. This form of tool is akin to an autonomous support system that automatically suggests solutions to detected problems.

This system also had the 'route constraints' tool of the previous system and the 'sketching' tool of the previous two systems. Thus, the person could also use these tools to explore solutions.

Underlying all three system designs is the provision of support to ask 'what if' questions. That is, they encourage the operator to ask 'what if I do this?' (e.g., 'What type of solution does the computer suggest if I use constraints of light turbulence and moderate precipitation?', or 'What happens to my fuel remaining if I deviate north instead of south?'). We were interested in whether people used the tools available to them, how the available tools affected the cognitive processes of the person using the system, and how the available tools affected the solutions that person chose.

Subjects

Thirty male commercial airline pilots volunteered to help evaluate the three systems. These pilots came from the flying community at large. Each pilot was paid for the three hours that it took to participate; approximately half of that time was spent training the pilot on the system he would be using. Each pilot was randomly assigned to one of the system design conditions, either the 'sketching only' condition, the 'route constraints and sketching' condition, or the 'automatic route constraints, route constraints, and sketching' condition. The pilots came from 8 major airlines, with an average of 9,300 hours of flying experience experience as commercial pilots (range: 1200 - 28000 hours) and 1800 hours of experience in military aircraft (range: 0 - 5000 hours). In the results presented below, there were no apparent relationships between the pilots' performances and their levels or types of flying experience, nor with their levels of previous computer experience.

Cases

Following training on the use of the system, each of the subjects was presented four enroute flight planning cases in which he was given some preliminary information about the flight (e.g., origin, destination, time of day, etc.) and was then told to "decide what the plane should do". All of the subjects went through the same four cases in the same order. Whereas the subjects in the 'sketching only' and 'route constraints and sketching' conditions started each case with only their original route of flight, the subjects in the 'automatic route constraints, route constraints, and sketching' condition were also given an alternate route suggested by the computer based on the default constraints of finding a route that was predicted to avoid all turbulence and precipitation. Details on these cases are included in discussions of the results.

Results and Discussion

Below we describe the performances of the pilots on the four test cases.

Case 1

The following scenario was read to the subjects prior to their working on this case:

> "It is summer and you're on a flight from Battleground (Portland) to Northbrook. Your dispatcher gave you a southerly route in order to avoid an occluded front. The front has dropped to the south as well, however, and has generated some thunderstorms. Time out was 1700 Zulu and you are five minutes into the flight. Decide what you think the plane should do."

For subjects in the treatment condition in which the computer automatically suggested a solution upon loading the case, the following two lines were added (prior to "Decide what you think..."):

> "The computer has suggested the orange route as an alternative to the original plan (the green route) based on constraints of no turbulence and no precipitation. You may accept either of these plans or develop your own."

The original route, the current aircraft position, and the current composite radar are shown in Figure 8. The radar returns show a solid line of thunderstorms with cell tops at 37,000 feet. (For this experiment, the pilots were told the aircraft's maximum altitude was 33,000 feet.) Furthermore, the gap between the two cells was forecast to close. Therefore, a deviation was obviously required. The forecast storm movement was to the east, but was very small.

Insert Figure 8 about here

To provide a concrete sense of the performances of the subjects, the behaviors of 3 representative pilots are first summarized below. Then summary statistics are provided for the entire group.

Subject S1: 'Sketching Only' Version. Subject S1 looked at the composite radar and fronts (current and forecast) and concluded: "Going to have to go north or south around it". This pilot then sketched a northern deviation and compared it with the original route, noting that the deviation saved time and fuel and avoided the turbulence. He then sketched a southern deviation. While sketching the deviation, he inferred that "it could move a little further south [than forecast]", so he adjusted the southern alternative for that contingency. When the route was completed he looked at the computer's estimates for time and fuel consumption and stated: "That one's quite a bit longer." He concluded: "We could go that way if we had to." The pilot decided, however, to take the northern route.

Subject C3: 'Route Constraints and Sketching' Version. Subject C3 looked at the composite radar and concluded: "I can see right now that what I want to do is come to the north..." After also looking at the clouds, he decided: "There's a line [of thunderstorms] so I definitely don't want to get anywhere near that..." After observing that "it looks like a shorter route here [north], anyhow" and looking at the winds, he decided to let the computer find a deviation based on constraints of light turbulence and light precipitation. The subject looked at the resultant northern deviation suggested by the computer and stated: "That looks like about what I would have in mind." After checking the data displayed on the national map to make sure that the northern deviation had "no problems with turbulence or precipitation", he compared it with the original route and noted that: "The total distance is actually a little less. Fuel left is more, and we'll actually cut time off our flight with this route." He then decided to fly the computer recommended northern deviation.

Subject A9: 'Automatic Route Constraints, Route Constraints and Sketching Version'. The computer automatically displayed a recommendation around the north of the storm to this pilot. He began his evaluation by comparing the estimated time and fuel consumption for this suggested route (to the north of the storm) with the performance parameters for the original route. He looked at the composite radar and noted that: "[The] original route goes right through an area of...heavy precipitation. A lot of echoes. Alternate route goes above [north of] it." Next, this pilot looked at the winds and decided: "The winds are more favorable with the southerly [original] route, but obviously the weather's not that great." After "looking at the comfort level of the passengers", this subject concluded: "The alternate route certainly looks better to me and I would stick with that." He then looked again at the destination parameters for the two routes and summarized their differences as follows: "It's [the deviation] a little bit quicker and we aren't going to have any turbulence. We're going to get there a little sooner. The distance is less. The alternate route looks good to me." Finally, he said: "I'd go with the [computer's suggested] route. I really can't see any better way I could plan it right now."

Comparison of Sample Subjects. Figure 9 shows the routes explored in detail by these sample subjects. The subject in the 'sketching only' version of FPT (S1) explored the far northern route and the southern route, and elected to take the

computer's suggested northern deviation. Only two of the ten subjects in the 'sketching only' version selected that route. Six of the ten subjects in the 'sketching only' version selected a more conservative northern deviation. (Based on a Chi-Square test, these differences are significant at $\alpha<.004$.)

Differences in Exploration. As shown in Table 5, subjects using the 'sketching only' version explored multiple classes of solutions in detail more often than did the subjects in the other two conditions. (In this case, exploring a solution north of the storm was defined as one class of solution, while exploring a solution south of the storm was a second.) This difference was significant at $\alpha<.01$.

Insert Table 5 about here

Table 6 shows data regarding another measure of the amount of exploration. This table shows the number of subjects who explored multiple specific solutions in detail (as contrasted with multiple *classes* of solutions as summarized in Table 5). Again, the subjects in the 'sketching only' version showed evidence of more exploration ($\alpha<.014$).

Insert Table 6 about here

Differences in Information Search. The information which the subjects looked at was also analyzed on the basis of treatment condition. The number of subjects in each condition who looked at current or forecast fronts, current or forecast radar weather (composite or at altitude), current or forecast winds at altitude, and jet routes is presented in Table 7.

Insert Table 7 about here

As can be seen from this table, there are no clear differences between groups in information searched, with the exception that more of the 'sketching only' and 'route constraints and sketching' subjects looked at the jet routes than the 'automatic route constraints, route constraints, and sketching' subjects. This latter fact suggests the possibility that half of the 'automatic route constraints' subjects evaluated the suggested route at a fairly abstract level (this one difference is significant at $\alpha<.013$.)

Case 1 - Discussion. Prior to the experiment, we made two predictions that are relevant to these results. Specifically, we predicted that, in general, the pilots using the 'automatic' version might be:

1. Less likely than the 'sketching only' subjects to explore as many alternatives in detail;
2. Less likely than the 'sketching only' subjects to consider the uncertainty associated with weather forecasts, consequently accepting the computer's recommendation without adequate evaluation.

The results for Case 1 are very consistent with these general predictions. Tables 5 and 6, for example, indicate that the 'sketching only' subjects explored more alternatives. Furthermore, the concurrent verbal reports indicate that the 'sketching only' subjects who deviated further north (see Figure 9) were indeed considering the uncertainty associated with the forecast, making statements like:

> "If the system moved further north and the thunderstorms started to pop up... Let's take a look at how much further north we could go."

One way to explain these effects is to say that the pilots in the 'automatic' conditions were 'overreliant' or 'overtrusting' of the system. These are rather shallow labels, however, and don't really provide much insight into the influence of the system's design on the user's cognitive processes.

A more detailed analysis suggests that the effect of automatically suggesting a route is on two stages (generating options and evaluating options) in the planning process as modeled in Figure 10.

Insert Figure 10 about here

The clearest example of this effect occurred at the point where the subjects had to decide whether to stay north of the storm, from DPR to RWF, or to begin turning south toward the destination, from DPR to FSD. (See Figure 11). It appears that, because the system design induced the 'sketching only' subjects to view the display shown in this figure if they wanted to complete a reasonable northern deviation:

1. The subjects observed that the route from DPR to FSD cut close to the forecast storm activity;
2. This observation influenced them to consider the possibility that the forecast might be wrong and that the storm might move further north or east than predicted;

3. They consequently chose the more conservative path from DPR to FSD.

This contrasts with the behaviors of all but two of the subjects in the two route constraints function conditions, who viewed the computer's recommended solution at the national map level (often without even displaying the jet routes) and simply concluded that it looked okay without closely focusing on the choices at DPR. For example, while looking at the national map, Subject C4 stated:

> "See if I can get the computer to find a route. (He used the route constraints function with the constraints of no turbulence and no precipitation and the computer suggested a northerly route.) With a northerly deviation, I can get by with the constraints I placed on it. Now I want to check and make sure... (He observed the destination parameters for estimated time and fuel consumption.) That gives me, actually, a shorter flight plan and plenty of fuel at arrival. So I would go ahead and select that route at that point."

Insert Figure 11 about here

Unlike the 'sketching only' subject described earlier, there is no evidence that he considered the uncertainty associated with the storm or that he considered a more conservative northerly deviation. In short, rather than "explaining" the effects of the automatic display of suggestions as "overreliance," it is more informative to conclude:

Initial Evaluation of System Designs. In Case 1, we can't really criticize either the computer's suggested route or either of the more conservative northerly routes selected by the pilots in the 'sketching only' version. All of them are quite reasonable. We might, however, speculate that, in other circumstances, the *cognitive processes* induced by the 'sketching only' version (*if* these cognitive processes persist in other scenarios) could lead to more exploration and deeper consideration of the implications of uncertainty in the forecast, leading to the selection of a superior route. (Data relevant to this hypothesis will be presented in Case 3.)

If this behavior persists in other scenarios, it might be construed as an advantage in the design of the 'sketching only' system. There was also evidence of behaviors in Case 1, however, where the 'sketching only' version put some of the subjects at a disadvantage. In particular, two of the 'sketching only' subjects selected a plan that deviated from the original plan at DBS, a second possible deviation point, rather than MYL, the earliest possible deviation point. This second deviation point is less preferable in terms of fuel consumption.

In abstract terms, then, we again see important effects induced by the system designs. The subjects in the 'route constraints and sketching' and the 'automatic route constraints' conditions let the computer pick a fuel efficient point for deviation from the original plan. Because of the large solution space, however, the 'sketching only' subjects were faced with a reasonably difficult task in identifying the best deviation point.

Case 1 Discussion - Overview. Case 1 provides clear evidence that the design of the system has strong effects on pilots' performances. More importantly, it provides insights into the ways in which design features interact with the characteristics of this task (scenario) to influence the user's cognitive processes.

The data from Case 1 indicate that, in some ways, the use of the computer to produce suggested plans degrades the process of evaluating plans on the part of the pilots, while in other ways, (i.e., finding fuel efficient solutions to avoid the bad weather) it enhances performance. The following cases provide further data to assess this apparent tradeoff between these different design concepts.

Case 2

Case 2 was designed so that there were two initially plausible directions for deviating (north or south of a storm). The scenario consisted of the following:

> "It's summer and you are eight minutes into a flight from Oakland to Joliet. You got off the ground at 1600 Zulu. You notice that there is a solid line of convective thunderstorms directly in your path. Decide what you think the plane should do."

For subjects in the treatment condition in which the computer automatically suggested a solution upon loading the case, the following two lines were added (prior to "Decide what you think..."):

> "The computer has suggested the orange route as an alternative to the original plan (the green route) based on constraints of no turbulence and no precipitation. You may accept either of these plans to develop another alternative on your own."

Figures 12 and 13 show the weather for this case.

Insert Figures 12 and 13 about here

Subject S6: 'Sketching Only' Version. It was hypothesized, prior to the experiment, that many of the subjects using the 'sketching only' version would explore and select a southern deviation, since the southern thunderstorm cell appears to be smaller than the northern cell. Because the southern cell is smaller than the northern cell, it seemed possible that some pilots would judge the southern deviation to require less distance be traversed. In order to completely avoid the predicted thunderstorms and turbulence, however, the deviations to the north and the south were nearly equidistant. Because of tail winds to the north, and head winds to the south, a northern deviation was clearly preferable in terms of fuel consumption and time of arrival.

After looking at the current and forecast fronts and composite radar (see Figures 12 and 13), this subject sketched a southern deviation, compared it with the original route, and checked it for turbulence. This route is depicted in Figures 12 and 13. After determining that the route did not have any predicted turbulence, he decided to fly it. This is the only solution he sketched.

Subject C3: 'Route Constraints and Sketching' Version. Subject C3 looked at the current and forecast composite radar and concluded that he could deviate either to the north or the south. He decided to let the computer find a deviation based on constraints of light turbulence and light precipitation. The computer suggested the northern deviation shown in Figures 12 and 13, and the subject checked it for turbulence. After finding no turbulence along the deviation, he checked it for clearance from the thunderstorms. The subject determined that the distance between the route and the thunderstorms was adequate. He then decided to fly the computer-suggested northern route, but stated that he would keep an eye on the thunderstorms.

Subject A9: 'Automatic Route Constraints, Route Constraints, and Sketching' Version. This subject first looked at the composite radar for the current weather map. He compared the time and fuel consumption for the two routes (the original route and the automatically suggested northern route) and noted their differences. Finally, he gathered some more weather information, including winds, and decided to accept the computer-suggested northern route.

Case 2 - Summary Statistics. While nearly all of the 'route constraints' and 'automatic' subjects decided to deviate north of the original route, a significant proportion of the 'sketching only' subjects deviated to the south, as shown in Table 8. Based on a Chi-Square test, this difference was significant at $\alpha<.044$.

Insert Table 8 about here

Nevertheless, as shown in Tables 9 and 10, the 'sketching only' subjects were not the only ones to explore both northern and southern deviations in detail. As in Case 1, however, more of the 'sketching only' subjects explored alternative routes in detail. For Case 2, though, these differences are not statistically significant ($\alpha <.366$).

Insert Tables 9 and 10 about here

As in Case 1, the information which the subjects looked at was also analyzed on the basis of treatment condition. The number of subjects in each condition who looked at current or forecast fronts, current or forecast radar weather (composite or altitude), current or forecast winds at altitude, and jet routes is presented in Table 11.

Insert Table 11 about here

Case 2 - Discussion. As stated earlier, one of our hypotheses was that, because of the large number of possible solutions to explore, subjects in the 'sketching only' version would be less likely to find the most efficient route in terms of fuel consumption that avoided the bad weather. This effect was clearly shown in Case 2, where 40% of the 'sketching only' subjects selected a southern deviation. The various southern deviations selected used about 3% more fuel and took about 8 minutes longer.

This difficulty in identifying the most fuel efficient deviation was in part due to a failure to access all of the data in evaluating solutions. Three of the subjects in the 'sketching only' version failed to look at the map display for winds, and consequently did not realize the southern deviation had significant headwinds.

Thus, because of the large "solution space" and the large "data space," subjects in the 'sketching only' version had more difficulty in generating the best route and in evaluating the less satisfactory southern route. In terms of the amount of exploration, the trend again indicated more exploration by the 'sketching only' subjects. It is important to note, however, that:

1. Requiring the human planner to sketch his own solution does not ensure that he will explore more alternatives in detail or look at all of the relevant data to evaluate an alternative;
2. Just because the computer suggests a solution doesn't mean that the human planner won't explore other alternatives on his own.

Indeed, combined with the results from Case 1, the data strongly suggest that the effects of the system design on exploration are very dependent on the characteristics of the scenario. This result is shown even more strongly in the next case, where the 'sketching only' subjects actually explored fewer paths.

Case 3

Case 3 was designed to present the pilots with a difficult planning problem and to put the various system designs to a demanding test. Unlike the previous cases, the thunderstorms in Case 3 were not localized and their tops were not all at the same altitude. Like Case 2, there were two likely directions for deviating, but neither was without potential problems. In particular, a deviation that avoided storms at the beginning of the route had to pass through more severe storms later. Finally, flight safety was a bigger concern on this case than the previous cases.

Description of the Case. The following scenario was read to the subjects prior to their working on the case:

> "It's summer and you're on a flight from Cheyenne to San Antonio. You got off the ground at 1900 Zulu and are now two minutes into the flight. Decide what you think the plane should do."

For subjects in the treatment condition in which the computer automatically suggested a solution upon loading the case, the following two lines were added (prior to "Decide what you think..."):

> "The computer has suggested the orange route as an alternative to the original plan (the green route) based on constraints of no turbulence and no precipitation. You may accept either of these plans or develop your own."

The original route, the current aircraft position, and the current composite radar are shown in Figure 14. The current radar shows a number of thunderstorm cells with tops ranging from 28,000 to 43,000 feet, but the aircraft's maximum altitude was 33,000 feet. One of the cells directly on the flight path had a top of 43,000 feet. The forecast radar showed that the cells were predicted to move north and slightly east, as well as join. The winds were light and variable.

In summary, Case 3 presented subjects with a rather complex planning problem. The weather was dispersed over a large area and was changing somewhat unpredictably. This scenario required that the pilots anticipate various possible outcomes and plan accordingly.

Insert Figure 14 about here

The routes suggested by the computer in the 'route constraints and sketching' and 'automatic route constraints, route constraints, and sketching' conditions are shown in Figure 15. There were two routes suggested by the computer, depending upon the constraints placed on it. Constraints of no turbulence and no precipitation caused the computer to suggest the eastern route (hereafter referred to as the 'eastern' route). Constraints that allowed light turbulence and precipitation caused the computer to suggest the western route (hereafter referred to as the 'western' route). In the 'automatic route constraints, route constraints, and sketching' treatment condition, the computer automatically suggested the *eastern* route to the subjects. These subjects had to modify the constraints on the computer or sketch their own route in order to come up with a western route.

Insert Figure 15 about here

The eastern route passed between two large, severe thunderstorm cells. Summer thunderstorms in Texas are notorious for their volatility and it was very possible that the two cells on either side of the eastern route would grow and build together. Furthermore, the eastern route passes extremely close to a forecast intense cell location.

It was hypothesized, prior to the experiment, that many of the subjects would have difficulty searching the space of possible solutions and that some of the subjects in the 'automatic route constraints' treatment condition would select the eastern deviation, since it was the one initially recommended by the computer, in spite of the fact that it is a very questionable choice in both relative and absolute terms. (This case was deliberately selected because the automatic suggestion provided by the computer was poor - poor because the computer treated the forecasts as reality, rather than reasoning about the uncertainty associated with the forecasts. The weather pattern is, however, realistic. Indeed it is based on real weather data provided by the National Center for Atmospheric Research.)

Subject S1: 'Sketching Only' Version. This subject first indicated that he would have preferred waiting for the weather to clear. Since the plane was already enroute, however, he considered trying to fly above the weather. He rejected that possibility upon seeing the cell tops rising up to 43,000 feet. The subject then spent some time assessing the weather before coming up with two options for dealing with it. He decided to first try going all the way around the back side of the weather (a far western deviation), but decided against that option. Deciding to try a western deviation, Subject S1 first tried to deviate from TBE to TCC in order to avoid the cells that lay on the jet route from PUB to TCC. Realizing that wasn't possible, the subject tried to avoid the worst of the forecast cells by deviating from PUB to LVS and then back to TCC. After completing the deviation to SAT, the subject compared it to the original route and determined that there wasn't much fuel remaining.

Subject S1 then looked briefly at a far eastern deviation, but instead decided to try a far western deviation around the back of the storm again. After completing the deviation and checking it for turbulence, the subject decided that he would continue trying options, but that he would start flying a far western deviation. He noticed that this route had increased fuel burn, but the subject also noted that Albuquerque, El Paso, and Dallas were potential alternate destinations. The subject then raised the descent profile from INK to JNC in an effort to avoid the moderate turbulence and to conserve fuel. After comparing the altered profile with the original altitude profile for the deviation, he decided (based on fuel consumption) that he would stick with the original altitude profile.

Finally, Subject S1 sketched another western deviation, but began from AMA rather than PUB. Once again, it appeared as though the subject was trying to avoid the forecast thunderstorm cells south of PUB. Thinking that this route might have saved some fuel, he compared it to the others and noted that the difference wasn't that large. He then reiterated his choice of a far western route. (Much further west than the western route shown in Figure 15.)

Subject S6: 'Sketching Only' Version. Subject S6 spent a fair amount of time assessing the weather before deciding to deviate east from APA to SPS to DFW (see Figure 15). Like Subject S1, he planned his deviations using forecast weather. In particular, he had zoomed the display around the Denver area when he decided to deviate east; this view clearly showed some moderate thunderstorm cells just south of Pueblo--these likely contributed to his decision to go east. That is, he eliminated possible western deviations from consideration based on a localized criterion or aspect (Kahneman, 1972). It is important to note that this decision was based on forecast conditions, not current conditions; current weather did not indicate any cells south of Pueblo. This initial decision led the subject to generate and select the eastern route shown in Figure 15, which passed between two close, severe thunderstorms near SPS. He did not go back and reconsider his choice of deviation directions to find a more suitable option. Rather, he announced his intention to fly the eastern deviation. In the debrief, the subject indicated that the western deviation was clearly preferable (in spite of his choice of the eastern deviation when actually generating his own plan).

Subject C3: 'Route Constraints and Sketching' Condition. Subject C3 first considered staying on the original route and picking his way between the thunderstorm cells. The subject made a brief inspection of the weather and then decided to see what the computer suggested. He selected constraints of light turbulence and light precipitation and the computer suggested the western deviation. After comparing the new route to the original one, the subject determined that the route didn't add much time and noted that the original route would have passed right through the thunderstorms. He decided to take the western route suggested by the computer.

Subject C8: 'Route Constraints and Sketching' Condition. Subject C8 briefly looked at weather information before using the route constraints function with no turbulence and no precipitation. The computer suggested an eastern deviation based on those constraints. After checking the route for turbulence and then examining the weather some more, the subject decided to sketch a western deviation beginning with a leg from PUB to TCC. The subject completed the western deviation (shown in Figure 15) and checked it for turbulence. He then raised the altitude of the leg from INK to JCT to avoid the moderate turbulence there. Next, the subject tried to find out what was causing the turbulence in the first place. Subject C8 looked at the destination parameters and indicated that he preferred the western route. He then examined the eastern deviation for turbulence and returned to looking at the weather.

The subject next modified the western deviation so that it went from PUB to LVS before returning to TCC. At this point he spent considerable time examining the two deviations he had sketched and the weather trends. He finally decided to fly the western deviation that he had sketched first, with the provision that it might have to be modified later depending on how the weather actually developed.

Subject A9: 'Automatic Route Constraints, Route Constraints, and Sketching' Condition. Subject A9 started out by comparing the suggested eastern deviation with the original route (before even looking at weather information). After noting the differences between the routes in terms of destination parameters and turbulence, the subject began comparing the routes on the basis of weather. He then sketched a western deviation beginning at AMA and going to ROW. He checked the turbulence forecast for this western route and rejected it because it passed through an area where moderate turbulence was predicted up to 29,000 feet for the last third of the flight. He subsequently decided to take the eastern deviation recommended by the computer. In the debriefing, he indicated that he would actually prefer the western deviation over the plan he had selected.

Case 3 - Summary Statistics. As with the previous two cases, the three treatment conditions were analyzed for differences in final route choices, number of subjects who explored multiple classes of solutions in detail, number of subjects who explored multiple routes in detail, and information viewed.

Differences in Final Routes. Table 12 contrasts subjects in terms of whether they selected the computer-suggested eastern route. In addition, as in Case 2, the routes chosen by the 'sketching only' subjects were much more varied than the ones chosen by the subjects in the other two treatment conditions.

Insert Table 12 about here

Differences in Detailed Exploration. Case 3 stands in contrast to the previous two cases, in that the 'sketching only' subjects did not explore multiple classes of solutions in detail more often than did the subjects in the other two groups. Instead, it was the 'automatic route constraints, route constraints, and sketching' group who explored multiple classes of solutions in detail more often than did the subjects in the other two groups ($\alpha<.022$). The number of subjects who explored multiple classes of solutions in detail in each system design condition is summarized in Table 13.

Insert Table 13 about here

Differences in Information Search. As in the two previous cases, the information which the subjects looked at was analyzed on the basis of treatment condition. The number of subjects in each condition who looked at current or forecast fronts, current or forecast radar weather (composite or at altitude), current or forecast winds at altitude, and jet routes is presented in Table 14.

Insert Table 14 about here

There are no clear, statistically significant differences between groups in information searched. The trend, however, seems to be that the 'route constraints and sketching' subjects looked at less information than the 'sketching only' and 'automatic route' constraints, route constraints, and sketching' subjects.

Case 3 - Discussion. Once again, the data indicate that the system design strongly influences the exploration and plan selection processes of the subjects.

Search Difficulties. Some of the same challenges in searching the space of possible solutions that occurred in Case 2 recurred in Case 3 for subjects in the 'sketching only' condition. For example, Subject S10 made six attempts at sketching routes (some were completed, some were aborted) before sketching the route that he finally chose. Similarly, Subject S7 made six attempts at sketching routes before choosing one of them. This difficulty experienced by the 'sketching only' subjects in generating effective plans was strikingly illustrated by one pilot who developed and chose a deviation all the way east around the entire storm, using up 24% more fuel than the more reasonable western deviation.

Poor Search Strategies. Subject S6, described in detail earlier, illustrated a fascinating example of how particular strategies can lead to very poor solutions. His strategy can be characterized as an elimination by aspects approach (Kahneman, 1972), where the aspects are local decisions about which waypoint to go to next.

In particular, he began by saying: Where should I go next, from PUB to TCC or from PUB to AMA? He selected AMA because it was further away from the storm west of TCC. He then considered: Should I go from AMA to SPS or to ABI or to TCC? (See Figure 16.) He selected SPS. Because of these localized decisions, he *never even considered* whether this eastern deviation was to be preferred globally to the western route.

Similarly, several subjects in the automatic version exhibited ineffective strategies. Specifically, they first noted the computer's automatic suggestion of the eastern deviation (see Figure 16). They subsequently generated the western deviation (either by sketching it or by changing the constraints and having the computer generate it). They then viewed the display of predicted turbulence and rejected the western deviation based on the presence of moderate turbulence at some altitudes in the last third of the flight. They did not note any other plausible alternatives, so they accepted the computer's initially suggested (but very poor) eastern route.

Two underlying processes appear to be contributing to this poor performance. First, these subjects are using a single aspect or criterion to reject a plan, rather than evaluating the plan globally on an absolute basis or in comparison to alternatives. Second, they appeared to accept the computer's initial suggestion by default after they rejected the western deviation. In particular, like the pilots in the automatic version in Case 1, they did not show evidence of considering the uncertainty associated with the weather around the eastern deviation.

Disorientation. A final interesting behavior was the failure of some pilots to view the appropriate data when evaluating an alternative. These pilots were looking at the forecast weather while making decisions about the initial segment of the flight. They should have looked at the original weather display to guide decisions concerning that early in the flight. (They appeared to be unaware of which weather display - forecast as current weather - they were looking at.)

Summary. In short, a number of subjects in all three conditions exhibited poor performance in Case 3. Although more subjects appeared to be biased toward a poor solution when it was suggested by the computer:

1. This bias cannot be explained as simply due to "overreliance." These subjects showed clear evidence of generating and evaluating alternatives. Thus, much deeper explanations had to be developed to account for their acceptance of the computer's poor suggestion;
2. Forcing the pilots to be "more involved" by making them sketch their own solutions resulted in the selection of fewer poor plans.

Nevertheless, because of the use of an elimination by aspects strategy by one subject, he generated and selected the poor eastern deviation all by himself (without any suggestions from the computer).

Case 4

Case 4 presented subjects with a situation in which the shortest and most fuel-efficient deviation, north, required the pilots to violate one of their standard heuristics (fly upwind of thunderstorms). The storm in this case could also be topped, although that would have put the plane in turbulence above the storm. Furthermore, there was some risk of the storm growing quickly. As in the previous two cases, there were two likely directions for deviating; in this case those directions were north and south of the storm.

The following scenario was read to the subjects prior to their working on the case:

> "You are on a flight from Albuquerque to New Orleans. You got off the ground at 1400 Zulu. You are now 19 minutes into the flight and have noticed a thunderstorm cell outside of Dallas. Decide what you think the plane should do."

For subjects in the treatment condition in which the computer automatically suggested a solution upon loading the case, the following two lines were added (prior to "Decide what you think..."):

> "The computer has suggested the orange route as an alternative to the original plan (the green route) based on constraints of no turbulence and no precipitation. You may accept either of these plans or develop your own."

The original route, the current aircraft position, and the current composite radar are shown in Figure 17 along with the likely deviations north and south of the storm. The forecast weather showed the storm moving slowly to the northeast.

Insert Figure 17 about here

Subject S1, 'Sketching Only' Condition. Subject S1 began by looking at weather information and may have been considering flying over the top of the weather; he wondered aloud how high the cell went and noted that it went up to 28,000 feet and that the plane was planned to fly at 33,000 feet. Upon noticing moderate turbulence, however, the subject decided to try a southern route. After sketching a southern deviation, he checked it for turbulence and compared it to the original route. The subject then reviewed the weather and the original route and sketched a route to the north. After checking the route for turbulence, he decided that either route would work. Since the storm was isolated, he decided to take the route which consumed the least fuel, which was the northern route (even though the storm was moving north, as he noted).

Subject C8, 'Route Constraints and Sketching' Condition. Subject C8 started by checking the weather and then decided to use the route constraints function to find a new route based on constraints of no turbulence and no precipitation. The computer suggested a northern deviation which the subject checked for turbulence and compared with the original route. Subject C8 then decided to sketch a southern deviation to see if it was any better or shorter. In comparing the northern and southern routes, he noted the tradeoff between the two: the northern route took less time, but the storm was slowly moving in that direction. He rechecked the weather and the turbulence on the southern route and stated that it didn't matter which one he chose. He was continuing to look at the weather and the southern route when he noticed the possibility of flying above the weather. This prompted him to relax his constraints to light turbulence and light precipitation and try the route constraints function again. The computer again suggested the northern route. The subject then went through a process of reasoning about the uncertainty of the forecast , the position of the aircraft relative to the weather, and the costs of avoiding all of the uncertainty. This resulted in him choosing the southern deviation so that he would be assured of avoiding the weather.

Subject A7, 'Automatic Route Constraints, Route Constraints, and Sketching' Condition. Subject A7 first compared the destination parameters of the original route and the computer-suggested northern deviation. He then checked the deviation for turbulence and continued investigating the weather. Subject A7 decided to try a southern deviation and compared the destination parameters of that route to those of the other routes. After gathering more weather information, this pilot diverted to the south.

Case 4 - Summary Statistics. Below, data for the entire 30 subjects are presented.

Differences in Final Routes. For the most part, there were three reasonably likely route alternatives in Case 4: North of the original route, south of the original route, and the original route (at a higher altitude). Subjects were grouped on the basis of choosing a route similar to the computer-suggested northern deviation, a southern deviation, or the original route. This analysis is presented in Table 15. In terms of fuel consumption and time of arrival, the northern deviation is slightly better than the southern one: A southern deviation consumes 368 lbs. more fuel (about 2% of the fuel consumed by the northern deviation) and takes an additional three minutes. On the other hand, isolated thunderstorms in Texas are sometimes called 'super cells' because of their volatility and unpredictability. A third of the subjects felt the tradeoff in time and fuel was worth the added security of a southern deviation (since the storm was moving northeast).

Insert Table 15 about here

Differences in Detailed Exploration. The number of subjects who explored multiple classes of solutions in each system design condition is summarized in Table 16. Case 4 is like Case 3, in that the 'sketching only' subjects show a trend to not explore multiple classes of solutions in detail as often as subjects in the other two groups. This trend in this direction is only very marginally significant ($\alpha < .142$).

Insert Table 16 about here

Differences in Information Search. As in previous cases, the information which the subjects looked at was analyzed on the basis of treatment condition. The number of subjects in each condition who looked at current or forecast fronts, current or forecast radar weather (composite or at altitude), current or forecast winds at altitude, and jet routes is presented in Table 17. There were no clear differences in the groups.

Insert Table 17 about here

Case 4 - Discussion. Unlike the previous cases, the data do not provide strong evidence that the system design strongly influenced the exploration and plan selection processes of the subjects, although there is a trend toward the 'automatic route constraints' subjects choosing the computer's suggested route more often.

Individual Differences. Although the data again suggest a possible (non-significant) biasing effect due to the computer's automatic suggestion, the primary result of interest is the evidence that pilots differ in their evaluations of alternatives. Some clearly preferred deviating north to save time and fuel. Others clearly preferred the more conservative southern deviation to decrease the likelihood of encountering the storm. (The available data are not informative regarding the causes of such differences. They could be due to different mental models of the weather or air traffic, differences in utility functions, etc.)

Conclusion

It is clear that, for the foreseeable future, it will be infeasible to fully automate tasks like enroute flight planning given the current state of technology. Feasible methods for adequately dealing with reasoning about such complex, uncertain events, and for considering the tradeoffs among goals like safety, cost and passenger comfort, simply do not exist at present.

On the other hand, current and developing technologies seem to offer interesting opportunities for enhancing flight planning activities. Four areas seem most promising:

1. Providing access to more complete and accurate information on weather, air traffic and airport conditions in a timely fashion;

2. Designing better interfaces to provide more perspicuous displays of such data and information and to incorporate graphical interfaces that allow direct manipulation of routes to explore alternatives;
3. Using optimization and expert systems technologies to assist users in generating and evaluating alternative plans and to provide intelligent alerting functions;
4. Using the computer to enhance communication and cooperation among the various people concerned with flight planning (dispatchers, flight crews, ATC, etc).

Consequently, it is critical to address the question: How can advanced technologies be applied to develop cooperative planning systems that effectively support the activities of users?

In spite of the emphasis in this paper on errors induced by FPT, overall the design features of all three versions supported very successful efforts. In Cases 1, 2 and 4, all of the plans selected using all 3 versions of the system were quite acceptable, although some were less efficient in terms of fuel consumption and flight time. The overall efficacy of the design of FPT as a cooperative system was further supported by the reactions of the pilots, such as:

> "I think it's great. It gives you another piece of information to consider. It's like delegating responsibility,"

> "It would be great if you could sit down with your dispatcher and do this sort of thing before a flight."

"I like it. Being able to zoom in on the route and look at the weather and the projections is nice. It's pretty easy to use. It's pretty straightforward. It's got everything you need."

"I wish we had something like this now, especially in operations. You'd have to kill guys to get them off of it."

"I'm pretty impressed by this...If you could get the lunch menu on here too, you'd have it made!"

"Another nice thing that this gives you is the ability to create a route and see what the time and fuel's gonna be. The only thing on the 767, you could put in a different destination and see what fuel burn and time is, but you can't really do a whole routing. I mean, if you want to sit down and pull out a map and draw a course and measure it and do the whole spiel, you could, but that takes forever. It would be nice to have this information."

Nevertheless, as Case 3 most dramatically demonstrated, certain design features can induce unacceptable performances.

There will no doubt be a strong temptation to let technology drive the development of future flight planning systems because the potential value of the available computer and telecommunications technologies seems so apparent. This study, however, provides strong evidence that the design of the computer support system can clearly influence the exploration and evaluation of alternative system plans by users. The data demonstrated that, even when various alternative designs all provide access to the same data, some designs can exert powerful, undesirable effects on the problem-solving processes of the user and on the final product of these processes (the selected flight amendment).

Below we summarize the various undesirable effects observed in this study and discuss recommendations for system designs and future research.

Large "Data Spaces"

In the near future, it will be possible to provide flight planners with access to an incredibly rich set of data relevant to the planning process. As this study illustrated, however, more is not necessarily better.

Even with the limited sources of data available to users of FPT, we saw evidence of:

1. Disorientation;
2. Failure to attend to important data.

Such effects are likely to increase as we provide access to even more data displays.

Some pilots, for instance, failed to recognize that they were looking only at the forecast weather when planning early segments of the flight (where the current weather displays were clearly relevant). The result for one subject (in the 'sketching only' version) in Case 3 was to completely overlook the best solution, and to accept a poor flight plan.

In addition to such "disorientation," some pilots also failed to even look at important data such as the winds. This was a major contributing factor leading to the selection of the less desirable southern deviation in Case 2 by several 'sketching only' subjects.

Several design principles are suggested by such data:

1. When designing the computer system, select the data to display judiciously. Providing access to more kinds of data, even though they may all in principle be useful, does not ensure that they will be used effectively at the right time;
2. Develop good representations to make the implications of important data and relationships salient to the user. (One interesting example

of a problem was discovered with current displays of wind information: A number of pilots did not know how to interpret wind charts regarding the strength or direction of the winds.)

3. Consider designing integrated data displays to communicate information pertinent to a common goal for which those types of data are pertinent. FPT demonstrates the integration of weather data with displays of alternative flight paths. Displays that integrate data on precipitation and turbulence at different altitudes would similarly be useful (but not trivial to design);
4. Provide clear feedback about the state of the display (such as whether the displayed data represents current or forecast weather). It is not enough to present such data on the state of the display. It must be highly salient;
5. Consider incorporating intelligent alerting functions to ensure that critical data (or the implications of these data) are not overlooked.

Large "Solution Spaces"

Because of the large number of possible flight paths, the subjects in the 'sketching only' version sometimes had difficulty finding a good alternative. In circumstances where time is critical, such difficulties could also use up valuable time and attention.

This problem suggests the potential value of tools (based on optimization or expert system technologies) to help search for good solutions. Indeed, without such tools, the subjects frequently found solutions that used up significantly more flight time and fuel and were no better in terms of other criteria. One subject, for instance, selected a plan in Case 3 that used up 24% more fuel.

A counterargument to utilizing such technologies is that they are brittle. They may be good for routine situations that the designer has anticipated but they also fail unacceptably in unanticipated situations. Such a line of argument continues by suggesting that we keep the person "in the loop" by making him do more of the work, and by suggesting that, because he must therefore stay involved, he will notice and deal with unusual situations. In short, this argument suggests that, although people won't always find the best solution, by keeping them involved we will avoid bad solutions. Clearly, the extreme form of this argument is a "straw man." People make errors too. Consequently, we must somehow weigh the tradeoffs between the potential errors made by the designer (including those for situations that we don't know about, since otherwise the designer could design for them!) and errors made by users, and to design assuming both the designers and users are fallible.

Case 3 provided a nice illustration of the fact that keeping the person "in the loop" doesn't ensure that poor solutions will be avoided: One of the 'sketching only' subjects generated and selected the poor eastern route on his own. Thus, a principle like "avoid excessive automation in order to keep the person involved in the task" is too simplistic. Keeping the person involved does not ensure more exploration, nor does it ensure solutions will be chosen that are at least satisfactory. Instead, we must consider how specific types of designs will interact with users' cognitive processes in specific types of scenarios to produce undesirable behaviors. (The discussions of results for Cases 1 and 3 provide illustrations of such cognitive models.) In terms of this application area, what we need is a design that lets the computer use its power to help search the solution space, while keeping the person involved *and* while protecting against errors the person may make. The first two problems might be addressed by either:

1. Developing sophisticated perceptual displays that make alternatives easier to generate and evaluate. (One possibility would be a display

that allowed the user to prune undesirable jet route segments by setting constraints (e.g., telling the computer to hide or dim all jet routes on the map that pass through more than light turbulence);

2. Using optimization or expert systems technologies to let the computer generate alternatives (which is what FPT does using the route constraints tool), but improving the design by having the computer generate the best alternative(s) for each class of solutions, and then letting the user evaluate these alternatives. Thus, the computer might display the "best" deviations both north and south of a storm for comparison by the user.

We speculate that both of these potential solutions would keep that person involved because he would have to look at the data to make choices among alternatives.

A solution to the third problem is more complicated, though, as we need to first predict the nature of the errors the person might make. This is discussed further below.

Overreliance

As pointed out above, system users sometimes develop poor plans even when they are kept "in the loop." (Case 3 illustrated this behavior.) On the other hand, because of the limitations and brittleness of the technology used in FPT, the route constraints function also produced a poor suggestion in Case 3. (This resulted from the fact that FPT does not reason about the uncertainty associated with forecasts.) Our study illustrated that, even though subjects in the automatic suggestion version used the available "manual" functions to explore alternatives to the computer's suggestion, 40% still wound up accepting this poor plan. Two points are worth emphasizing based on this result:

1. The effects of providing automatic suggestions by the computer can be quite pronounced. Subjects in Cases 1 and 3 who were presented

with the computer's suggestion clearly reasoned less (or not at all) about the uncertainty associated with the forecast, leading them to accept a poor flight plan in Case 3;

2. These effects cannot be explained by a simple label like "overreliance." The design of the computer influences users in a complex, scenario-specific fashion. (The discussions of the results for Cases 1 and 3 present cognitive models of such effects.) Thus, to evaluate proposed support tools, scenario-sensitive cognitive models need to be considered.

This failure by subjects to reason about uncertainty when viewing the computer's suggestion might be alleviated by either of the two solutions outlined above. Just as using the 'sketching only' version induced subjects to look at critical data, causing them to ask the question "which path is better if the forecast is wrong," requiring subjects to choose from among several alternatives suggested by the computer might induce them to look at the critical data and ask the same question.

A further form of protection against such failures to consider uncertainty would be the incorporation of an intelligent alerting function that either:

1. Warned the person when a route might be "too close" to a developing problem;

or 2. Inhibited the display of a suggested route by the computer if it appeared to be "too close" to a developing problem (thus making the computer very conservative in suggesting alternatives).

One caution is in order regarding these potential solutions, however. Subjects may fixate on the alternative solutions suggested by the computer and consequently fail to note an even better solution that the computer missed or fail to note that the computer has suggested a poor solution.

Maladaptive Strategies

The literature on human problem-solving provides numerous examples of how, in order to reduce the complexity of a decision, people apply simplifying heuristics (Elstein, Shulman and Sprafka, 1978). One such strategy is to eliminate an alternative based on a single criterion, rather than evaluating the alternative more globally (in terms of all of the relevant criteria). In Case 3, this type of strategy was exhibited by subjects using all three versions of the system. The result was the selection of a poor plan by 10% of the subjects in the 'sketching only' version, 30% of the subjects in the 'sketching and route constraints' version and 40% of the subjects in the automatic suggestion version.

Having the computer indicate several possible solutions might help encourage a more global evaluation. In addition, it might be helpful to use animation to create displays to help the user view the data over the entire flight, and to include redundancy in the evaluation of plans (e.g., letting the flight crew look at displays of paths proposed by a dispatcher or vice versa).

Supporting Individual Differences

Finally, results like those in Case 4 provide strong evidence for the need to give the person the option to explore alternatives on their own. Because people differ in terms of their preferences and mental models of a situation, and because we have no objective way to say who is "right" for each such situation, we need to give people the tools necessary to allow them to create their own alternatives and to play "what if" games, even if the computer provides some suggestions.

Final Note

This study demonstrates that the design of an effective cooperative system for a complex task like flight planning is a significant challenge. It requires careful consideration of how system design features influence the cognitive processes of users in specific types of scenarios. While there are important directions for further research, the results highlight a number of considerations for designers of flight planning systems to support dispatchers and flight crews in particular, and as well as for designers of cooperative problem-solving systems in general.

Are such considerations worth the effort? The ability of a system design to induce 40% of the pilots to select a poor flight plan suggests that there is indeed a very real need to explore these issues further and to take them seriously when implementing commercial systems.

Acknowledgements

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Table 1. Planning objects.

1. boiling water;
2. kitchen;
3. coffee-bean store;
4. grinder store;
6. coffee grinder;
7. brewed-coffee store;
8. bank;
9. money.

Table 2. ABSTRIPS operators.

Operator	*Preconditions*	*Postconditions*
pour coffee	have brewed coffee	problem solved
make coffee	have beans have grinder have boiling water be in kitchen	have brewed coffee
buy something	be at store have money	have something
go somewhere	place exists	be at place not at any other place
get money	be at bank	have money
boil water	be in the kitchen	have boiling water

Table 3. Partial ordering supplied to ABSTRIPS.

Precondition	*Initial criticality*
place exists	3
have something	2
be somewhere	1

Table 4. ABSTRIPS precondition critically values.

Precondition	*Criticality*
bean store exists	5
brewed-coffee store exists	5
bank exists	5
kitchen exists	5
have grinder	4
have beans, boiling water, money	2
be at brewed coffe store, bean store, bank	1

Table 5. Number of classes of solutions explored in Case 1.

	# of Subjects Who Explored Multiple Classes	# of Subjects Who Explored A Single Class
Sketching	4	6
Constraints	0	10
Auto	0	10

Table 6. Number of specific routes explored in Case 1.

	# of Subjects Who Explored Multiple Routes	# of Subjects Who Explored A Single Route
Sketching	6	4
Constraints	1	9
Auto	1	9

Table 7. Information search performance in Case 1.

	Fronts	Radar	Winds	Jet Routes
Sketch	9	9	7	10
Constraints	8	10	5	9
Auto	9	9	6	5

Table 8. Routes selected in Case 2.

	North	South	Radar
Sketch	6	4	10
Constraints	9	1	10
Auto	10	0	10

Table 9. Number of classes of solutions explored in Case 2.

	# of Subjects Who Explored Multiple Classes	# of Subjects Who Explored A Single Class
Sketching	8	2
Constraints	5	5
Auto	4	6

Table 10. Number of specific routes explored in Case 2.

	# of Subjects Who Explored Multiple Routes	# of Subjects Who Explored A Single Route
Sketching	8	2
Constraints	6	4
Auto	5	5

Table 11. Case 2 information search characteristics.

	Fronts	Radar	Winds	Jet Routes
Sketch	7	10	7	10
Constraints	7	10	3	9
Auto	8	9	7	8

Table 12. Final route choices for Case 3.

	Computer-Suggested Eastern Route	Other
Sketch	1	9
Constraints	3	7
Auto	4	6

Table 13. Number of solution classes explored in Case 3.

	# of Subjects Who Explored Multiple Classes	# of Subjects Who Explored A Single Class
Sketching	5	5
Constraints	3	7
Auto	9	1

Table 14. Information search in Case 3.

	Fronts	Radar	Winds	Jet Routes
Sketch	10	10	5	10
Constraints	6	10	1	7
Auto	8	10	5	9

Table 15. Final route choices for Case 4.

	North	South	Original
Sketch	5	4	1
Constraints	5	4	1
Auto	7	2	1

Table 16. Number of solution classes explored in Case 4

	# of Subjects Who Explored Multiple Classes	# of Subjects Who Explored A Single Class
Sketching	6	4
Constraints	5	5
Auto	9	1

Table 17. Information search characteristics for Case 4.

	Fronts	Radar	Winds	Jet Routes
Sketch	8	10	6	10
Constraints	7	10	4	8
Auto	6	10	4	9

List of Figures

FIGURE 1

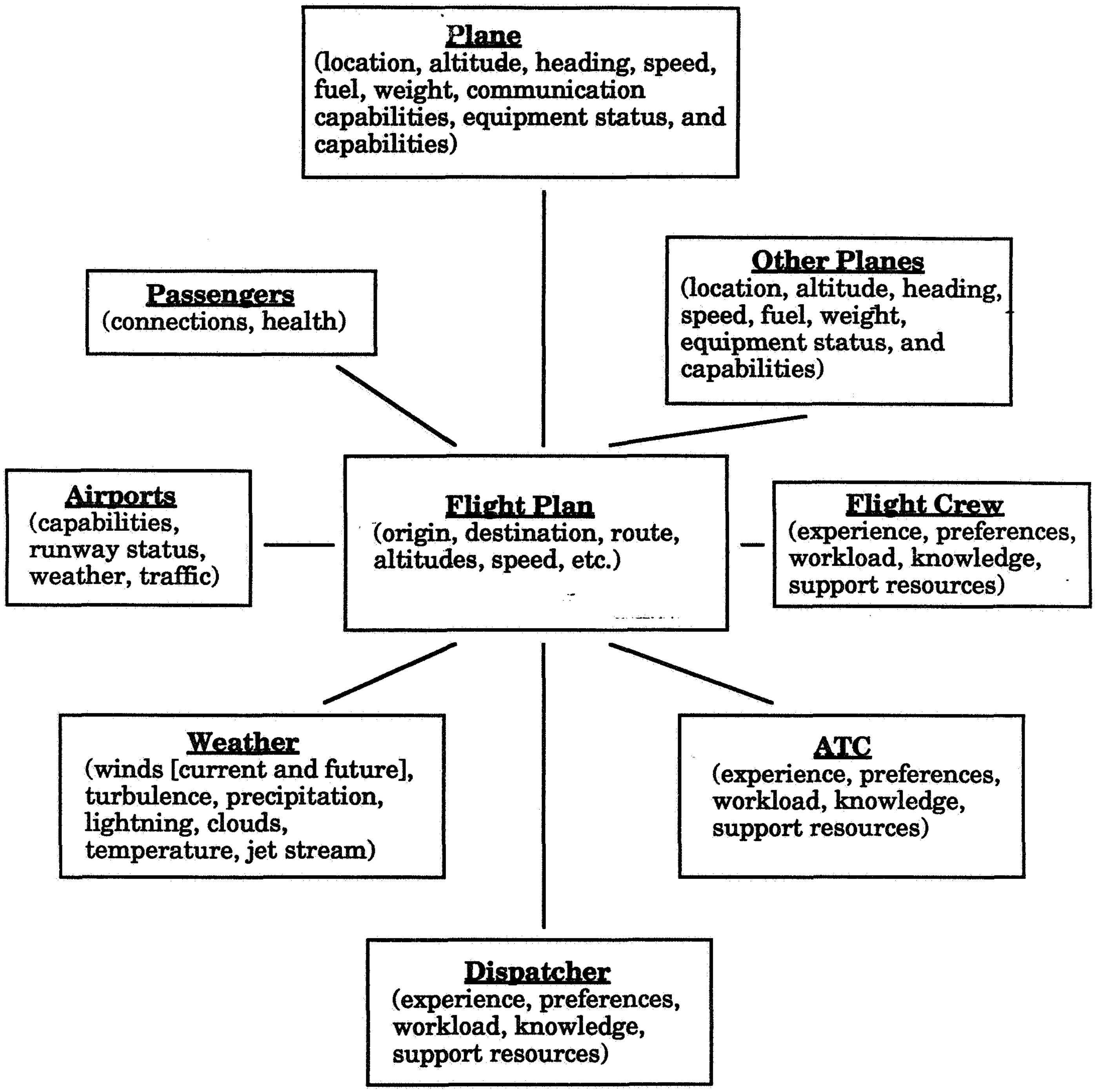
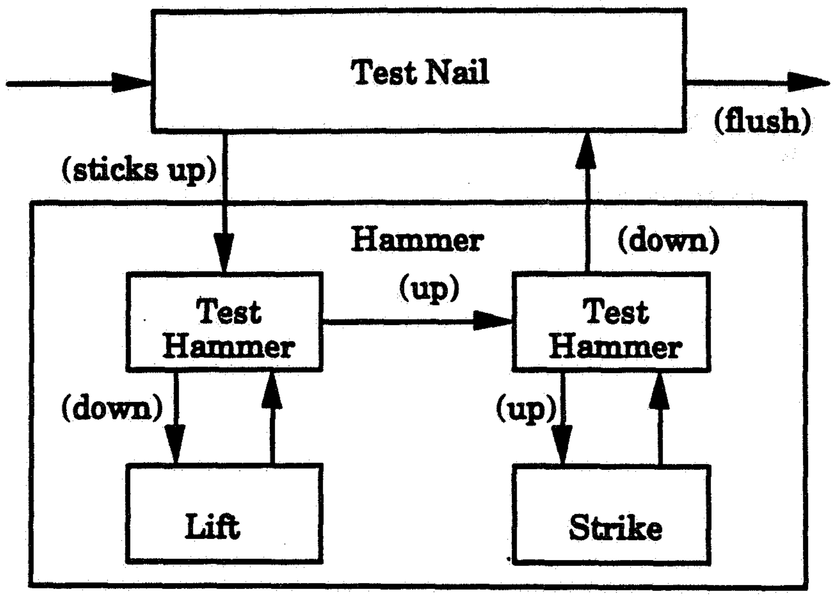
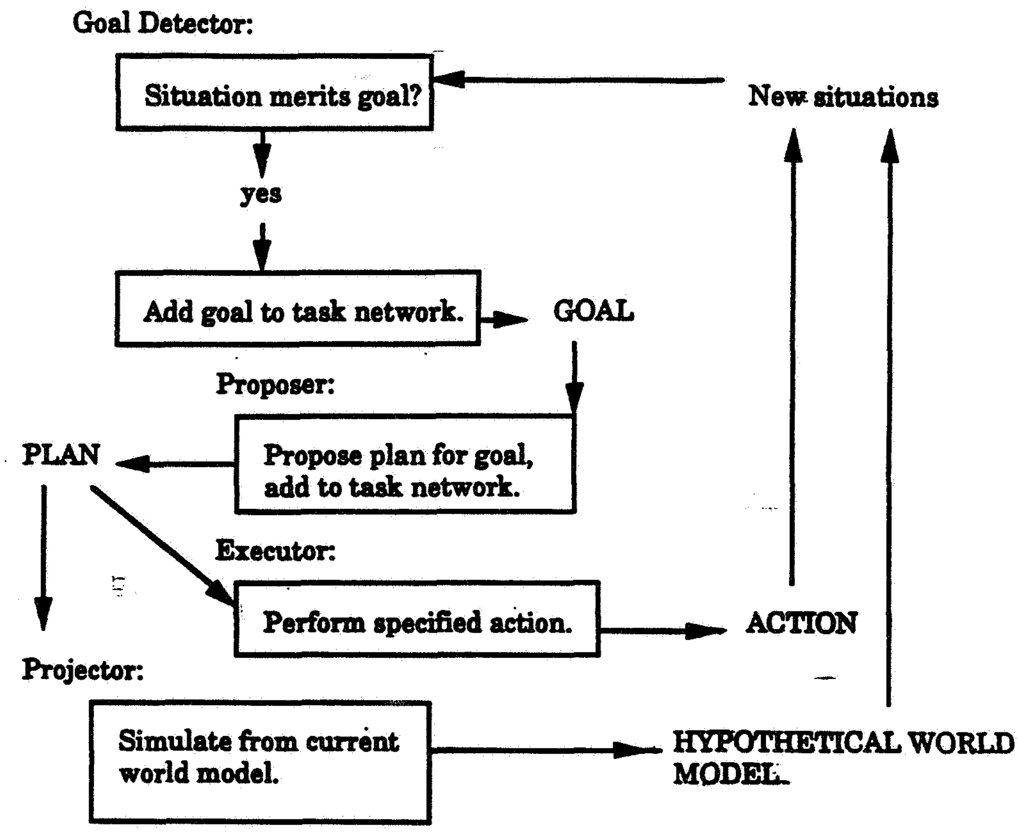

Plane
(location, altitude, heading, speed, fuel, weight, communication capabilities, equipment status, and capabilities)
Passengers
(connections, health)
Other Planes
(location, altitude, heading, speed, fuel, weight, equipment status, and capabilities)
Airports
(capabilities, runway status, weather, traffic)
Flight Plan
(origin, destination, route, altitudes, speed, etc.)
Flight Crew
(experience, preferences, workload, knowledge, support resources)
Weather
(winds [current and future], turbulence, precipitation, lightning, clouds, temperature, jet stream)
ATC
(experience, preferences, workload, knowledge, support resources)
Dispatcher
(experience, preferences, workload, knowledge, support resources)

FIGURE 2

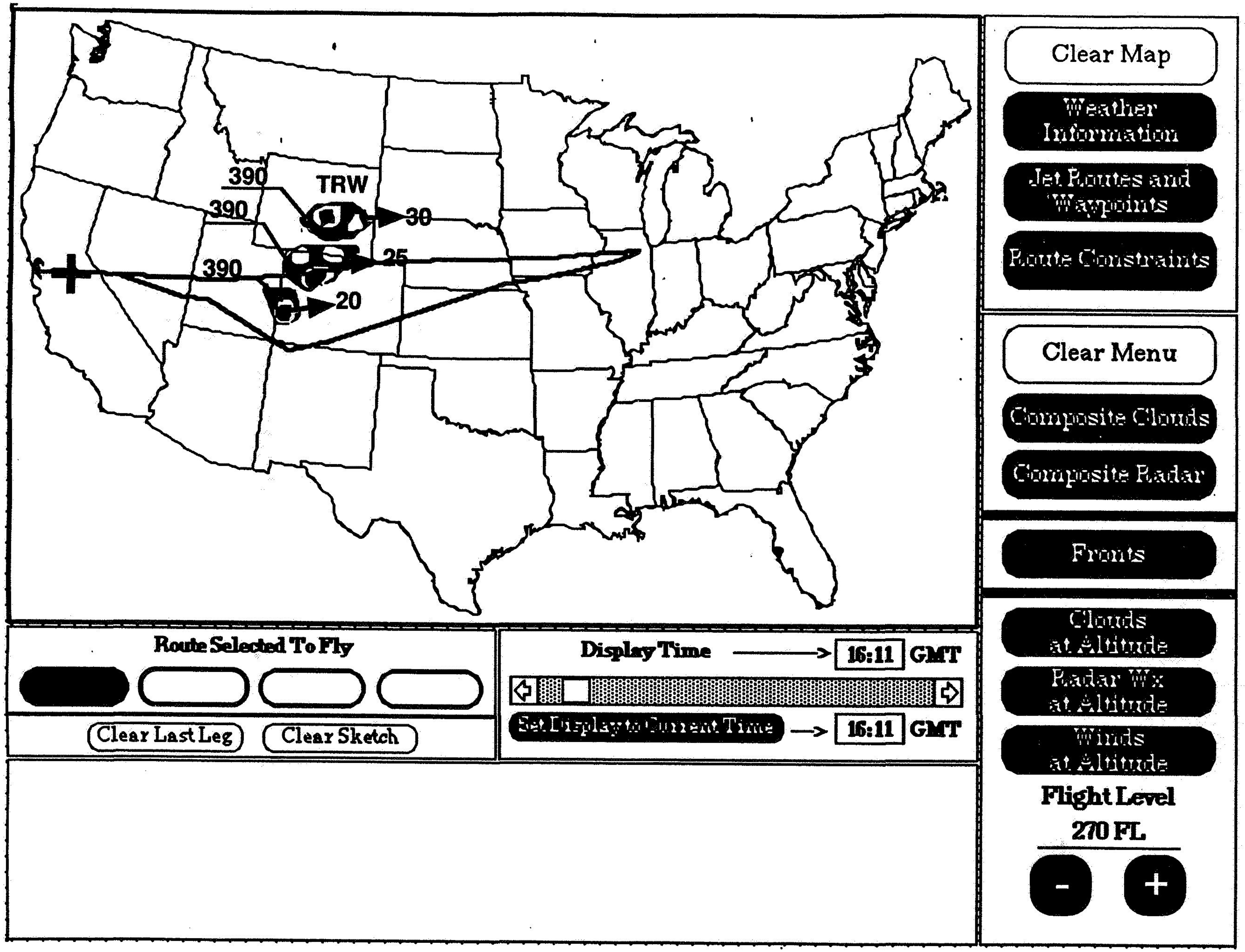


Test Nail
(flush)
(sticks up)
Hammer
(down)
(up)
Test
Hammer
Test
Hammer
(down)
(up)
Lift
Strike

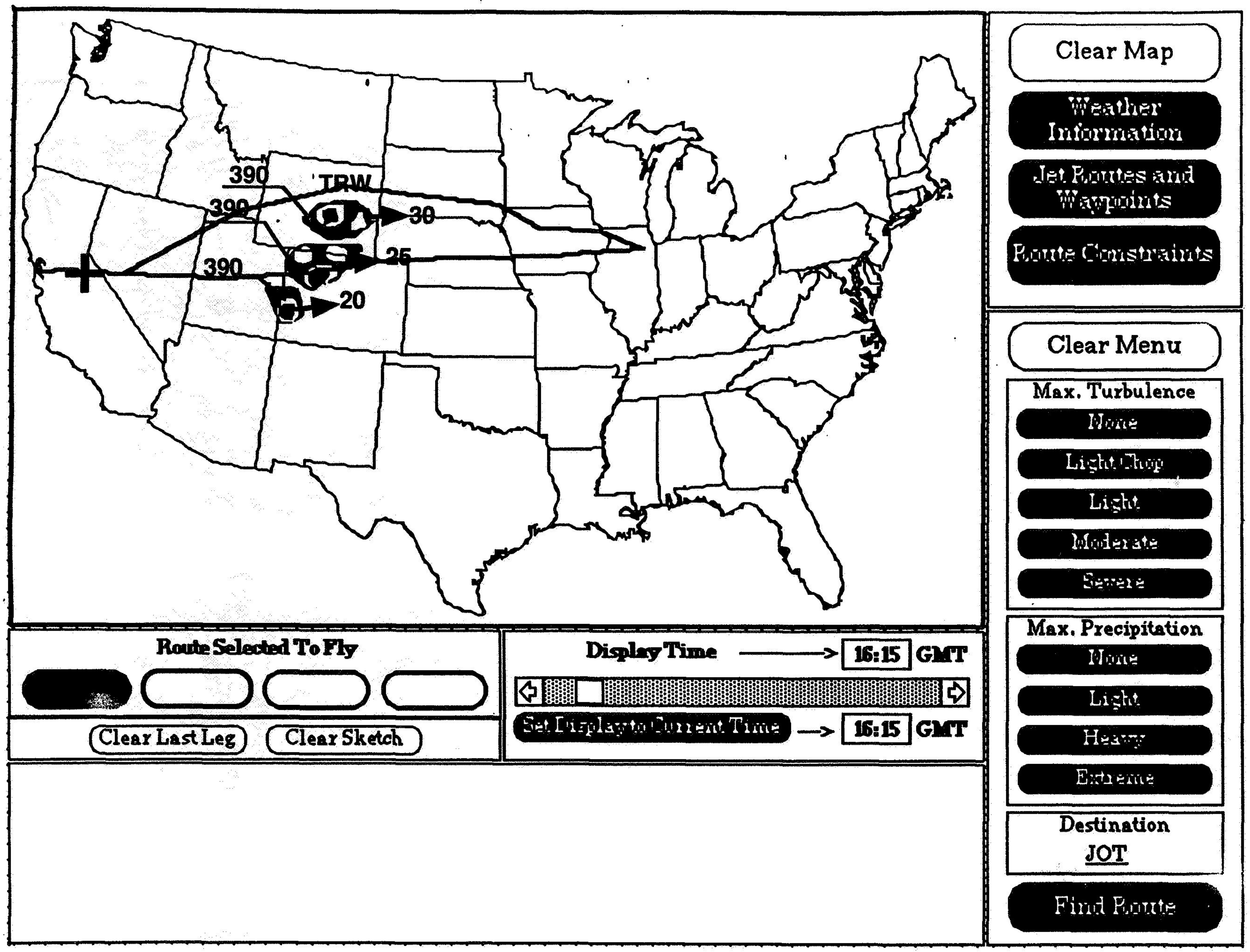
FIGURE 3



Goal Detector:
Situation merits goal?
yes
Add goal to task network.
GOAL
Proposer:
Propose plan for goal, add to task network.
PLAN
Executor:
Perform specified action.
ACTION
Projector:
Simulate from current world model.
HYPOTHETICAL WORLD MODEL.
New situations

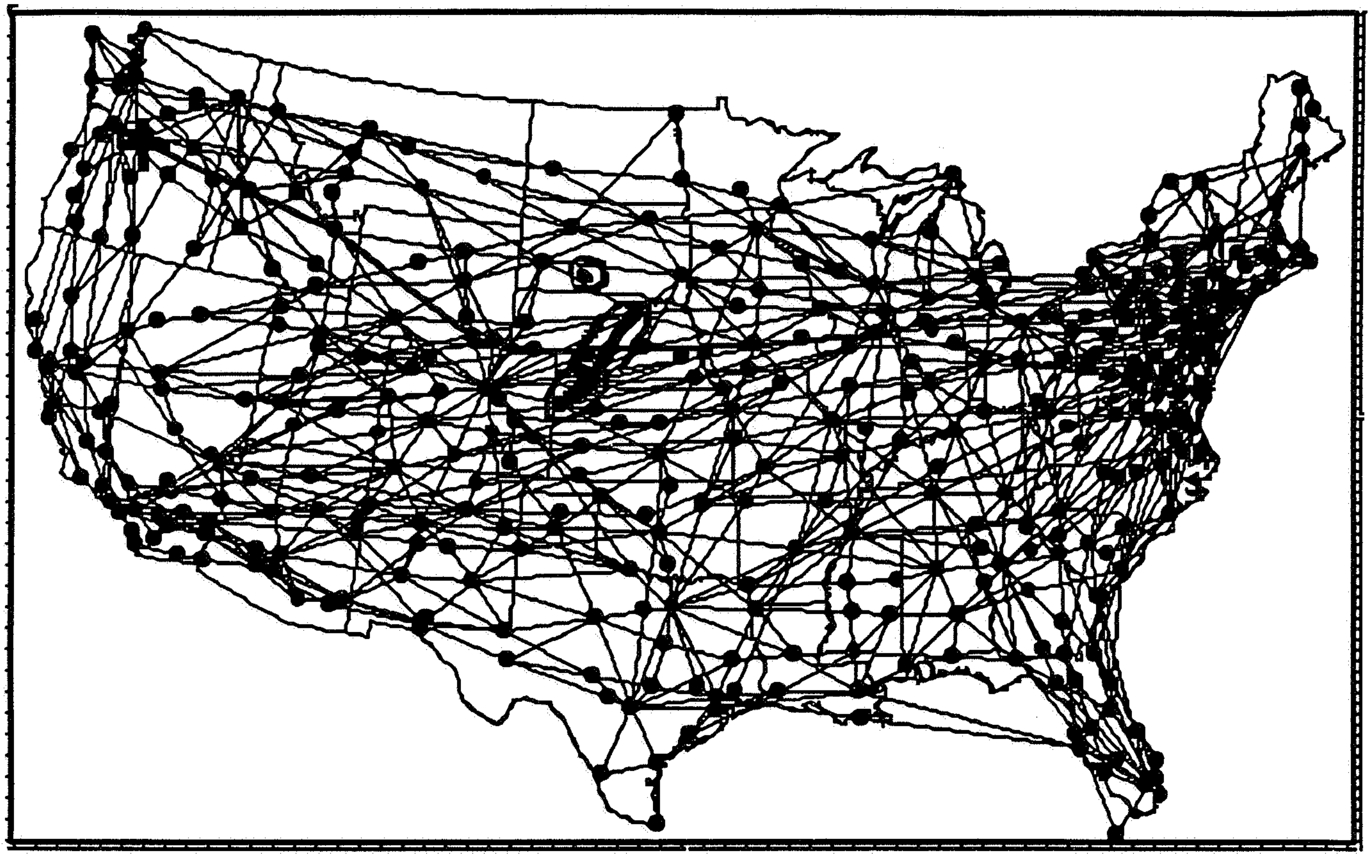


390
TRW
30
390
25
390
20
Clear Map
Weather Information
Jet Routes and Waypoints
Route Constraints
Clear Menu
Composite Clouds
Composite Radar
Fronts
Clouds at Altitude
Radar Wx at Altitude
Winds at Altitude
Flight Level
270 FL
-
+
Route Selected To Fly
Clear Last Leg
Clear Sketch
Display Time
16:11 GMT
Set Display to Current Time
16:11 GMT



390
TRW
390
30
25
390
20
Clear Map
Weather Information
Jet Routes and Waypoints
Route Constraints
Clear Menu
Max. Turbulence
None
Light Chop
Light
Moderate
Severe
Max. Precipitation
None
Light
Heavy
Extreme
Destination
JOT
Find Route
Route Selected To Fly
Clear Last Leg
Clear Sketch
Display Time
16:15 GMT
Set Display to Current Time
16:15 GMT

FIGURE 6

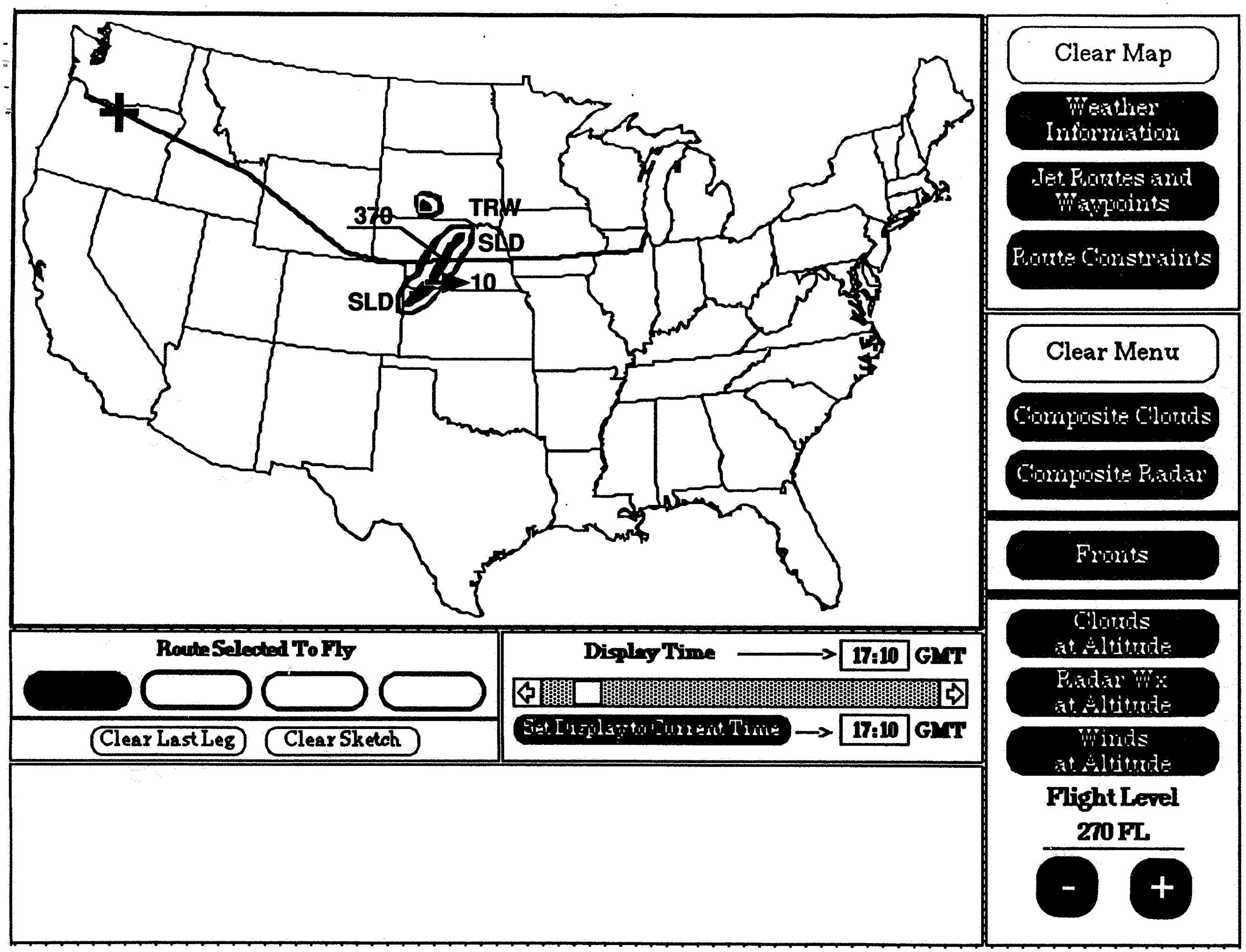


Display Display Display Display

Save Clear Copy Calculate	Route:	OBH	010	DSM	010	IOW	060	JOT
	Altitude: Speed:		FL 330 Mach .66		FL330 Mach .70		FL 270 Mach .62	
Time of Arrival (G.M.T.):		1953		2026		2039		2103
Fuel Remaining (1000 lbs):		18		14		13		11
Distance (miles): Next Info			211		91		148	

		OBH	010	DSM	010	IOW	060	JOT
	FL 330		moder					
Turbulence	FL 290		moder					
Wind Components								
Wind Direction/Speed	FL 270		moder					
	FL 250		moder					
Least Fuel Altitude	FL 230		moder					
Planned Altitude	GRND							

Time of Arrival:	21:13 GMT	Time of Arrival:	20:55 GMT	Time of Arrival:	20:55 GMT	Time of Arrival:	19:01 GMT
Time Enroute:	4:13	Time Enroute:	3:55	Time Enroute:	3:55	Time Enroute:	2:01
Fuel Remaining:	10952 lbs	Fuel Remaining:	13054 lbs.	Fuel Remaining:	13054 lbs	Fuel Remaining:	26581 lbs
Total Distance:	1606 nm	Total Distance:	1524 nm	Total Distance:	1524 nm	Total Distance:	770 nm



370
TRW
SLD
10
SLD
Clear Map
Weather Information
Jet Routes and Waypoints
Route Constraints
Clear Menu
Composite Clouds
Composite Radar
Fronts
Clouds at Altitude
Radar Wx at Altitude
Winds at Altitude
Flight Level
270 FL
-
+
Route Selected To Fly
Clear Last Leg
Clear Sketch
Display Time
17:10 GMT
Set Display to Current Time
17:10 GMT

FIGURE 9

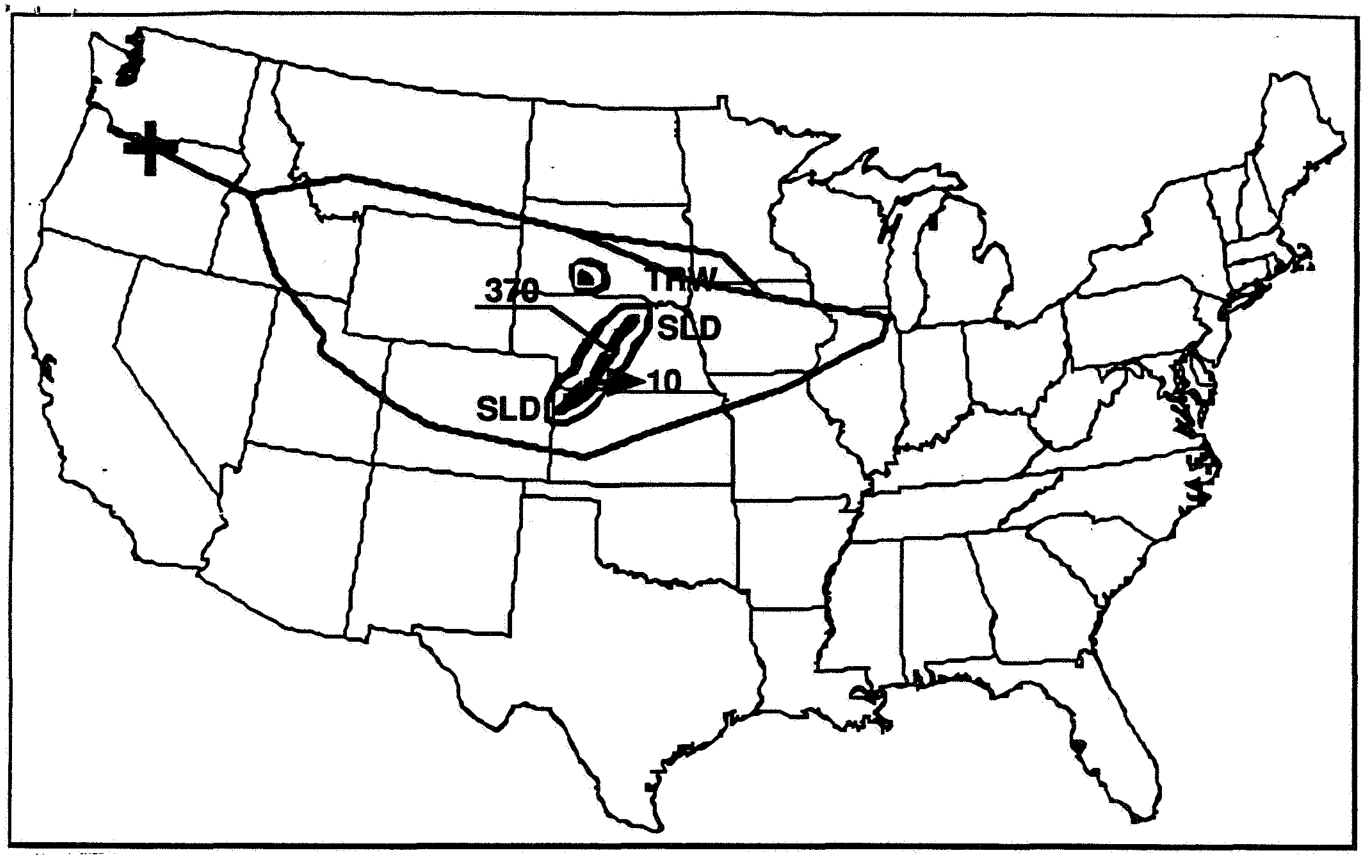


FIGURE 10

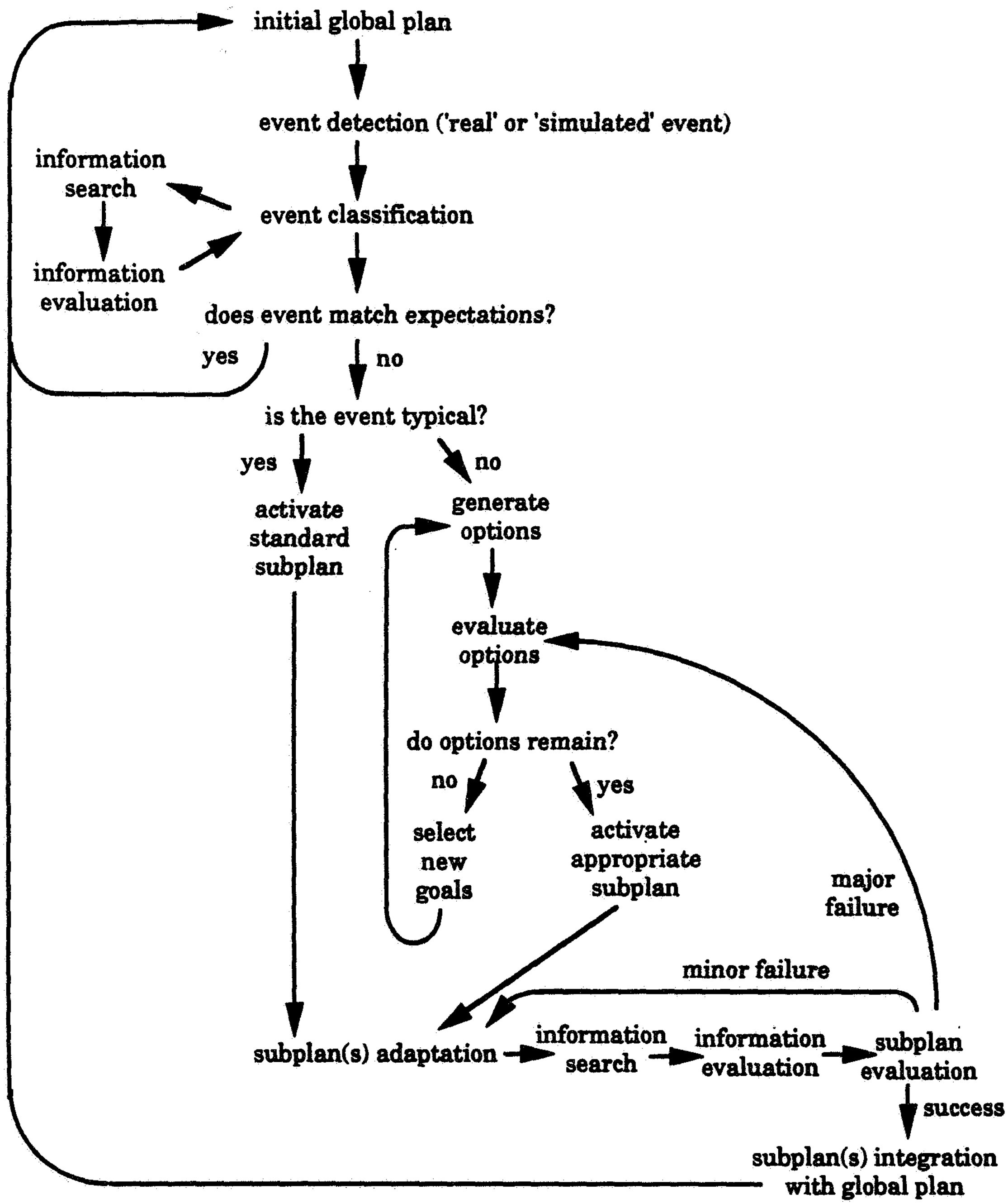
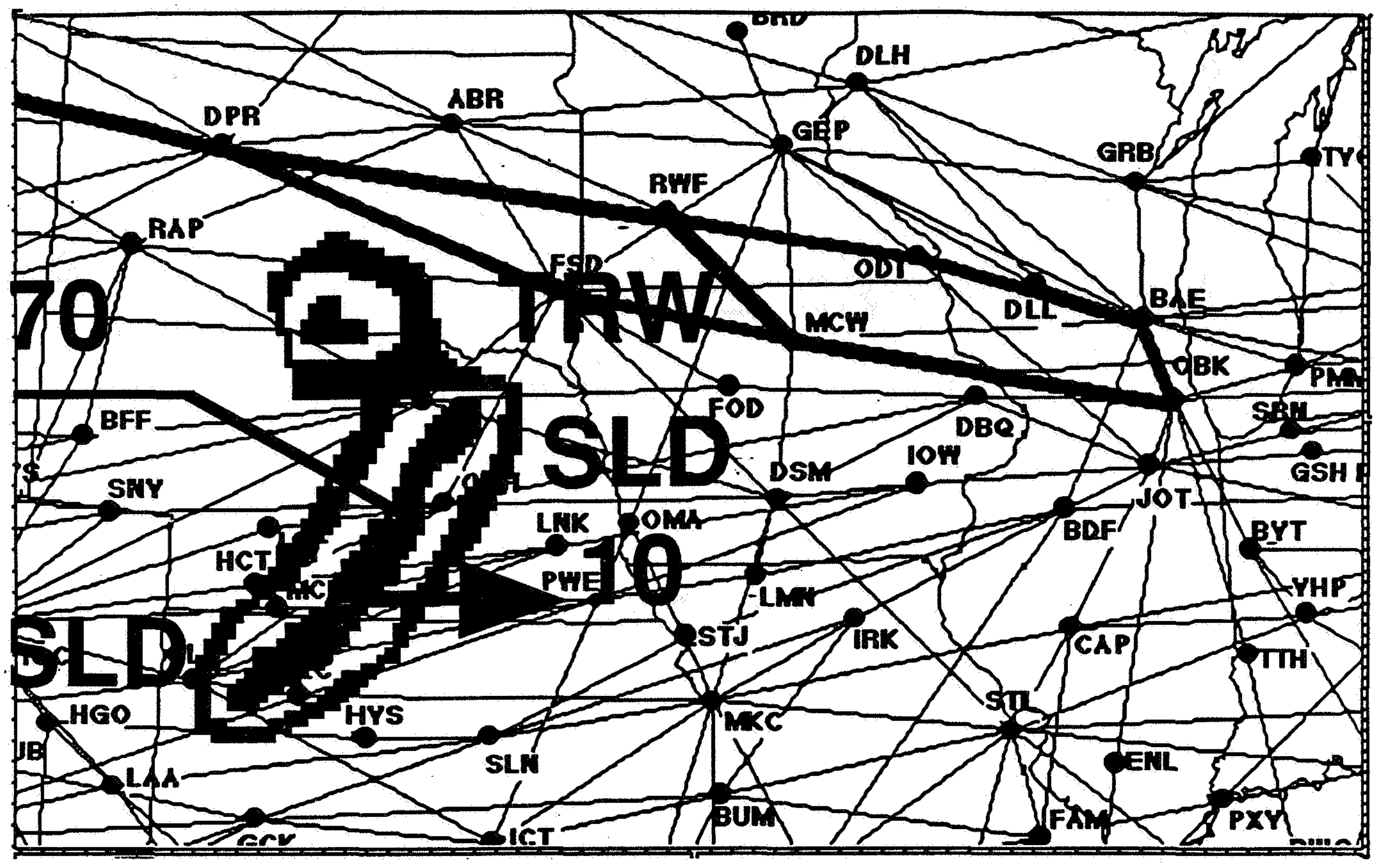

initial global plan
event detection ('real' or 'simulated' event)
information search
event classification
information evaluation
does event match expectations?
yes
no
is the event typical?
yes
no
activate standard subplan
generate options
evaluate options
do options remain?
no
yes
select new goals
activate appropriate subplan
major failure
minor failure
subplan(s) adaptation
information search
information evaluation
subplan evaluation
success
subplan(s) integration with global plan

FIGURE 11



DLH
DPR
ABR
GEP
GRB
RWF
RAP
FSD
ODT
70
TRW
MCW
DLL
BAE
OBK
FOD
BFF
SLD
DBQ
SBN
IOW
GSH
DSM
SNY
JOT
LNK
OMA
BDF
BYT
HCT
10
PWE
LMN
YHP
SLD
STJ
IRK
CAP
TTH
STL
HGO
HYS
MKC
SLN
ENL
LAA
BUM
FAM
PXY

FIGURE 12

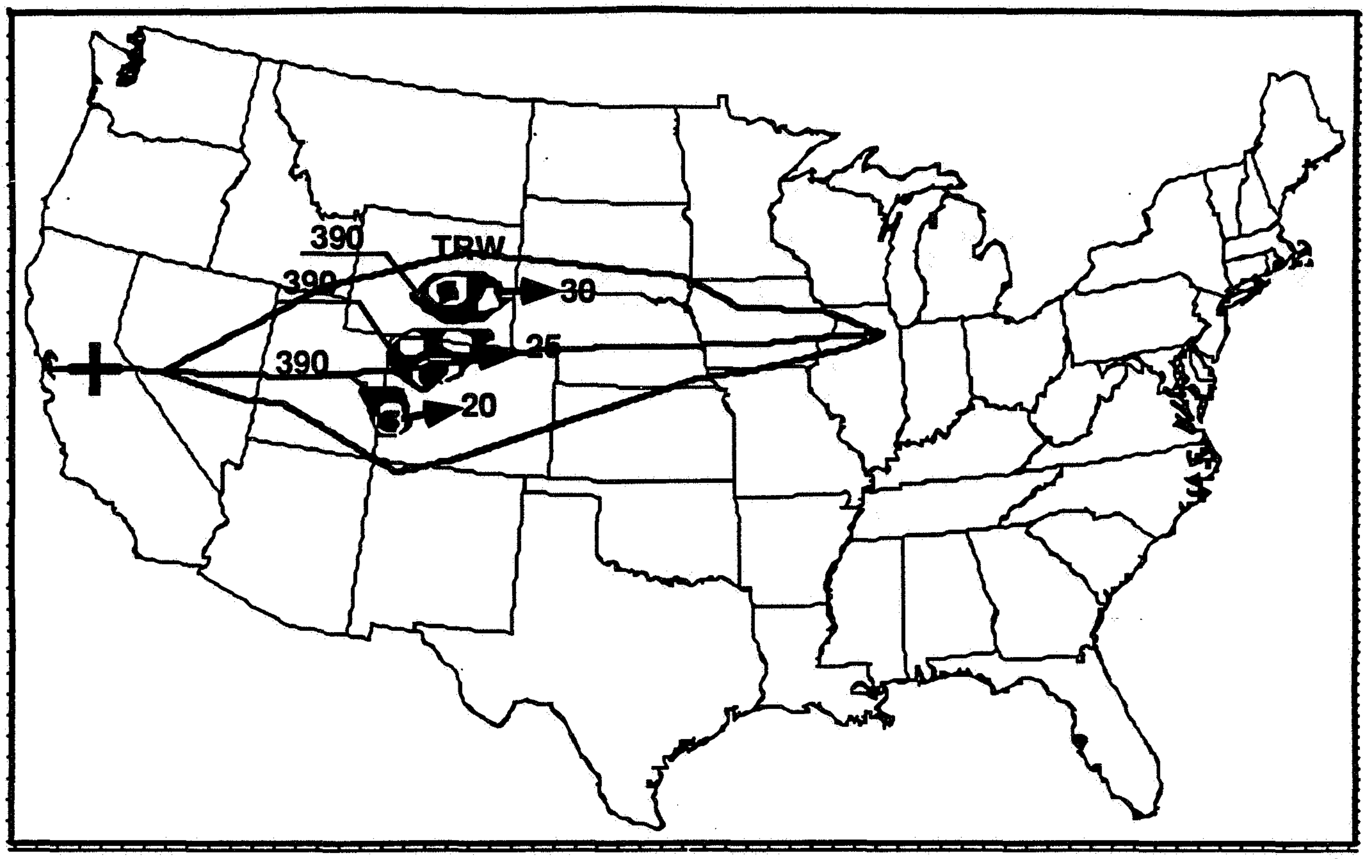


FIGURE 13

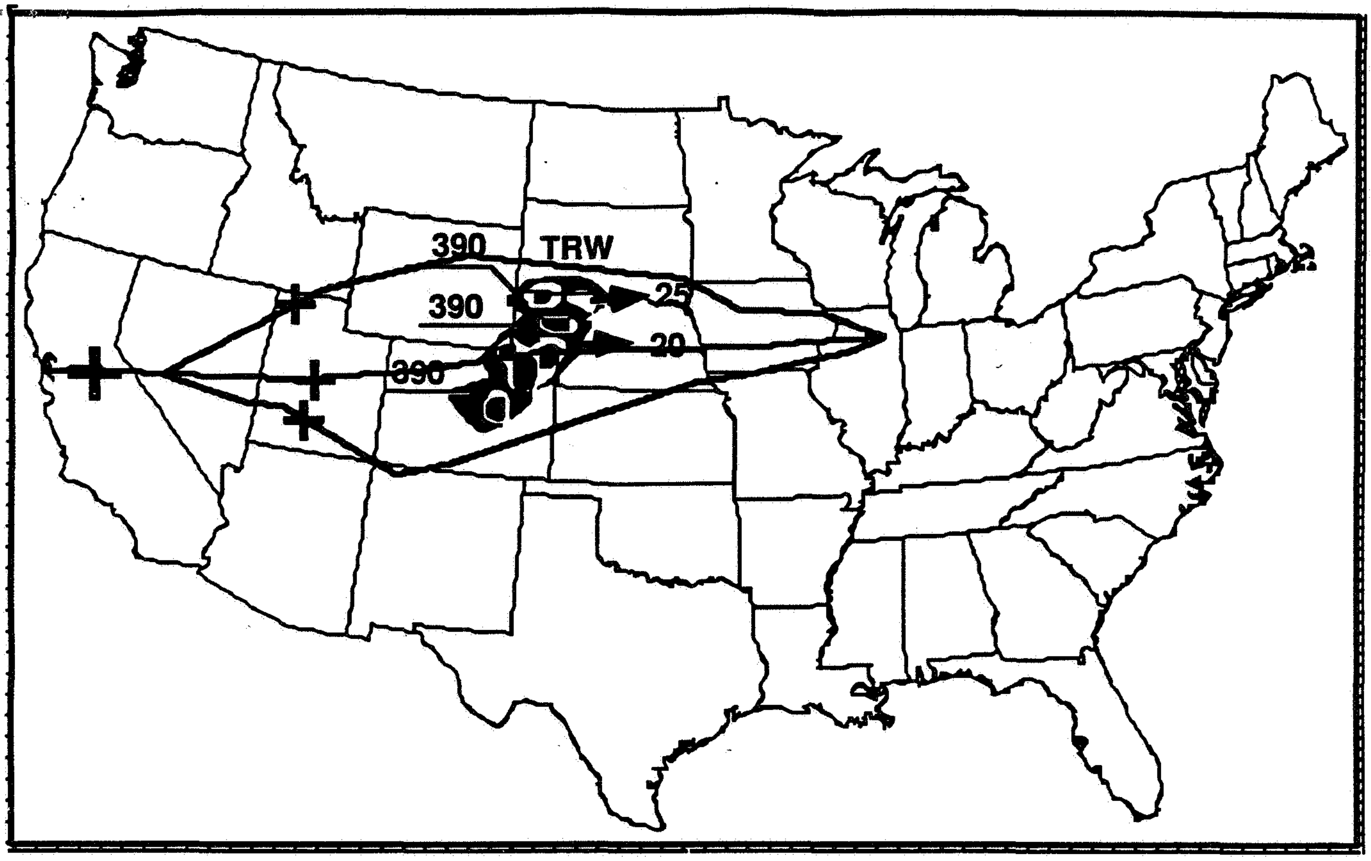
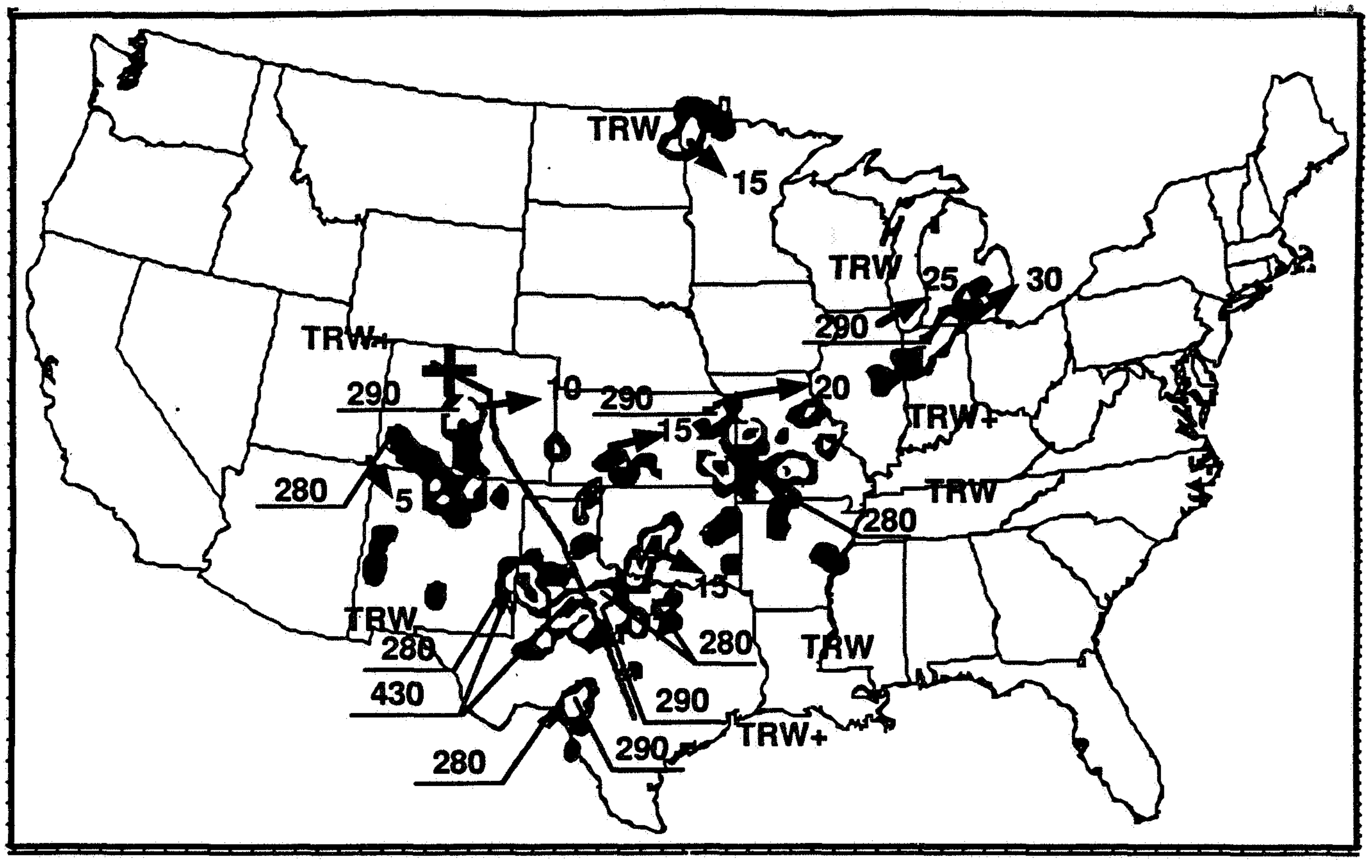
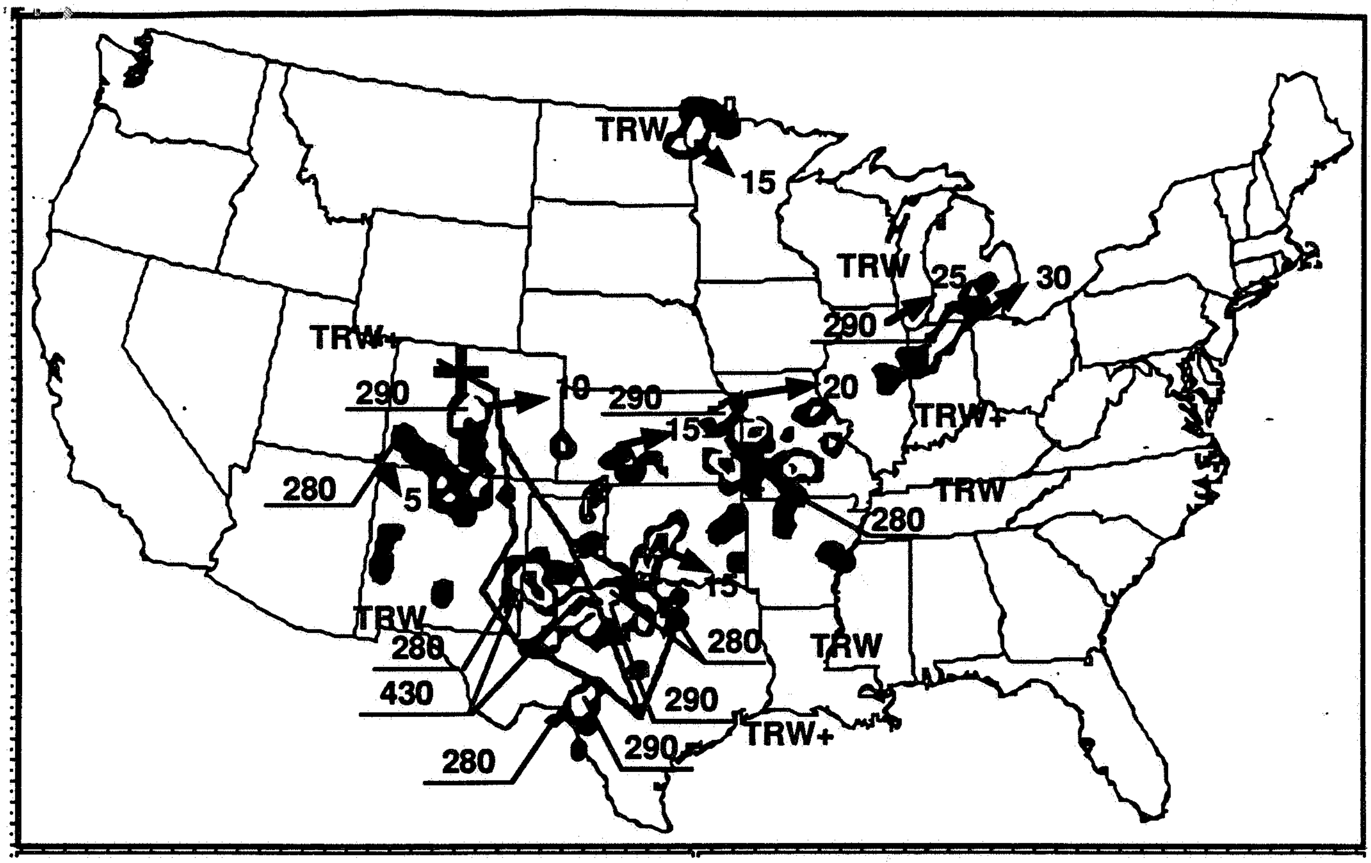


FIGURE 14



TRW
15
TRW
25
30
290
TRW+
290
10
290
20
15
TRW+
280
5
TRW
280
15
TRW
280
280
TRW
430
290
TRW+
280
290

FIGURE 15



TRW
15
TRW
25
30
290
TRW+
290
10
290
20
TRW+
15
280
5
TRW
280
15
TRW
280
280
TRW
288
430
290
280
290
TRW+

FIGURE 16

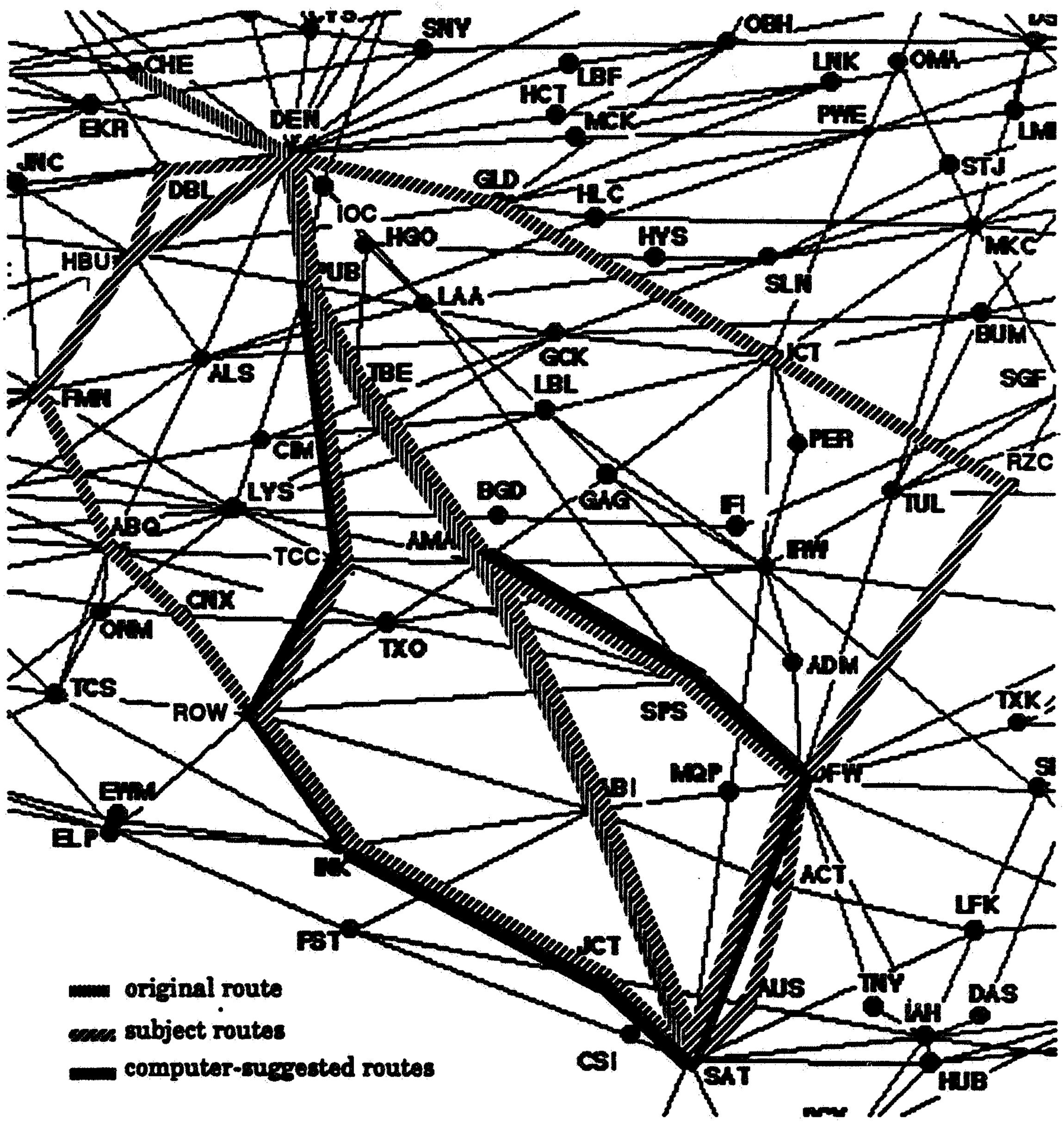
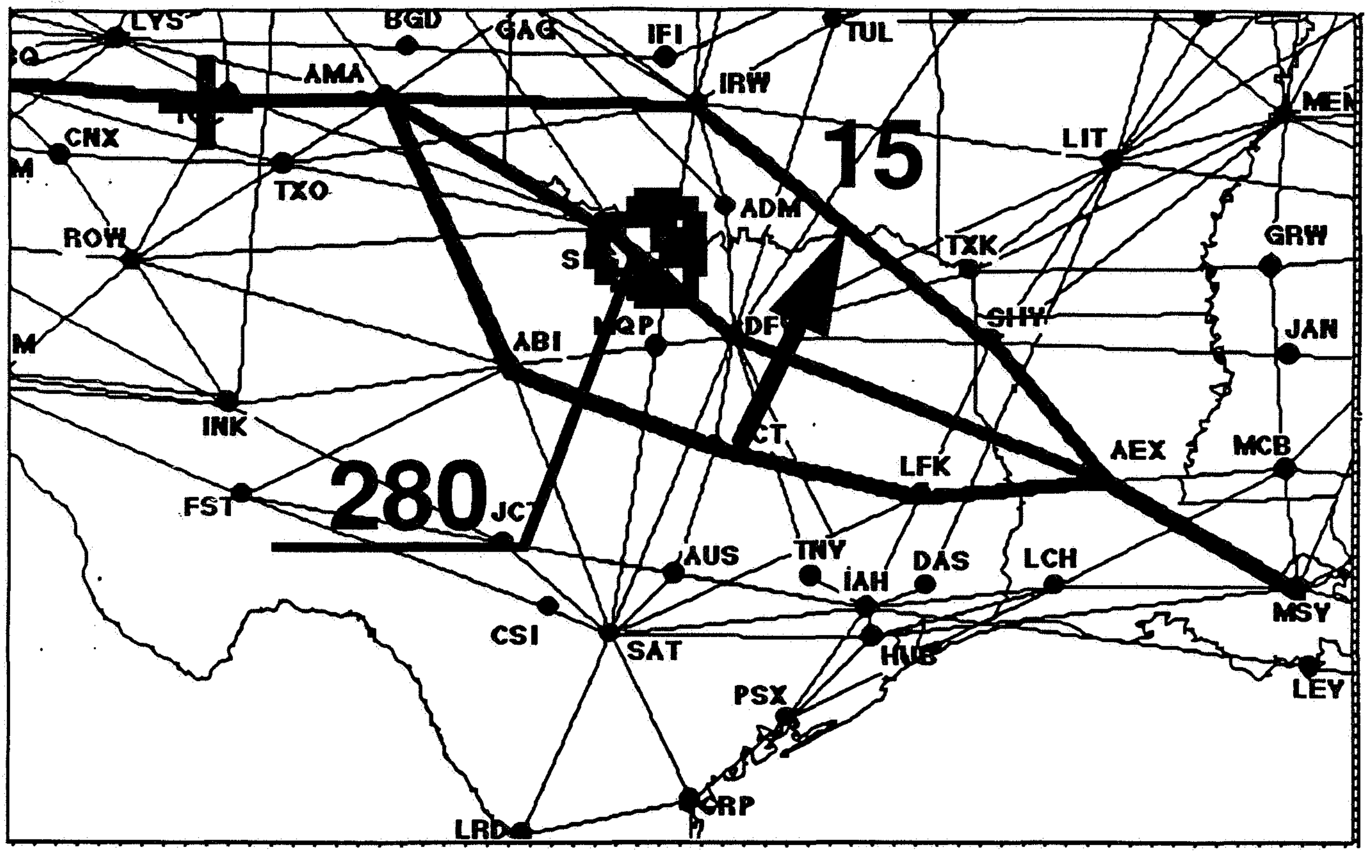

SNY
OBH
CHE
LBF
HCT
LNK
OMA
EKR
DEN
MCK
PWE
JNC
GLD
HLC
STJ
DBL
IOC
HGO
HYS
MKC
HBU
PUB
LAA
SLN
BUM
GCK
ICT
ALS
TBE
SGF
FMN
LBL
PER
CIM
RZC
LYS
BGD
GAG
TUL
ABQ
TCC
AMA
IRW
CNX
ONM
TXO
ADM
TCS
ROW
SPS
TXK
EWM
MQP
DFW
ELP
INK
ACT
LFK
FST
JCT
AUS
TNV
DAS
IAH
CSI
SAT
HUB
original route
subject routes
computer-suggested routes

FIGURE 17



LYS
BGD
GAG
IFI
TUL
AMA
IRW
MEM
CNX
TXO
15
LIT
ADM
ROW
TXK
GRW
SHV
JAN
ABI
MQP
DFW
INK
ACT
AEX
MCB
LFK
280
FST
JCT
AUS
TNY
DAS
LCH
IAH
MSY
CSI
SAT
HUB
LEY
PSX
CRP
LRD