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DESIGN OF AN EXPERT SYSTEM FOR AIRCRAFT GATE ASSIGNMENT

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Abstract—The task of assigning arriving flights at an airport to the available gates is a key activity in airline station operations. With the development of large connecting hub operations, and the resulting volumes of passengers and baggage transferring between flights, the complexity of the task and the number of factors to be considered have increased significantly. Traditional approaches utilizing classical operations research techniques have difficulty with uncertain information and multiple performance criteria, and do not adapt well to the needs of real-time operations support. As a result, several airlines have been exploring the use of expert systems for operational control of ramp activity.

This paper discusses the factors that arise in deciding how to allocate flights to gates, and describes the knowledge base structure, data requirements and inference process of an expert system that would recommend gate allocation decisions to ramp control personnel, taking into account the constraints imposed by the available facilities and personnel to handle the aircraft, and the consequences on downstream operations of particular assignment decisions. The paper describes how these concepts have been implemented in a prototype expert system that has been designed to address a restricted set of gate assignment issues within a framework that could be extended to consider a broader range of factors. The operation of the expert system is illustrated through a case study application to a typical flight schedule at a major hub airport.

Airline station operations consist of those functions involved in the handling of aircraft, passengers, baggage and cargo at the airports served by a carrier. Although these activities generally account for a smaller part of the overall cost of an airline's operations than the flight operations themselves, they can have a major impact on the efficiency with which the flight schedules are maintained and on the level of passenger satisfaction with the service. The task of assigning a schedule of arriving flights at an airport to the available gates is a key activity in airline station operations. With the increasing importance of large connecting hubs in airline networks, the ability to handle large volumes of aircraft, passengers and baggage in a relatively short time has become critical to the successful operation of the connecting banks of flights. Air traffic delays and severe weather can disrupt schedules and compound the difficulty of maintaining smooth station operations. In addition to ensuring that aircraft already on gates do not block later arrivals, the peaking created by late arrivals and the need to transfer passengers and large amounts of baggage between flights can delay subsequent departures or result in missed connections.

The task of station operations planning is to ensure that adequate resources are available to handle the traffic expected, and to deploy those resources in the most cost-effective way. These two goals are obviously related, since the less effectively resources are used, the more will be required for a given level of traffic. However, a related concern is the level of service provided to the passenger. Costs can be reduced by reducing staffing levels or facilities, but at the price of more delays, greater crowding, and missed flights. Appropriate levels of service for particular situations are policy questions, that depend on an airline's marketing strategy and competitive position. Thus station operations planning attempts to meet predetermined service levels in the least costly way.

The complexity of station operations, particularly at large hubs, has resulted in the development of a variety of analytical tools to assist in planning and operations management (Schoeder, 1972; Hamon & Weissert, 1980; Audsley *et al.*, 1985; Porter, 1985; Martin-Martin & Mary, 1986). These have typically been based on well-established operations research techniques. However, classical operations research techniques such as integer programming have difficulty handling uncertain information and multiple performance criteria, where the importance to be assigned to different factors in the objective function may be situation dependent. Formal optimization techniques also do not adapt well to the needs of real-time operations support, where what is usually needed is a minor change to an established plan, rather than a completely new solution. As a result, several airlines have been exploring the use of expert systems for operational control of ramp activity.

This paper discusses the factors that arise in deciding how to allocate flights to gates, and describes the knowledge base structure, data requirements and inference process of a prototype expert system to recommend gate allocation decisions to ramp control personnel. The system considers both the constraints imposed by the available facilities and personnel to handle the aircraft and the consequences on downstream operations of particular assignment decisions. The operation of the expert system is illustrated through a case study application to a typical flight schedule at a major hub airport.

AIRCRAFT GATE ASSIGNMENT

The decision of which flights to assign to which airport gates affects not only the deployment of ramp personnel and equipment, but the time required to transfer passengers and baggage between flights. In situations in which the number of aircraft to be handled approaches the number of gates available, poor gate assignment decisions can increase delays in getting aircraft onto a gate, due to other aircraft that are obstructing access to available gates. When schedule disruptions result in the number of flights to be handled exceeding the available gates, then good assignment decisions can reduce the resulting delays and missed connections.

The transfer of the large amounts of connecting baggage at major hubs requires careful attention in both the design of the facilities and the deployment of ramp personnel and equipment. The need to ensure that baggage does not miss connections is of primary concern. Unfortunately, many existing hub airport terminals were not designed with these requirements in mind, although some amount of retrofitting has taken place.

When inbound flights are delayed, the possibility arises that connecting passengers may miss flights. Even if the passengers make their connections, their baggage may not. The time required to accomplish the transfer of passengers and bags between two flights can be reduced through assigning the flights to adjacent gates, as well as appropriate allocation of personnel and equipment. When such techniques are not possible, or not sufficient to avoid missed connections, a decision on whether to delay the outbound flight must be made. This decision should take into consideration the downstream effects of the delay, as well as the impact on the operation at the station. If another aircraft is scheduled into the gate, delaying a departure may delay that arrival or require the flight to be reassigned to another gate.

Because the way in which arriving flights are assigned to gate positions affects so many other aspects of station operations, it deserves particular attention. The considerations that can bear on the gate assignment decisions include: (i) aircraft size; (ii) passenger walking distance; (iii) baggage transfer; (iv) aircraft servicing requirements; (v) ramp congestion; (vi) flight crew and aircraft rotation; and (vii) use of remote parking stands.

While it is self-evident that an aircraft cannot be assigned to a gate position that is too small to accomodate it, the situation is often complicated in practice by the fact that the apron can be marked to allow overlapping parking positions. For example, a ramp position may accomodate one large aircraft, such as a DC-10 or two smaller ones, such as B-737's. How these positions can be used may depend upon the number and position of air bridges. The size of an aircraft in a particular position may also limit the use of adjacent positions, or even restrict access to more distant positions, by reducing clearances to apron taxilanes. These constraints can be expressed through a gate interaction matrix for each pair of gates, that gives the restrictions imposed on the use of each gate by every aircraft type depending on the aircraft type using the other gate. While simple to use, these matrices contain a large amount of redundant information than can be efficiently expressed through critical constraint tables, as described by Gosling (1982).

Other things being equal, there is merit to assigning flights to gates so as to reduce the distance that passengers have to walk. This has been the objective of several past studies (Babic *et al.*, 1984; Mangoubi & Mathaisel, 1985). However, reducing total walking distance may not be as important as avoiding very long walking distances, such as when passengers must transfer between flights in different piers or satellite terminals. Not only must the distance itself be considered, but also the time available to cover it, since this affects not only the walking speed required but the ability to arrange assistance for those who need it. Thus reducing the walking distance for passengers with tight connections may be more important than reducing total walking distance. Although the minimum connection time allowed by the reservation system (termed a "legal transfer") takes account of the potential distance involved, problems can still arise when a flight arrives late. There are also obvious penalties from increasing legal transfer times at hubs in total passenger travel time, reduced aircraft utilization or elimination of potential connections. Consideration should also be given to the dynamic aspects of gate assignment. Reassigning a late arriving flight will require passengers who have already gathered at the original gate to walk to the new gate.

As important a consideration as passenger walking distance is baggage transfer. With centralized sorting systems, the time savings from assigning a flight to a gate closer to the sorting facility are not usually very large. However, with zone sorting systems, keeping flights with tight connections within the same gate group can significantly reduce transfer time. On the other hand, if ramp crews only work one zone and several flights arrive at that gate group over a short period, assigning a flight to another zone that is not busy may reduce the unload and transfer time, compared to waiting until a crew is free at the busy zone.

Aircraft servicing requirements that must be considered include availability of fuel hydrants, ground power and air, as well as ground handling equipment. Equipment is often aircraft type specific, and long moves from one gate position to the next will waste time, as well as complicate crew supervision. The movement of aircraft and ground vehicles on the ramp and taxilanes can result in congestion, delaying arriving and departing flights. Since aircraft cannot in general pass each other, an arriving flight may prevent a number of departures from leaving until it has cleared the apron taxilane. The rotation of flight crews and aircraft to flights must also be taken into consideration. Since flight crews have duties to perform before an aircraft is ready to leave the gate, delaying an arriving aircraft until an assigned gate is free may impact the departing flight using that aircraft or flown by that crew. When insufficient gates are available, the use of remote parking positions may be considered. This will require vehicles to transport the passengers to the terminal, and may cause problems with greeters not knowing where to wait for arriving passengers. Another possibility is to move aircraft off the gate positions once they have been unloaded and park them elsewhere until they can be moved onto a gate to load.

Assignment of arriving international flights to appropriate gates must take account of government inspection requirements (immigration, customs, health, etc.), which will generally restrict the available gates and require a longer turnaround time. If the aircraft is continuing as a domestic flight, it may have to be moved to a different gate for loading.

Aircraft gate assignment decisions arise in at least three different levels of station planning. During the preparation of schedule revisions, sometimes weeks or months in advance, station management will be required to examine their ability to accomodate proposed schedules. Once the schedules have been determined, daily plans will need to be prepared to ensure that adequate resources are scheduled to handle the traffic, and that irregular conditions, such as extra flights, nonstandard equipment or maintenance requirements, can be accomodated. Finally, decisions will be needed to respond to disruption of the planned schedule, such as flight delays, severe weather, or equipment failure.

These different planning levels have corresponding implications for different types of station management decision. The longer range planning identifies future resource requirements, including the need for additional facilities and personnel. The daily plans determine how the available resources are deployed, and control the cost of routine station operations. The response to schedule disruption determines how delays are allocated, and has broad implications for passenger service levels and delay-related costs.

CONVENTIONAL OPERATIONS RESEARCH APPROACHES

The gate assignment problem has been subject to considerable attention over the years by operations research specialists in airlines and elsewhere, and a variety of techniques have been applied, including integer and linear programming, simulation and heuristic methods (e.g. Schoeder, 1972; Krauter & Khan, 1978; Hamon & Weissert, 1980; Martin-Martin & Mary, 1986).

The advantages of these approaches are that they can provide optimal or near-optimal solutions, the techniques themselves are well understood, and fairly robust software has been developed to apply them. However, there are also disadvantages. As in any complex environment, it is often difficult to define an appropriate objective function that captures all the relevant concerns. Use of single metrics, such as passenger walking distance or minutes of delay, results in solutions that may not satisfy other important criteria. For example, Mangoubi and Mathaisel (1985) used an objective function that assigned the average intergate walking distance to transfer passengers, thus biasing the assignment in favor or originating and terminating passengers and concentrating most of the flights at a few gates. While they discussed an alternative formulation that explicitly considered the passengers connecting between each flight, they noted that this would be difficult to solve, and did not attempt to do so. Another disadvantage is that many problems are sufficiently large that, even with modern computers, optimized solutions may take considerable amounts of machine time. The linear programming solution developed by Mangoubi and Maithaisel took over 6 minutes of CPU time on an IBM 370/168 computer to assign 138 flights to 20 gates, although they were able to reduce this to less than a minute of CPU time by using a heuristic algorithm to provide an initial basis for the optimization. While the time required to obtain a solution may not be a concern for advance planning, it reduces the usefulness of the techniques for operational control. In addition, much of the existing software is not suitable for on-line use, requiring careful problem formulation and data preparation by experienced users, while the reasoning process within the software is often not very transparent to the end users at the station level, making it difficult for them to weight the recommended solution against other considerations. Hamzawi (1986) describes a microcomputer-based gate assignment simulation model that makes extensive use of graphics displays and menus to simplify the input of data and interpretation of results. However, the assignment logic does not appear to consider any factors other than limitations on the use of particular gates by a given airline, aircraft type or requirement for inspection facilities. Finally, modification of the software to respond to changing problems is difficult and time consuming.

EXPERT SYSTEMS APPLICATIONS

Expert systems provide an alternative approach to conventional operations research techniques. Although experience to date is too limited to determine how useful this approach may prove to be in practice, the characteristics of expert systems suggest that they may offer some advantages over more traditional approaches. The objectives of applying expert system techniques to station operations planning include: (i) the ability to incorporate the extensive experience of line personnel in a form understandable to operational staff and that can be expanded as necessary; (ii) the ability to incorporate a wide range of operational factors in the knowledge base, and to handle local and short term variation in considerations; (iii) the use of established techniques for handling uncertainty in available data; and (iv) the ease of providing an interactive decision-support environment.

While in principle anything that could be done by an expert system, could also be done by a more conventional algorithmic program, given enough software development effort, the central question becomes the relative ease of meeting requirements with one technique or another. Given the extensive experience with traditional algorithmic solutions, it appears likely that more experience will have to be gained in developing expert system applications before the answer is clear.

Current experience

In contrast to more traditional approaches, much of the experience in applying expert systems to station operations problems to date has been exploratory in nature, motivated in part by a desire to gain experience with expert systems. One of the first operational applications is a Gate Assignment Display System developed by Texas Instruments Data Systems Group for United Air Lines, that is in operation at Chicago O'Hare and Denver Stapleton airports. This system provides a graphical display for airline gate controllers, showing the location of each aircraft, and is reported to use expert system techniques to assist the controllers assign flights to gates (Shifrin, 1988). Information on flight movements is obtained through links to the airline's flight information data system, and the display automatically adjusts as information is revised. The extent and nature of knowledge incorporated in the system is not clear from information published to date, but discussions with United Airlines personnel indicate that the system can identify conflicts between aircraft in adjacent gates, but is not currently used to assign aircraft to gates.

A similar system is under development for Texas Air airlines (Fisher, 1988). This system also utilizes flight status and routing information from the airline flight operations computer, and is able to access passenger information from the passenger processing system.

A number of expert system applications have been examined by British Airways as part of a wider effort to explore their potential use in airline operations (Birch, 1986), while other work has been directed at developing decision support systems for aircraft gate assignment (Clegg, 1986).

Design considerations

In selecting appropriate expert system tools for developing station operations applications, consideration should be given to a number of design aspects. The expert system will need to be able to interface with very large real-time databases, so that relevant information can be shared with the various information systems that support modern airline operations. These include the flight schedule, passenger reservations, and flight control systems, as well as station records on personnel and equipment availability. The expert system will also need to be able to incorporate algorithmic techniques, so that conventional analysis can be performed as part of the process, when appropriate.

Careful attention should be given to the user interface, particularly if the system is to be used by line operating staff in the course of their regular duties. Beyond the usual requirements for user-friendliness, thought should be given to how best to present the information that users require to make decisions. While graphical techniques may be useful, care should be taken to ensure that display features serve a functional purpose.

Consideration should be given to the maintainability of the system, particularly in operational service when the developers may have moved on to other problems. Ideally, users should be able to modify the knowledge base fairly easily to reflect changing conditions and continuing experience. The incorporation of a learning capability would greatly enhance the usefulness of a system. Although techniques for automatic learning are not very well developed, the users should be able to incorporate new knowledge derived from previous use of the system.

REQUIREMENTS FOR A GATE ASSIGNMENT EXPERT SYSTEM

An important operational function that a gate assignment expert system could perform is to advise ramp operations control personnel how best to utilize gates, equipment and personnel, in situations when flight operations depart from a predefined plan, due to causes such as weather disruption. Indeed, this appears to be the focus of current airline applications, as discussed above. Such a system should be designed to anticipate future problems, and suggest modifications to the gate use plan and redeployment of personnel and equipment. Where inbound flights are delayed, and passengers may miss connections, it should recommend where departure delays are appropriate and identify the need for protection packages of reservations on later flights where connections have not been maintained.

The general structure of such a system is shown in Fig. 1. The usual three components of an expert system are the knowledge base, inference engine and user interface. In addition to procedural knowledge contained in the knowledge base, the inference pro-

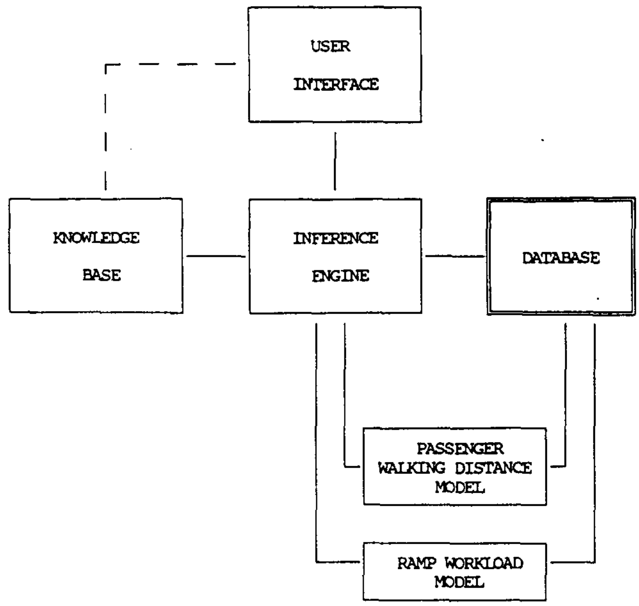

Fig. 1. Expert system structure.

cess will need to have access to conventional operational data, that is periodically updated in the normal course of operations to reflect the changing state of the system. Since these activities take place outside of the operation of the expert system, the system will need to be able to access an external database that it shares with other airline functions. In order to reflect the trade-offs inherent in ramp management decisions, the inference process must consider a variety of different factors in formulating its recommendations. While some, such as the number of missed connections, are simply a matter of calculation, factors such as passenger walking distance and ramp workload are more complex and can be incorporated into the reasoning through the use of analytical models based on the operational data and the actions considered. These may consist of separate routines, developed using traditional algorithmic software, that can be called by the rules in the inference process. For use in an operational environment, the user interface must not only be designed to facilitate entry of relevant information and display of results, but should also allow operational personnel to update the knowledge base by adding or modifying rules, as circumstances warrant.

Database

The operational data requirements consist of four categories of information. The first is the flight schedule and predefined aircraft rotation and gate use plan. The second consists of the numbers of passengers and amount of baggage (and possibly cargo) connecting between flights, as well as the originating and terminating traffic. The third category is flight movement data reported by the aircraft or upstream dispatch personnel, which provide estimated arrival times or information on changes of flight equipment. The final category is the availability of ramp personnel and equipment, and any existing assignment plan.

These data will generally reside in existing operational databases, and ways for the system to access the data will be needed. One approach would be for the system to request specific data by exchanging messages with the operational databases. While some of the data are static over the time frame of interest to the system, other data will change while the system is running. Thus, consideration must be given to ensuring that the system is working with the most recent data. How this is best done will depend in part on the way the operational databases function.

Knowledge base structure

The knowledge base will contain both the site-specific information and the procedural knowledge necessary for the inference process. This can be represented using three different techniques.

The principal component will consist of production rules to identify problems and constraints. These will include the gate constraint rules that determine which aircraft types can use which gates. Some typical rules are shown in Fig. 2. These use higher level constructs, such as "wider than a B727" or "minimum turn time movement M". Additional rules will be necessary to determine whether, for example, a B757 is in fact wider than an MD-80. This avoids having to write a separate rule for every combination of aircraft types and gates. The use of higher level constructs in the formulation of a rule allows parameters, such as the minimum turn time for a given movement, to depend on other factors, expressed by additional rules, while keeping the rule itself fairly

```
IF gate 16 is occupied by an aircraft wider
      than a B727
THEN gate 17 is not available to aircraft wider
      than an MD-80


IF (movement assigned to gate 15A) = M2
   AND (ETA movement M2) = T3
   AND (ETD movement M2) = T4
THEN gate 15B is blocked by movement M2 from T3 to T4


IF (ETA movement M1) = T1
   AND (ETD movement M1) = T2
   AND gate 15B is blocked by movement M from T3 to T4
   AND T4 > T1 - buffer
   AND T3 < T2 + buffer
THEN movement M1 cannot be assigned to gate 15B before
      T4 + buffer


IF movement M1 cannot be assigned to gate 15B before T5
   AND (minimum turn time movement M1) = TT
   AND T5 + TT > (ETD movement M1)
   AND gate 15B is blocked by movement M from T3 to T4
   AND T4 > T5 - buffer
   AND NEXT(T3,T4) - T4 > TT + 2*buffer
   AND MIN(T4) = T6
   AND T6 + buffer = T7
   AND T7 + TT = T8
   AND NEXT(T3,T6) - buffer = T9
THEN movement M1 can be assigned to gate 15B at T7
   AND movement M1 cannot depart from gate 15B before
      T8
   AND movement M1 should depart from gate 15B no later
      than T9
```

Fig. 2. Typical gate constraint rules.

simple. This also has the advantage that changes in the rule base affecting a particular parameter only have to be made at one place, and not in every rule influenced by that parameter. The rules in Fig. 2 also illustrate the importance of an explicit accounting of the time dimension. Gate 15B is only unavailable while it is blocked by the aircraft in gate 15A. If movement M1 is willing to wait, it could use 15B eventually. These rules also illustrate another aspect. A particular condition may be satisfied by several flights, with associated arrival and departure times. Thus the variables identifying the movement and times may assume multiple values. Similarly a rule may apply to several gates. As multiple clauses are evaluated, those cases that are not true can be dropped from the set of values. The ability of the inference engine to handle such complex rule constructs will greatly influence the number of rules required.

The production rules can be supported by model-based reasoning using analytical models that return values for parameters such as passenger walking distance or ramp workload measures. Calculation of the walking distance distribution can be based on the actual connecting passenger volumes and gate to gate distances, or probability distributions and passenger loads. Ramp workload models can be based on the minutes of personnel and equipment resources required to handle a specific flight, as a function of the flight characteristics. Overall workload measures will indicate how fully committed each type of resource is over time, and will depend on how resources are allocated.

Thirdly, heuristic search techniques can be used to reduce the size of the search space in examining alternative gate allocations. Effective gate assignment strategies require forward planning to anticipate the effect of future arrivals and delays. Although aircraft are assigned to gates sequentially, they do not have to be assigned in order of expected arrival. Similarly, an aircraft can be assigned to a gate that already has a flight allocated to it or that would be obstructed by other aircraft, provided those aircraft have not yet arrived.

Inference process

The inference process is event driven. Events of interest will include a revised flight arrival time, or change in the status of a ramp resource, such as a flight departure making a gate available or a shift change. Given a new state of the system, defined by an event or set of events, forward chaining rules, that develop intermediate conclusions from conditions that are satisfied by the system state, can be used to identify future problems. Backward chaining rules, that identify conditions that must hold for system goals to be met, can then be applied to identify actions that resolve these problems to the extent possible. This two-stage approach has the advantage that the user can be made aware of problems before the system has developed recommended actions, providing some benefits even if the system is unable to develop satisfactory recommendations.

The process of assigning a particular aircraft to a gate involves a search of possible gate positions. At each gate position, one of three conditions will hold: (1) it cannot be used by an aircraft of the type in question, (2) it is able to accept the aircraft for its expected gate occupancy (including buffer time to allow for delays in actual departure and time to push back and clear the gate), or (3) it is blocked for some part of the occupancy time by one or more aircraft at constraining gates. The first two conditions do not require any further search. In the third case, however, the aircraft may still use the gate if it waits until constraining aircraft depart or the constraining aircraft are reassigned to other gates. In addition to aircraft that block the gate during the expected occupancy time, any delay in using the gate may generate new conflicts from aircraft arriving at constraining gates after the expected departure time. If a constraining aircraft is reassigned, other constraining aircraft may also have to be reassigned to create a large enough unconstrained window to permit use of the gate. By ordering the constraining aircraft by time of departure, a set of possible assignment times is defined with progressively increasing arrival delay at the gate. For each assignment time, there will be a set of constraining aircraft that will have to be reassigned. For relatively small arrival delays, it may not be necessary to revise the planned departure time. However, if the time remaining before the planned departure time becomes shorter than the minimum time required to service the aircraft, then the departure will also be delayed. For each set of constraining aircraft to reassign, there are further levels of the search tree involving the possible gate positions for these aircraft, and so on.

Such a tree can be searched in a number of ways. In addition to deciding whether to search breadth-first or depth-first, the control strategy must also decide in which order to examine the gates, in which order to examine the different assignment times for a given gate, and in which order to reassign constraining aircraft. It is also necessary to be able to decide whether one particular assignment is superior to another, in order to select between them. The advantage of depth-first search in a real-time control situation is that a solution is available fairly quickly. The search can be terminated without being completed if a decision is required or if the search does not appear to be making much improvement in the solution. The disadvantage of a depth-first search is that time is taken exploring solutions that may later be rejected. This disadvantage can be reduced by making use of rules that establish the order in which the gate positions are searched, so that more likely solutions are examined first.

In the case of aircraft gate assignment, for each gate and aircraft class combination, an ordered list of alternative gates can be developed to guide the reassignment search. This allows better reassignment solutions to be searched first, and ensures that the search can be stopped at the first acceptable solution. The concept of a preference structure for guiding gate assignment has been described by Gosling (1982) and Levy (1988). While developing such lists is a significant task for large numbers of gates, they allow complex or qualitative factors, such as ramp congestion or passenger amenities, to be taken into account, while greatly reducing computation time by allowing the search to stop as soon as a suitable gate is found. Rules can be established to modify such lists in response to changing conditions, providing an even greater degree of flexibility.

IMPLEMENTATION

A prototype expert system was developed using the shell M.1 (Teknowledge, 1986) with the capability to address three types of operational problem: (1) late arrivals; (2) delayed departures; and (3) equipment changes. The choice of M.1 was based largely on the author's previous experience with several features that proved useful in the current application. These included the ability to process data as lists of variable length and to fire rules recursively. Any other production rule based shell with similar features might have served the purpose as well, and the goal of the research was not to evaluate different shells, but to understand how to structure the knowledge base and inference process.

Knowledge engineering

The gate assignment task was studied in the course of several visits to three different airline station operations centers over an extended period. Informal discussions were held with operations personnel involved in gate assignment and station operations control, and their decisions were observed and discussed. At one station, detailed information was collected on the existing operating rules and constraints, as well as the gate configuration and sample schedules. This information was then structured in an appropriate form for incorporation into the prototype expert system.

Based on the discussions with operations personnel, it became clear that a significant part of the expertise in performing gate assignment consists of deciding whether an assignment to one particular gate is better than another, taking all the various factors into account. At any point in time this knowledge can be represented by the preference order of available gates, that reflects a judgemental weighing of the different factors. For the prototype expert system, a gate preference order was developed for each gate based on the field data collected. Rules to adapt this to other situations is an area for further research.

Expert system structure

For each type of event, rules were developed to determine if the change will cause a problem. In the case of a late arrival, these rules check if the expected turn-round time will result in a late departure, and if so whether this will block the gate for a subsequent arrival. Delayed departures are checked for conflicts with subsequent arrivals. In the case of an equipment change, the rules check the suitability of the gate for the new aircraft type and adjacent gate restrictions.

If a problem is identified, the expert system then explores alternative gate assignments that eliminate or reduce the problem. Because of the proximity of the gates, no consideration is given to constraints imposed on the gate choice by minimum zone to zone transfer times, although the gate search order reassigns flights within the same zone if possible.

Gates are searched in a defined order for the aircraft type being reassigned. This order varies with the gate originally assigned, and takes account of passenger walking distance and ramp workload considerations by searching gates by increasing distance from original gate, first searching those in the same ramp zone and favoring gates closer to the terminal entrance and exit. Checks are performed to ensure that gates are large enough for any aircraft assigned to them, and that any adjacent gate constraints are not violated. In the case of a delayed arrival, a check is made to identify the first subsequent departure, to which passengers might connect. If the time available to make the connection is less than 20 minutes, the gate search order is based on the gate of the critical departure rather than the original gate, thus attempting to reassign the aircraft closer to this departure. The search continues until the first usable empty gate is found as well as the first gate with aircraft that can be switched with the aircraft being reassigned. One of these two gates is selected, using fairly simple rules that consider the impact on ramp workload and passenger walking distance. Although not implemented in the current version, these rules could contain links to analytical routines to compute more complex performance measures for walking distance and ramp workload. However, it is not immediately obvious what are the best measures to use, or how to combine the different factors, and this area deserves further research.

The rule set makes extensive use of recursive searching to reduce the number of rules, and the use of lists of variable length to allow more than one movement to meet a test criteria. A "movement" consists of a single aircraft arriving at and departing from a gate. It may thus be one flight or two. In the latter case it is designated by both flight numbers (e.g. 899/310). Rules are simplified by the use of such constructs as "reassign(M)", which is set true after all possible reassignments of movement M have been identified and the best selected, or "constraints (G,M)", the value of which is a list of movements that violate adjacent gate constraints for movement M in gate G. The use of recursion to search a list of variable length is illustrated by the following rules, which find the first empty gate:

if empty(GL)
then free (M,GL) = nil.

if sched(M) = [ETA,ETD,E]
and flights(G,ETA,ETD) = []
and conflicts(G,M) = []
then free(M,[G|GL]) = G.

if free(M,GL) = GF
then free(M,[G|GL]) = GF.

When other rules cause the inference process to seek a value for the term **free(M,L)**, the first available empty gate for movement **M** in the gate list **L**, the first rule fails because **L** is not an empty list and the second of the above rules is fired, with **G** set to the first gate in the list and **GL** set to the remainder of the list. The first clause sets **ETA** and **ETD** to the expected time of arrival and expected time of departure of movement **M**. The second clause causes a value to be sought for **flights()**, a list of movements occupying gate **G** between **ETA** and **ETD**. If this list is empty, then the third clause causes a value to be sought for **conflicts()**, a list of movements with conflicts with movement **M** if it were assigned to gate **G**. If this list is also empty, then **free()** is set to **G**, the first gate in the list. However, if either clause fails, then the rule fails and the inference process moves on to the third rule, the first clause of which causes a value to be sought for **free(M,GL)**, where this time **GL** is the remainder of the gate list. This in turn causes the second rule to be fired again, with **GL** in the place of **L**, and the next gate in the list is checked. If this also fails, the process repeats until a gate is found or there are no more gates in the list,

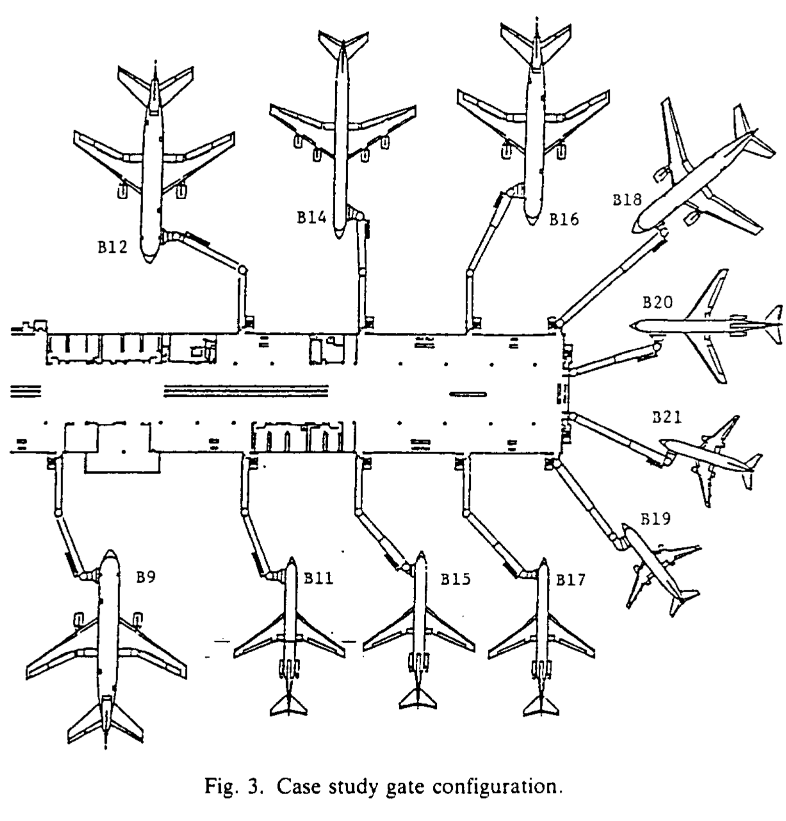

Fig. 3. Case study gate configuration.

Table 1. Aircraft classes

Aircraft Type	Class
B-737-100 B-737-200	1
B-737-300	2
B-727-100 B-727-200	3
DC-8-60	4
B-767	5
DC-10	6

in which case the first rule succeeds and **free()** is set to **nil**. Other rules use similar recursive techniques to search for values for **flights()**, **conflicts()**, etc.

The knowledge base contains 190 rules, of which 27 contain flight schedule information and a further 38 are used to keep track of gate assignments. In an operational system, the flight schedule rules would be replaced with links to the flight information database.

CASE STUDY

In order to illustrate the operation of the expert system, a case study application has been developed based on a typical operation at a major airline hub. While the case study is based on actual data for Denver Stapleton Airport, some simplification has been made to reduce the scale and complexity of the problem for illustrative purposes. The airline is assumed to occupy 11 gate positions, as shown in Fig. 3. Some gates are limited in the size of the aircraft that they can accomodate, and use of some gates depends on the size of any aircraft in adjacent gates. The airline fleet comprises eight aircraft types, which may be grouped into six size classes, as shown in Table 1. Gate restrictions due to clearance between adjacent gate positions and other factors are given in Table 2. It is assumed that there is sufficient clearance between each gate position and the apron taxilanes that no aircraft on a gate blocks access to any other gate. Although an aircraft being pushed back for departure could delay an arriving aircraft, this situation is not generally a problem with hub operations, and has not been included as a restriction.

The gates are divided into two ramp zones, corresponding to the odd and even numbered gates. Baggage is assumed to be preloaded by zone at the origin station, and sorted for reloading in each zone. Therefore within zone baggage transfers take less time than transfers between zones. It is also desirable to have an even distribution of arrival and departure times within each zone, to reduce peak workload.

Table 2. Gate restrictions

Gate	Constraining Gate	Aircraft Class	Size Limit
B11	B15	any	3
B15	B11	4,5,6	none
	B17	4,5,6	none
B17	B15	any	3
B16	Cannot handle class 2 and 5		

A typical flight schedule for a three hour period in the afternoon is shown in Table 3. A departing bank of flights ends at 3:45pm. This is followed by an arriving bank until 4:37pm, then a second departing bank from 5:02pm to 5:23pm and a second arriving bank from 5:25pm. There are a few arrivals and departures outside the corresponding banks. Passengers arriving on flights prior to 5:00pm can connect to any of the later departures. This schedule illustrates the operation of a connecting complex. At 3:46pm there is only one aircraft on the gates. By 4:37pm this has increased to 9. From 5:02pm the number is reduced by departures, until at 5:24pm there are 3 aircraft on the gates. The number then increases during the following arrival bank, reaching a maximum of 10 by 5:55pm. The aircraft rotation and gate assignment plan for the three hour period is shown in Fig. 4.

Examples

This section describes the application of the expert system to each of the three types of problem described above.

Table 3. Typical schedule

Time	Arrival	From/To	Departure	Equipment
3:01		ATL	886	B-727-100
3:10		ORD	234	DC-10
3:18	248	SFO		B-727-200
3:18		KCI	704	B-737-200
3:19		LGA	164	B-727-200
3:20		EWK	176	B-767
3:27		PHL	494	DC-10
3:45		ORD	246	DC-10
3:48	345	MSP		B-727-200
3:53	173	EWK		DC-10
3:56	163	LGA		B-767
3:58	283	IAD		DC-10
4:00		TUL	248	B-727-200
4:17	305	DSM		B-727-200
4:18	236	SEA		DC-8-60
4:26	865	MDW		B-737-300
4:29	645	MSY		B-737-200
4:37	899	CLE		B-727-200
4:37	505	DET		B-727-200
5:02		ANC	163	B-767
5:11	286	RNO		B-727-200
5:14		OAK	645	B-737-200
5:15		LAS	305	B-727-200
5:15		ORD	236	DC-8-60
5:15		SEA	173	DC-10
5:20		GEG	505	B-727-200
5:20		LAX	283	DC-10
5:22	434	BOI		B-737-200
5:23		SAN	865	B-737-300
5:25	235	ORD		DC-10
5:39	720	SAN		B-727-200
5:46	662	ABQ		B-727-100
5:47	414	BIL		B-727-100
5:50	240	ANC		B-767
5:52	346	SFO		DC-10
5:55	794	SEA		DC-10

```
Gate     15:00      16:00        17:00       18:00
           |          |            |           |
B9       ====246====>     <====236====> <===235/238==>
           |      45  |   18       | 15 25     |   30
           |          |            |           |
B11      =704==>      |     <====865====>   <===414===
           |  18      |     26     |  23    47 |
           |          |            |           |
B12   =886=>          |   <====305====>   <=====720===
          01          |   17       | 15   39   |
           |          |            |           |
B14      =176==>     <=====163=====>         <=240==
           |  20     56          02          50|  20
           |          |            |           |
B15      =164==>    <=345=   <===505==>     <===662===
           |  19    48|  15   37    |  20     46 |
           |          |            |           |
B16      ==494==>    <======173=======>       <==794==
           |  27     53            | 15       55
           |          |            |           |
B17        |   <==248=>      <=========899/310=======
           |   18    00      37    |           |
           |          |            |           |
B18     =234=>        <=======283======>     <===346==
           |10        58           | 20      52|
           |          |            |           |
B19        |          |     <===645==> <======434=====
           |          |     29     | 14 22      |
           |          |            |           |
B20        |          |            |           |
           |          |            |           |
B21        |          |            | <=======286======
           |          |            | 11        |
```

Fig. 4. Aircraft rotation and gate assignment plan.

The first problem was a late arrival of flight 236 at 4:45pm. This flight was originally scheduled to arrive at 4:10pm and depart 57 minutes later. Due to the late arrival, its departure would be delayed to 5:30pm, blocking the use of gate B9 by flight 235 that was scheduled to arrive at 5:25pm. Also it now had a critical connection with flight 163 that was scheduled to depart from gate B14 only 17 minutes after its revised arrival time. The expert system therefore attempted to reassign flight 236 to a closer gate to flight 163. The search of alternative assignments resulted in a recommendation to switch flight 236 with flight 305 in gate B12, not only reducing passenger walking distance but putting both aircraft in the same ramp zone, thereby facilitating baggage transfer.

The second problem was a delayed departure of flight 645 from 5:14pm to 5:35pm, blocking the use of gate B19 by flight 434 that was scheduled to arrive at 5:22pm. In this case, since flight 645 was already on the gate, flight 434 had to be reassigned. The only free gate for the duration of flight 434 was gate B20, in the other ramp zone. A check of possible switches within its own ramp zone showed that although flight 414 in gate B11 and flight 662 in gate B15 were scheduled to arrive after the revised departure of flight 645, the departure times of the preceeding flights in these gates left insufficient buffer time to accept flight 434 without possible delay. Therefore flight 434 was reassigned to gate B20.

The third problem was a change of equipment on flight 899/310 from a 727-200 to a 767. With the planned assignment, this would cause a size conflict with flights 505 and 662 in gate B15. The search for alternative assignments identified that there were no free gates able to take this aircraft, and that no switches within its own ramp zone improved the situation. Therefore the expert system recommended switching flight 899/310 with flights 305 and 720 in gate B12, resulting in a more even distribution of workload in the two ramp zones and reduced passenger walking distance compared to reassigning flights 505 and 662 to gate B20.

Examination of these results indicate that expert system correctly identified the problems, satisfied the gate constraints, and recommended reasonable reassignments. Each problem took less than a minute to run on an IBM PC-AT. Given the rate at which problems of this sort arise in practice, this appears to be an acceptable performance. Obviously, as more gates are required to be examined, or more assignment criteria considered, run times will increase, and additional rules may be required to constrain the search.

CONCLUSIONS

Many of the problems that arise in airline station operations appear to be appropriate for the application of decision support systems incorporating expert system techniques. The large number of factors to be considered and the continually changing information on the state of the system make conventional operations research approaches difficult to use. By linking a knowledge base containing site-specific information and procedures based on existing operational practice with real-time operations data, expert systems can be developed to advise and support station control personnel.

The gate assignment problem has attracted considerable airline interest for expert systems application, and several systems are currently under development. Identifying the relevant information and defining the constraints are not particularly difficult tasks. Nor is managing the data flows difficult in principle, although careful attention to system architecture is required because of the large amount of data involved and the need to continuously adjust to changing circumstances. The most difficult part of the problem is identifying the rules to guide the assignment process, because of the large number of factors to be taken into account.

A simple expert system has been developed to gain some understanding of the issues involved, and has demonstrated the ability to take some of these factors into account in solving a restricted set of gate assignment problems. Further work is required to extend the class of problems that can be addressed, and to better integrate the inference process with operational databases. In particular, better ways are needed to allow end users to modify the knowledge base to tailor the system to local conditions and changing requirements.

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