Use of a Knowledge-Based Expert System to Maximize Airport Capacity in Harmony with Noise-Mitigation Plans

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Noise control and capacity are major concerns at many major airports. Expected growth will exacerbate these problems. Because of high cost and public opposition to new facilities, managers are trying to squeeze what they can out of the existing airports. Unfortunately, requirements for noise control and capacity are seldom in harmony. An appropriate balance between noise abatement and capacity requires considerable analysis and compromise. The overriding concern at many airports is compliance with noise limits mandated by law or regulation. Effects on capacity are secondary as long as they do not interfere with regular operations. However, congestion and delay during peak hours are forcing some airports to reevaluate their noise-abatement strategies. New computer tools are needed by the airport operators and noise-control specialists to analyze the effects of noise-mitigation measures on capacity. The use of artificial intelligence may be one way to use computers to assist in the noise mitigation/capacity analysis. This paper explores the use of expert systems, a subset of artificial intelligence, to accomplish this goal. Rule formulation is derived to permit analysis of the effects of noise-control strategies on capacity. Two attempts to incorporate these rules into a knowledge-based expert system commercial shell are discussed. The first attempt was only partially successful but highlighted the need to carefully review the limitations of any selected shell. The second attempt proved much more successful and showed good agreement with opinions obtained during interviews at selected airports. This work indicates that expert systems may be used to seek an optimum balance between noise mitigation and airport capacity.

Aircraft noise and inadequate capacity are vexing problems at many major U.S. commercial airports. Aircraft operations are expected to increase, and this will exacerbate the problems. J. Donald Reilly of the Airport Operators Council International recently stated that "the lack of adequate capacity will be the major problem facing U.S. aviation over the next fifteen years" (*1*). Because of the high cost and public opposition to new facilities, management is trying to squeeze what it can out of existing airports. Only in a few cases, such as Denver, are new airport facilities being considered. However, the interest of airport neighbors in aircraft noise control is often at odds with efforts to increase airport activity. Optimization of each (noise abatement and capacity) in the limits possible requires considerable analysis and compromise.

To analyze the effect of noise-mitigation measures on capacity, new computer tools are needed by the airport operators and noise-control specialists. The use of a subset of artificial intelligence (AI) called expert systems may be one way to effectively use computers to assist in the noise mitigation/capacity analysis. Correct implementation of such software could allow concurrent evaluations of noise-control plans and effects on capacity. This paper explores the use of expert systems to accomplish this goal.

APPLICABILITY OF EXPERT SYSTEMS TO AIRPORT CAPACITY/NOISE-CONTROL ANALYSIS

Before beginning a detailed discussion of expert systems, a brief overview is necessary. Expert systems are a subset of the field of AI, which is a branch of computer science. Artificial intelligence is an attempt to copy the way humans think. Many advances have been made in AI, including natural language processing (the ability to understand the written or spoken word), pattern recognition (the ability to see and recognize an object), robotics (the ability to move or accomplish physical tasks), and development of expert systems (simulation of how humans gather and process information to solve specific problems).

A human expert uses education and experience to solve particular types of problems, usually in a narrow (specialized) scope. The expert uses established rules and sometimes rules of thumb (heuristic rules) to develop a solution. Judgment, reasoning, and the ability to make decisions are all required in the solution process. A computer program that solves problems in a similar way, using knowledge contained in the program, is known as a knowledge-based system.

In the computer, knowledge is represented as rules or attributes. A rule is simply a logical progression based on facts. An example of a rule is

If an object is an animal,
And the animal has feathers,
Then the animal is a bird.

The use of attributes in the program is a way to associate properties with an object. For example, the object, bird, may have a list of attributes recognized by the program, of which one could be feathers. Accordingly, the computer would "associate" birds with feathers. This association could be used to control processing of information.

It is important to understand how an expert system pro-

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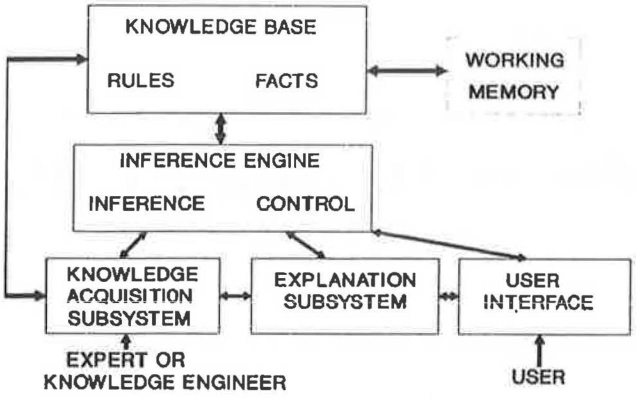


FIGURE 1 The architecture of a knowledge-based expert system (*2*).

cesses information. Conventional computer programs organize knowledge on two levels (data and program), but most expert systems organize knowledge on three levels (data, knowledge base, and control). Knowledge-based expert systems (KBES) differ from conventional programs because the problem-solving model is treated separately, rather than appearing only implicitly as part of the program. This part of the KBES (control) is known as the inference engine and selects sections of the overall program as needed to reach a conclusion.

Conventional programming algorithms have been used in design application programs in an attempt to incorporate expertise from data bases in the form of chained logic trees. The major developments in knowledge engineering, however, have occurred when the problem-solving techniques (the inference engine) and the domain-dependent knowledge were separated, permitting the continual addition of new domain knowledge within the existing problem-solving framework. This concept is shown graphically in Figure 1 (*2*). Also of note in Figure 1 is the division of the system into independent subsystems, which allow working memory to be stored, explanations to be provided to the user, and a user-friendly interface to be used. This KBES computer methodology could be very useful to airport officials.

The way in which rules are applied is usually graphically shown by the KBES in a logic tree. The logic tree shows the progression of the rules as applied for a particular input and problem by the KBES. It should be noted that different input for the same problem would result in a different logic tree. The logic tree is very important because it allows the user to review how the particular decision was reached.

There are three general categories of KBES development settings: languages, environments, and shells. An AI language, for example LISP, allows flexibility in programming but is time consuming to implement because the program must be developed from "scratch." Environments are less flexible but have many programming helps available to speed up the programming effort. Shells are the least flexible but very quick to implement because they are essentially an empty expert system with an inference engine waiting for rules and attributes. Because of time constraints and the nature of the project, a commercially available shell was chosen. In this way, quick prototyping could occur, allowing an analysis of the practicality of KBES for the problem at hand: airport capacity/noise-mitigation measure relationship.

Expert systems are increasingly applied to complex, real-world problems (*3–6*). Artificial-intelligence methods were seldom used in civil engineering before 1970. One of the first applications was developed in 1966 at the Massachusetts Institute of Technology by M. L. Manheim, using a hierarchical structure to decide highway location (*7*). Simple rules were used and the applications were limited. Manheim demonstrated, however, that AI could be used for decision making in civil engineering. After 1982, interest in the use of expert systems grew quickly, and extensive applications of AI in the field of civil engineering have been documented (*8*).

A KBES computer tool could be used by airport operators and noise-control officers to model and help optimize the balance between airport capacity and the noise-control goals. The knowledge base of the expert system could also provide guidance during evaluations, run separate conventional language programs to perform evaluations of various scenarios, and be much more user-friendly than conventional programming.

The use of a KBES instead of a conventional program to help solve the problem of developing airport capacity in harmony with noise control is indicated because, although many tasks are mathematical or occur in repeated patterns (logical rules), others are based on experience (heuristic rules). A KBES, unlike conventional computer languages, can easily accommodate both types of rules and the knowledge base can constantly be updated without reprogramming. Accordingly, a KBES acting as an interactive, user-friendly computer program could incorporate judgment, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice that would be difficult in any conventional programming.

KBESs have other advantages over strict logic programming because of the use of attributes (object-oriented programming) and the transparency of dialog and knowledge representation.

By allowing attributes to be associated with items, such as separate noise-control strategies, properties are associated with that item. This allows "decisions" to be made not only with specific rule programming but also by allowing noise-control strategies to be evaluated by their properties. The logic tree can grow continually as various forms of knowledge (rules, data, or attributes) are added to the system without changing the logic used in processing. Transparency of dialog and knowledge representation allow the user to be concerned only with relevant data for the program operation (i.e., user-friendly screen prompts), without specific data formats. In effect, the user "consults" with the software by supplying only the needed information, without becoming involved in the processing or decision making. Information can be stored in the knowledge base and be increased incrementally as system knowledge grows, without the program having to be redefined.

KBESs are usually developed through the cooperation of a "knowledge engineer" and a technical expert. For the purposes of this prototype work, the author has applied himself to the role of knowledge engineer. Technical expertise was obtained from the staff of the FAA and interviews with four airports that have active noise-control programs (Los Angeles International, Seattle-Tacoma, John Wayne/Orange County, and Nashville International).

The benefit of using a KBES may be best illustrated by an example. The management of Atlanta's Hartsfield International Airport analyzed the effects on capacity of noise-control programs (*9*). A detailed analysis was performed to relate noise-abatement measures to aircraft delays. Results showed that noise-abatement restrictions could cause up to 56,800 hr of aircraft delay annually by 1996. Various noise-control options were analyzed using the Airfield Delay Simulation Model (*10*) and the Capacity Delay Model (*11*).

The noise-abatement strategies were suggested by the airport management, and had probably been developed through experience and trial and error. In this instance, the list was probably complete. Had the staff been inexperienced, however, it would have been very difficult to develop a comprehensive list. The use of a KBES could allow such analyses to become commonplace, conform to FAA guidelines, and enable junior staff to produce useful results with minimal supervision.

Other benefits of the KBES are an expedited FAA review of local efforts and the fact that alternatives are less likely to be overlooked. A preprocessor might have helped to speed up the analysis and add accuracy to the overall procedure in Atlanta by selecting analytic programs and assembling data files. However, system control, guidance, decision assistance, and acquired knowledge would still have been absent. The use of an expert system could overcome all of these problems.

An expert system is not a substitute for professional judgment, but it can provide guidance, especially to junior staff. FAA-accepted practices and solicited expert opinions can be built into an expert system. In addition, local experience can be recorded so knowledge is not lost through personnel turnover.

CAPACITY AND ITS RELATION TO NOISE ABATEMENT

Airport capacity can be expressed for a variety of time periods, including hourly capacity, daily capacity, and annual service volume. Annual service volume and daily capacity are relatively insensitive to noise-control measures.

Hourly capacity is more responsive. This short-term measure is particularly useful in determining the effects of restrictions on airport operations during peak "push" hours, when capacity is under the greatest strain. Figure 2 shows this concept graphically. As demand increases (all other parameters held constant), the ratio of hourly demand to hourly capacity increases, causing increased delays. Any operational procedure such as noise mitigation that reduces hourly capacity increases delay. If the ratio of demand to capacity exceeds 0.8, even a small increase in demand or reduction in capacity will cause a substantial increase in delay.

Many airport planning studies refer to "practical capacity," which corresponds to a "reasonable" or "tolerable" level of delay (*12, 13*). That is, delays to departing aircraft of a predetermined length of time (often an average of 4 min) may be acceptable during the two adjacent peak hours of the day. For purposes of analysis, however, the FAA-recommended capacity measure is the "ultimate" or "saturation" capacity (the maximum number of aircraft that can be accommodated per unit of time without regard to delay) (*14*). For the purpose of this study, "ultimate" hourly capacity will be used as a reference when evaluating effects on capacity.

Hourly airport capacity is a function of taxiway, runway, airspace, and gate capacity. Different noise-control measures affect different combinations of these components. The capacity of each component is independent and for all but airspace capacity can be calculated using the methodology in *Airport Capacity and Delay* (*14*). Effects of noise-control measures on capacity can be analyzed by comparing the calculated capacity of the airport before and after the imposition of a noise-abatement measure.

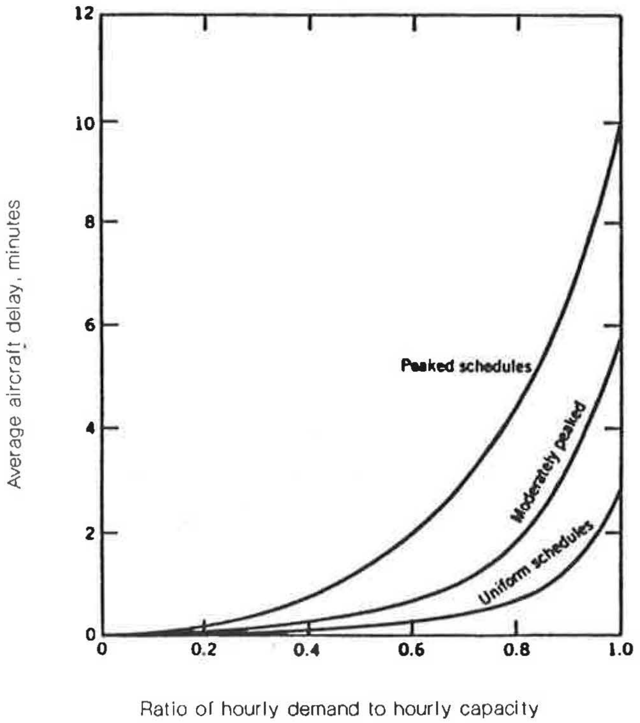


FIGURE 2 Relationship of demand-capacity ratio and demand fluctuation to average hourly aircraft delay (*15*).

Subcomponents of the airport hourly capacity (C_h) are mathematically defined in the FAA circular as

Runway: $C_h = C^* \times T \times E$ (1)

where

C^* = hourly capacity base,
T = touch and go factor, and
E = exit factor.

Taxiway: defined by graphs (*15*)

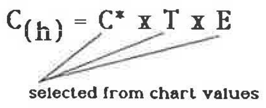
Gate: $C_h = G^* \times S \times N$ (2)

where

G^* = gate capacity base,
S = gate size factor, and
N = number of gates.

A graphic of how this methodology is used for runways is shown in Figure 3. The taxiway hourly capacity is selected from a graph and the gate capacity methodology is similar to the runway method.

The saturation airspace capacity may be calculated by using the error-free separation space as the maximum throughput capacity and calculating the increased separation space and



variables required:

for C^*
1. percent arrivals
2. percent class C and D aircraft (mix index= C+3D)

for T
1. percent touch and go
2. mix index

for E
1. exit range
2. mix index
3. percent arrivals
4. number of appropriate exits

FIGURE 3 Visual description of FAA runway capacity evaluation (as defined in text).

therefore decreased airway capacity. This concept is graphically shown in Figure 4. Mathematically this reduces to (*15*):

1. Aircraft overtaking lead aircraft:

$$m(v_2, v_1) = L_s/v_2 \quad (3)$$

2. Lead aircraft faster than following aircraft:

$$m(v_2, v_1) = L_s/v_2 + L[(1/v_2) - (1/v_1)] \quad (4)$$

where

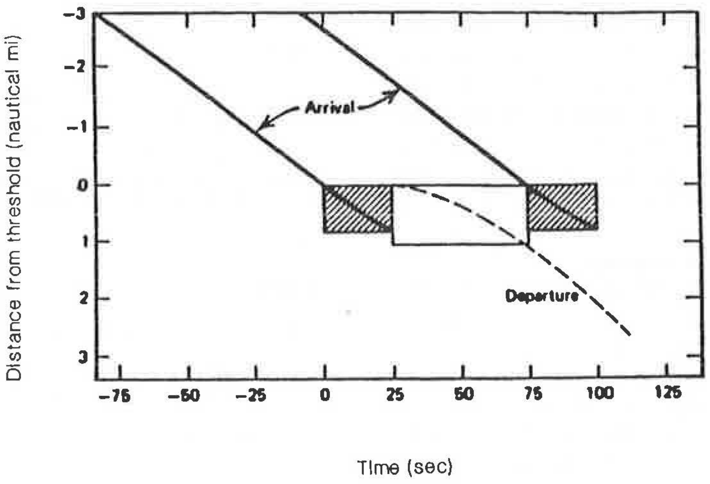
$m(v_2, v_1)$ = error-free minimum time separation over threshold for Aircraft 2 following Aircraft 1,
v_1 = speed of lead aircraft,
v_2 = speed of following aircraft,
L_s = minimum safety separation, and
L = length of common approach.

The value $m(v_2, v_1)$ could be calculated and compared with the increased time needed for the increased separation distance. From this increased time, the reduced amount of aircraft permitted to land could be calculated and the effect on capacity determined. For example, implementation of a noise-control measure that affects airspace would increase L_s from the minimum safe separation and could change L. Inserting the new variable values and making a comparison with the minimum-separation case would provide a measure on the effect of the airspace component on throughput capacity.

To evaluate how noise-control measures affect each subcomponent of capacity, strategies in effect at major U.S. commercial airports were evaluated. The FAA maintains a comprehensive listing of airport noise-control actions in its Airport Noise Control Strategies Data File (*16*). This data base includes approximately 400 airports, which accommodate more than 95 percent of the total U.S. air traffic (*17*). Thirty-seven noise-control strategies have been identified and are listed in Table 1. Some of these 37 noise-control strategies do not affect capacity directly. Numbers 1 through 8 are commitments to allow proper planning and policy analysis. Noise-control strategies numbers 27 through 33 involve land use control or insulation. These strategies reduce constraints that would otherwise be placed on airport capacity because of noise-mitigation measures but do not directly affect capacity. These 15 strategies contain components related to capacity but in themselves do not affect capacity and need not be considered further.

Control measure No. 9 (Restriction on Ground Runup) does not affect capacity if implemented. Control measure No. 26 would have to be evaluated on a case-by-case basis. Control measure No. 35 could reduce delay by the redistribution of traffic between two airports, but the capacity of the airport under evaluation would not change. These noise-control measures were not included in the prototype KBES development.

The remaining 19 noise-control strategies (numbers 10 through 25, 34, 36, and 37, which are shown in bold type in Table 1) can have a direct effect on airport capacity. To deter-



NOTE: Open box = runway occupied by departure. Cross-hatched box = runway occupied by arrival.

FIGURE 4 Time-distance diagram for two approaching and one departing aircraft (*15*).

TABLE 1 FAA NOISE-CONTROL STRATEGY CATEGORIES

CATEGORY NUMBER	DESCRIPTION
1	STATE NOISE LAW
2	LOCAL NOISE LAW OR ORDINANCE
3	AIRPORT MASTER PLAN
4	ANCLUC PLAN
5	PART 150 NOISE EXPOSURE MAP APPROVED
6	PART 150 NOISE COMPATIBILITY PLAN APPROVED
7	DEVELOPMENT OF AN EIS
8	NOISE MONITORING EQUIPMENT: TEMPORARY OR PERMANENT
9	RESTRICTION ON GROUND RUNUP
10	**LIMIT ON THE NUMBER OF OPERATIONS BY HOUR, DAY, MONTH, YEAR OR NOISE CAPACITY**
11	**PREFERENTIAL RUNWAY SYSTEM**
12	**RUNWAY RESTRICTIONS IMPOSED FOR SPECIFIC AIRCRAFT TYPE**
13	**USE RESTRICTION BY AIRCRAFT TYPE OR CLASS**
14	**USE RESTRICTION BASED ON NOISE LEVELS**
15	**USE RESTRICTION BASED ON PART 36**
16	**USE RESTRICTION BASED ON AC 36-3**
17	**COMPLETE CURFEW**
18	**ARRIVALS AND/OR DEPARTURES OVER A BODY OF WATER**
19	**DISPLACED RUNWAY THRESHOLD**
20	**ROTATIONAL RUNWAY SYSTEM**
21	**MAXIMUM SAFE CLIMB ON TAKEOFF**
22	**TAKEOFF THRUST REDUCTION**
23	**REVERSE THRUST LIMITS**
24	**FLIGHT TRAINING RESTRICTION**
25	**WEIGHT OR THRUST LIMIT**
26	INFORMAL FLIGHT OPERATION RESTRICTION
27	ZONING
28	PURCHASE LAND FOR NOISE CONTROL
29	USE OF CAPITAL IMPROVEMENTS TO DIRECT DEVELOPMENT
30	BUILDING CODES AND PERMITS TO CONTROL NOISE
31	NOISE EASEMENTS
32	PURCHASE ASSURANCE
33	SOUNDPROOFING PROGRAMS
34	**NOISE USE FEES**
35	SHIFT OPERATIONS TO A RELIEVER AIRPORT
36	**LOCAL PATTERN RESTRICTIONS**
37	**NAVIGATIONAL AID ASSISTED DEPARTURE**

mine which components of capacity are affected, the required input data for the FAA capacity model was evaluated for each FAA-listed control strategy. Table 2 lists each capacity component and the data input required to use the FAA methodology of evaluation.

The use of measures 10, 11, 17, 20, 23, and 24 places restrictions on runway use and so limits runway and taxiway capacity.

Measures 12 through 16, 19, 25, and 34 require changes to both the runway and gate usage. In addition, because these strategies directly affect fleet mix, the number of passengers that may be accommodated could also be affected.

Controls 18, 21, 22, 36, and 37 affect flight paths and circulation, and may reduce capacity by diverting aircraft from the most direct route. This occurs off airport property and usually before the final glide path. The effect on saturation capacity may be calculated if the increased flight distance can be estimated, as previously discussed.

Capacity measure evaluations must be chained to the appropriate noise-control strategy in the KBES to permit analysis of the selected noise-control measure.

The effect of airport noise on surrounding communities is usually measured by the population residing within the area that equals or exceeds the noise level of 65 dB, L_{dn} on the "A" scale. L_{dn} is the cumulative sound energy over a 24-hr period, adjusted to include a 10-dB penalty for noise exposure occurring during nighttime hours (10:00 p.m. to 7:00 a.m.). The "A-weighted" scale is an approximation of the way the ear would perceive the sound, accounting for frequency components. Levels above this metric (65 dB, L_{dn}) are considered to interfere with activities at sensitive receivers (i.e., resi-

TABLE 2 REQUIRED INPUT DATA FOR THE FAA THROUGHPUT CAPACITY METHODOLOGY (*14*)

OUTPUT	INPUT NEEDED
1. Hourly capacity of runway component	a. Ceiling and visibility (VFR, IFR, or PVC) b. Runway-use configuration c. Aircraft mix d. Percent Arrivals e. Percent touch and go f. Exit taxiway locations
2. Hourly capacity of taxiway component	a. Intersecting taxiway location b. Runway operation rate c. Aircraft mix on runway being crossed
3. Hourly capacity of gate group components	a. Number and type of gates in each gate group b. Gate mix c. Gate occupancy times
4. Airport hourly capacity	Capacity outputs from 1,2, and 3 above

dences, hospitals, homes for the aged, and so on). Accordingly, it is important to determine the number of receptors subjected to levels above this criterion. Aircraft noise levels in excess of 65 dB, L_{dn}, are generally encountered on or near the airport and are usually described graphically by a noise contour that surrounds the airport. *Airport Environmental Handbook* (*18*) describes the noise criteria in more detail.

Various mathematical models are used to determine the location of the 65-dB contour. An expert system could be used to help select the proper analysis method and act as a preprocessor to run the appropriate model externally from the KBES. The result would be reported to the user and could be added to the KBES knowledge base.

For example, if control measure No. 13 (Use Restriction by Aircraft Type or Class) were imposed, then the fleet mix would change, affecting capacity. The noise contours (airport "footprint") would change as a result of changes in the aircraft fleet. The FAA's Integrated Noise Model (INM) could be used to evaluate the change in the noise contour (*19*). The input file for the FORTRAN model (INM) would be developed by the KBES from stored knowledge and information. If other data were needed to complete the input file the user would be prompted by screen formats for any additional required data. Once the proper input file was prepared, INM would be executed by the KBES. After processing, the KBES would report results to the user (both noise and capacity). Various scenario outputs could be stored for future reference. Statistical interpolations could be performed by the KBES to present alternative levels of implementation, to allow the user to determine if the noise-control measure should be implemented in whole or in part.

In this way, working interactively with the KBES, compromises could be made to allow the noise-abatement goal to be reached (perhaps by suggestions to use other control measures in conjunction with control measure No. 13) while it was ascertained that required capacity for needed operations was not lost. In some cases this may not be possible; and this, along with the effect on capacity, would be reported to the user. At this point, further consultation (user with KBES) could occur to provide evaluation of other possible scenarios that would be suggested by the KBES.

In some cases other noise-control metric methodologies may be required. For example, if control measure No. 18 (Arrivals and/or Departures over a Body of Water) were proposed, use of the INM model alone might not be adequate. After determining the effect on capacity, the KBES could compare the land area and population of the affected residential zones before and after imposition of the measure, using demographic and cartographic data maintained in the knowledge base. The effectiveness of noise-control measures could be determined through comparisons of the population submitted to noise levels above a threshold.

SELECTION OF A KBES SHELL FOR PROTOTYPE DEVELOPMENT

An airport capacity/noise-control model could use a language commonly used in AI such as LISP, OPS-5, EXPERT, PROLOG, DUCK, SMALLTALK, FLAVORS, KEE, or LOOPS. The resulting model would be flexible and could be programmed to handle most conditions. As previously discussed, however, an expert system "shell" would allow quick development of the prototype. So, although use of a commercially available shell involves some loss of flexibility and generality, the time savings make this approach more desirable. Important considerations in selecting a system include the type of chaining (forward or backward), reasoning method (rule-based or inductive reasoning), allowance for degree of certainty of answer, text and graphic capabilities, data interface, the ability to interface with other languages, the ability to display the logic progression, hardware requirements, and price.

A backward-chaining KBES was initially thought to be desirable for this analysis, because the hypothesis that there exists a best noise-control measure that sacrifices the least capacity for given conditions was well defined. A rule-based system also seemed appropriate, because most considerations would be mathematical, legally enforced and required, or based on past experience (heuristic rules). As such, rules could be defined to drive the inference engine and be evaluated by the system using properly phrased questions, presented to the user as screen prompts. Additionally, rules could easily be added to update the system, change operational considerations, and modify the system for individual airports.

Logical rules were developed for the various noise-control strategies. For example, strategy Number 13 (Use Restriction by Aircraft Type or Class) would affect the aircraft fleet mix, causing hourly runway capacity to change. The new mix might also cause taxiway capacity to change. The gate mix would likewise be affected. All of these subcomponents of airport capacity must be considered together to determine the cumulative change in airport capacity. Because each is independent, the component with the greatest effect would be the limiting factor.

Heuristic rules are rules of thumb and experience gathered over long periods of time, usually by trial and error. For example, if strategy Number 25 (Weight or Thrust Limit) were implemented, airlines might not be able to make long-haul flights from the airport because of limits on fuel loading required. The KBES must also "consider" the number of seats available if aircraft size is limited and compare that information with the demand for air travel. The effect of thrust limits on aviation safety would also have to be considered. Accordingly, heuristic rules must also be formulated and expressed in a form usable by the KBES.

The ability to determine the probability that an answer is correct was thought to be only slightly useful for this prototype project but could be important if a full system were implemented. Text and graphic capability was thought to be important for reporting the results of the analysis, especially for the logic tree. The ability to display the logic progression is essential to inform the user of the basis for KBES decisions. The ability to interface with data bases and programs in other source languages is desirable to allow efficient calculations, run other models, and access past data. Hardware was limited to personal computers.

Many AI "shells," ranging in price from $99 to $7,500, fulfilled these requirements to varying degrees. Funding limitations for the project determined the selection. Two commercial tools that met most of the prescribed requirements, INSIGHT-2® and DECIDING FACTOR®, were available to the author without cost. DECIDING FACTOR seemed more applicable because of its flexible input format (to allow easy rule addition). Also, although DECIDING FACTOR cannot access data files or other programs, it does allow the user to exit the program and return after performing other operations. Accordingly, DECIDING FACTOR was the first choice for this project. Unfortunately, attempts to duplicate results of studies by trained experts using the developed DECIDING FACTOR KBES were only partially successful. Evaluation and troubleshooting revealed that the selected shell and developed rules were incompatible in some ways. It was difficult to program noise-control measure attributes (as rules) to be sufficiently recognizable during operation. This impeded attempts to program broad heuristic rules and led to the input of many specific rules. The inability of the shell to run external programs also proved to be a problem, requiring the user to exit the program and return to complete the analysis. With proper programming, most of these problems could have been overcome, but only with limitations.

To help overcome these limitations, a second KBES shell, VP-Expert®, was purchased. This shell was more flexible in rule recognition and allowed interfacing with external programs to build the input data files and execute programs. Output data could be imported to the KBES shell and stored in the knowledge base.

RULE DEVELOPMENT

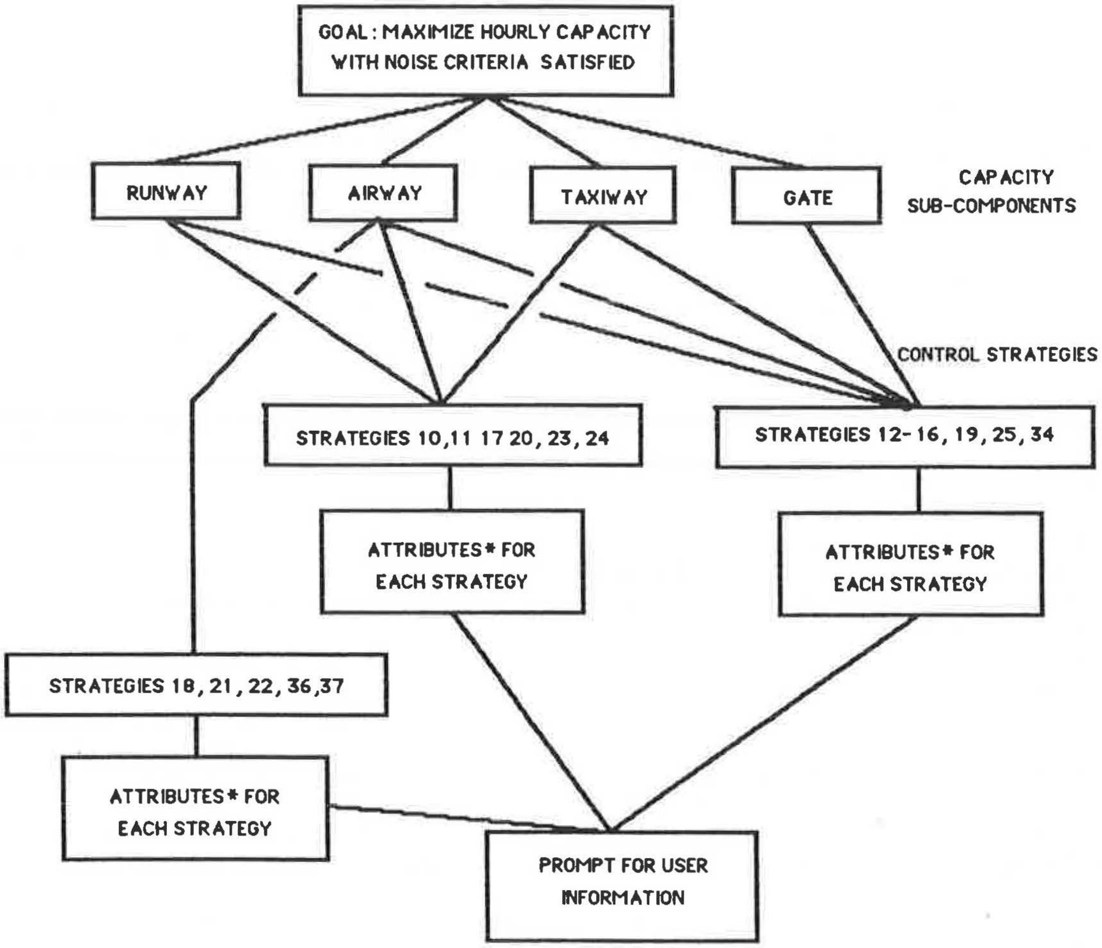
The preliminary work involved the use of DECIDING FACTOR. The process begins with a top-level hypothesis that the user would like to test. For example, for this KBES development the goal is to determine which noise-control measures could be implemented to meet noise criteria while minimizing effects on capacity. Noise controls are assumed to be independent of each other. The hypothesis is inferred from a series of intermediate goals also placed in a question format.

An intermediate goal is treated as a hypothesis with lower-level evidence to determine its truth value. For example, the intermediate goal: "Is the selected noise-control measure infeasible?" is solved by the KBES by reviewing the knowledge base on the selected control measure, which contains a list of types of control measures and their attributes (in rule form). The knowledge is stored by the program in a logic structure that might be compared to a pyramid. The top-level diagnosis is supported by lower-level inferences, based on factual assertions (rules). The outcome of rule "decisions" is based on information contained in the knowledge base and by responses given by the user to support decisions above it.

Each leaf (node) of the logic tree corresponds to a question that the user will be asked if the data are required for processing. The weighting of the final answer (the goal) is determined by the answers the user supplies along the path through the "leaves" or nodes. Figure 5 shows a simple diagram of how this logic tree was implemented into the KBES shell. For the first shell development (DECIDING FACTOR), answers to screen prompts can be rated by the user on a variable scale (based on a rating of -5 to $+5$, where -5 is a no and $+5$ is a yes). The ratings reflect the certainty of each answer, an elementary form of fuzzy reasoning.

The questions direct the line of reasoning so as to arrive at the top of the "tree" and derive a course of action that will satisfy noise criteria while allowing the maximum capacity. Each decision leads to the overall conclusion of which noise-control measures should be implemented, at what degree, to allow the least effect on capacity. Subsequent runs of the system could define additional courses of action as different control measures are selected by the user.

By combining the expert's knowledge, represented by rules programmed in the inference tree, the DECIDING FACTOR



*ATTRIBUTES ARE IN RULE FORM

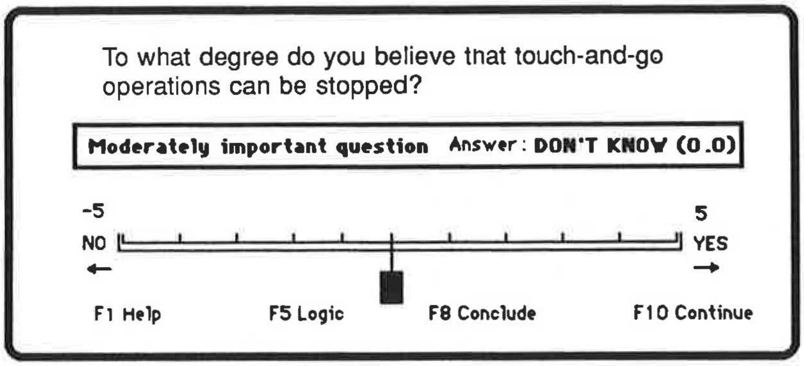
FIGURE 5 Simple diagram of rule hierarchy from domain engineering development.

shell allows intelligent natural language explanations of the reasoning paths. The shell can also provide additional background information entered by the knowledge engineer to elaborate on the required input. This allows explanations of questions asked of the users, to avoid confusion and ensure correct information entry. Input is facilitated by self-explanatory, graphic prompt screens. An example computer input screen for the DECIDING FACTOR shell is shown in Figure 6. This figure shows a simple question that only requires the "bar" to be slid (using a mouse or arrow keys) to the appropriate point to answer the question. The user is shown the answer to ensure correctness. For example, in Figure 6, the bar is in the center (at 0), so the corresponding answer DON'T KNOW (numeric value of 0.0) is displayed. The importance of the question to the solving of the goal is also presented. Other screens only require selection from several presented answers or input of numeric values.

This brief discussion of the shell DECIDING FACTOR should be sufficient to allow the reader to understand how this particular KBES shell was developed. Additional details are available in the software user's manual (*20*). Even though this selected shell was only partially successful at duplicating the findings of experts, the author believed that the relationship of capacity to noise control was suitable for analysis by AI and that the concepts developed to merge these two issues were correct. Accordingly, a second shell was obtained and the basic rule structure developed in the first shell was adapted for the second shell.

The limitations of the original shell had led to development of many rules that encumbered the shell. The second attempt, using the VP-Expert model, did not include the entire planning process. The effort was concentrated on the noise-control measures that directly affected all four subcomponents of capacity: Control Strategies 12 through 16, 19, 25, and 34 (see Figure 5). This work was sufficient for proof of the concept that AI can help to achieve a balance between noise and capacity.

The domain knowledge that had been gathered and pieced together in the development of the first KBES was used to guide quick programming of the VP-Expert shell. As before, the software development involved a predefined inference engine, user interface, and commands unique to the shell. The reader may wish to review the user manual (*21*) for complete implementation details. The same logic-tree structure



To what degree do you believe that touch-and-go operations can be stopped?

Moderately important question Answer: DON'T KNOW (0.0)

FIGURE 6 Image of screen used in DECIDING FACTOR to prompt user for answer and limit of belief.

was used and changed as appropriate (rules, data, or knowledge) in each leaf (node). VP-Expert permits rules to be used as needed. The knowledge engineer is permitted to program rules without assigning the order in which rules are to be executed. The software ensures that all applicable rules are implemented during the decision process. Conclusions cannot be drawn on the basis of partial information, which was a problem with the first shell. Alternate scenarios may be treated in different ways and heuristic rules are more easily applied to the program. Attributes are included as clauses. For example, a typical clause used as an attribute is:

```
IF STRATEGY_NO = 12 THEN RUNWAY31_CAP = 0
DISPLAY "RUNWAY 31 CAPACITY WILL NOT BE
AVAILABLE. IS THIS ACCEPTABLE?"
```

Based on the user answer, Control Strategy 12 will either be further evaluated or dismissed as infeasible.

After implementation of all rules, an initial evaluation of the model was conducted based on information gained in interviews at the four airports. This evaluation is discussed in the next section.

EVALUATIONS AND RESULTS

To evaluate the implementation of the KBES, tests were conducted for each defined strategy (noise-control strategies numbers 12 through 16, 19, 25, and 34). For example, it was assumed that an airport wished to evaluate the effect of implementing noise-control strategy Number 14 (Use Restriction Based on Noise Levels). As illustrated in Figure 7, the program first tests the strategy to determine if it is among the 19 FAA-defined control strategies that were determined to affect capacity (TESTING 1). The KBES determines this by comparison with a listing. If it is not among the list, the KBES advises the user that this strategy will not affect capacity and asks if the user would like to continue the evaluation. If it is among the list of the 19 control measures that affect capacity, the first attribute rule for that particular control strategy is applied. In this simple, prototype case, the KBES first determines if the airport is an international airport (shown as TESTING 3 in Figure 7). If so (TESTING 4 in Figure 7), the heuristic rule attribute for international airports is "fired." This programmed attribute recognizes that international and hub airports support many long-haul operations requiring particular aircraft and full fuel loading. The KBES delineates which aircraft are required for these operations (again from a list) and determines the sound-level contribution for each [based on *Estimated Airplane Noise Levels in A-Weighted Decibels* (*22*)]. These aircraft types are matched with a list of the aircraft types that use the airport. The noise level for each match is compared with the noise-level restrictions proposed by the airport. The list may vary with time of day, such as at John Wayne Airport, where lower noise limits are imposed at night. If the effect of limiting those aircraft that exceed specific noise levels is determined to be detrimental to the airport, this fact is reported to the user. If it is not considered detrimental, or if the airport is not a hub or international airport, then the analysis is allowed to proceed (TESTING 4 to CONTINUE 2).

At this point (TESTING 5) the selected strategy is reevaluated to determine what subcomponents of capacity are affected and how. Noise-calculation programs are then called and executed (with the KBES constructing the input file by calling programs written in other computer languages) to determine noise-abatement effectiveness. It should be noted that the KBES "remembers" the control strategy attributes and calls the appropriate rules (TESTING 5 and TESTING 5.1). Decisions are thus made on the strategy number based on rule attributes with no user input. In other words, based on the knowledge engineer's rules, the program makes "decisions" and only asks for information from the user when required. Finally, the effect on capacity is determined (STEP 3). Values for chart variables from *Airport Capacity and Delay* (*14*) were supplied manually for this prototype development. Full development should use the FAA computer model for capacity computations.

If another noise-control strategy had been selected, the rules would not have occurred in the same way and the same rules might not have been used. For example, if Control Strategy Number 11 (Preferential Runway System) had been selected, after determination of whether the selected strategy was among the 19 defined control measures that affect capacity, the first question would have been: Does the airport have sufficient capacity to limit runway use during peak hours of operation? Rule firing would have been based on this rule to begin the line of reasoning.

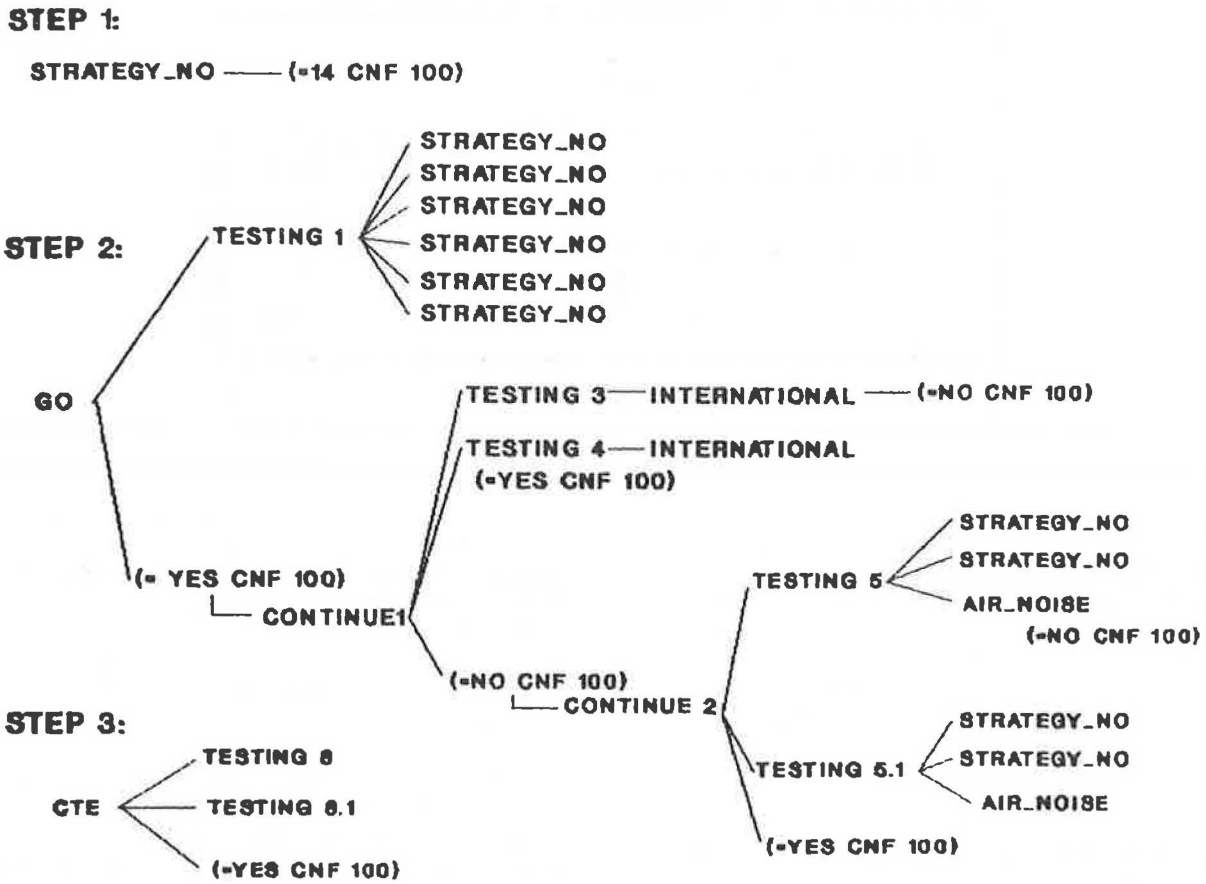


FIGURE 7 Flow chart displaying evaluation of noise-control measure No. 14 for hypothetical airport.

Simple analysis of the other defined control strategies (numbers 12 through 16, 19, 25, and 34) was conducted using VP-Expert and reasonable results were obtained consistent with what was expected from interviews conducted at the four airports. It should be noted that the results were considered consistent with airport opinions. Numerical evaluations were not possible because airports generally did not know how much airport operations were actually being affected by implementation of noise-control measures. For example, one airport reported that a preferential runway noise-control measure (noise-control strategy No. 11) reduced capacity by "about one-fifth." For this test case, capacity was predicted by the KBES to decrease by 16 percent. This was considered to be a very good result and to support the use of KBES in assisting airports in noise/capacity analysis. It is unfortunate that other more definitive testing did not materialize.

CONCLUSIONS

The use of KBESs in airport planning, specifically concerning noise control in harmony with capacity, would provide a valuable tool for the airport operator/noise-control officer to assist in efforts to keep up with the growing demand in air travel. The idea of using the 19 defined noise-control strategies with the defined FAA throughput capacity methodology in a KBES seems to be a promising analytic tool for evaluating the independent runway, taxiway, and gate components of capacity. Airway components of capacity would need to be evaluated using other methodologies, such as the minimum safety clearance between approaching aircraft as a degree of saturation capacity. The ratio of change could then be used to determine change in overall capacity. Although the first attempt to use a KBES was only partially successful, it allowed development of the rules needed to implement a useful KBES. The second attempt, based on the evaluation of the model from the first attempt, proved much more successful. More research is needed, and the next effort could be based on the results found during this project. Any selected shell should allow attributes of noise-control measures to be entered easily and recognized by the computer during the evaluation. The use of graphics would also enhance any new development. Validation by comparison of results with those of a trained individual at selected airports should be accomplished to help ensure proper programming. The shell must be able to use other computer programs in conventional languages, and models such as the FAA Capacity and Delay Model should be chained to the KBES control. Additionally, access to varied noise-prediction algorithms or models as required (such as INM) would greatly assist the user, allowing all noise evaluations to be performed under the control of the KBES.

KBESs do not offer a panacea to the programming problems associated with the implementation of a noise-control strategy without loss of capacity. Neither do KBESs offer a replacement for an experienced, trained noise-abatement officer. With a proper shell, however, knowledge at individual airports could be stored, the FAA could provide policy assistance, and noise-control expert opinions could be incorporated. This would permit continuity in programs and be a great help to junior staff.

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