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Abstract: There has always been great interest in the migration of waterfowl and other birds. We have applied queuing theory to modelling waterfowl migration, beginning with a prototype system for the Rocky Mountain Population of trumpeter swans (*Cygnus buccinator*) in Western North America. The queuing model can be classified as a D/BB/28 system, and we describe the input sources, service mechanism, and network configuration of queues and servers. The intrinsic nature of queuing theory is to represent the spatial and temporal characteristics of entities and how they move, are placed in queues, and are serviced. The service mechanism in our system is an algorithm representing how swans move through the flyway based on seasonal life cycle events. The system uses an observed number of swans at each of 27 areas for a breeding season as input and simulates their distribution through four seasonal steps. The result is a simulated distribution of birds for the subsequent year's breeding season. The model was built as a multiagent system with one agent handling movement algorithms, with one facilitating user interface, and with one to seven agents representing specific geographic areas for which swan management interventions can be implemented. The many parallels in queuing model servers and service mechanisms with waterfowl management areas and annual life cycle events made the transfer of the theory to practical application straightforward.
Keywords: Trumpeter swan; Waterfowl; Migration; Queuing theory; Multiagent system

1. INTRODUCTION

1.1 Waterfowl Migration

The annual migrations of birds have intrigued humans for centuries. The travels of North American waterfowl have been of particular interest to scientists, managers and the general public. Hochbaum [1955] defined migration as "the annually repeated cycle of travel that carries waterfowl away from their birthplace or breeding grounds to temperate wintering waters, returning them to the familiar homeland with the advent of spring". Migrating waterfowl may fly hundreds or thousands of kilometers traveling from breeding areas to wintering areas. Many use one or more intermediate stops for resting and feeding. These temporal and spatial changes in location during the annual cycle make waterfowl and other migratory birds difficult to study and to manage. For some species, migratory traditions that started, perhaps, thousands of years ago continue. Other patterns have been disrupted by natural or human induced causes. Trumpeter swans that nest in Alaska and in parts of western Canada still migrate to wintering areas far to the south. However, trumpeter swans were extirpated from most of the conterminous United States. The breeding swans that remained were confined to high elevation wetlands in the Greater Yellowstone Area and apparently lost the tradition of migration. Biologists and managers are interested in restoring migratory flocks of trumpeter swans throughout their former range. Modelling the movements of migrating trumpeter swans and their patterns of habitat use is of great interest to those working to restore migratory flocks. We believe queuing theory may provide an appropriate way to model waterfowl migration and have developed a prototype system for the Rocky Mountain Population of trumpeter swans.

1.2 Basic Queuing Components

Hillier and Lieberman [1995] describe four key components to any queuing process: the *input source* (customer arrival times and patterns), the *queue* (number of customers awaiting service), the *queue discipline* (order of customer service), and the *service mechanism* (the process and associated time to serve customers). Dshalalow [1995] also includes three additional components: the *number of servers*, the vacation or *idle discipline* (the process and time when a server has no customers to serve), and the *network configuration* (direction of service among multiple servers and steps). Our system is based on this description.

1.3 Terminology

We consider a multiagent system to be multiple intelligent agents interacting with each other within an underlying communication infrastructure and without a procedural control mechanism. We use the term, “area”, to designate actual geographic locations. A “server” is a virtual representation of an area within the model. “Refuge”, as used here, is a specific case of server that can have its acceptability to simulated swans altered by the multiagent system. When we use the term “refuge agent”, we specifically refer to the intelligent agent corresponding to one of the refuges. A “queue” is the set of all servers for a particular season.

2. QUEUING MODEL CONFIGURATION

Trumpeter swans of the Rocky Mountain Population have been surveyed routinely in September across large regions of Western North America, and that information was organized for 27 specific areas. This forms the structure of the D/BB/28 queuing model [Dshalalow 1995; Kendall 1953] which we developed (Figure 1). It models the movement of birds through a large portion of the Pacific Flyway, distributing them across time and space in one year increments. The output from the queuing model is a predicted number of swans pertaining to 27 areas and the unknown queue for four seasons.

The swan queuing model has a deterministic input source with birds moving, potentially, from server to server at the end of each season. The starting queue is theoretically of infinite size, but is represented by the total number of swans as surveyed in September of a particular year. Although this input source is comprised of September values, it is called a “breeding number” because it represents the size of the population at the end of the breeding queue. Intermediate queues are post-breeding, wintering, and pre-breeding; the final queue is subsequent breeding. The queue discipline is FIFO (first in, first out) but becomes somewhat inconsequential because the service mechanism is a batch process.

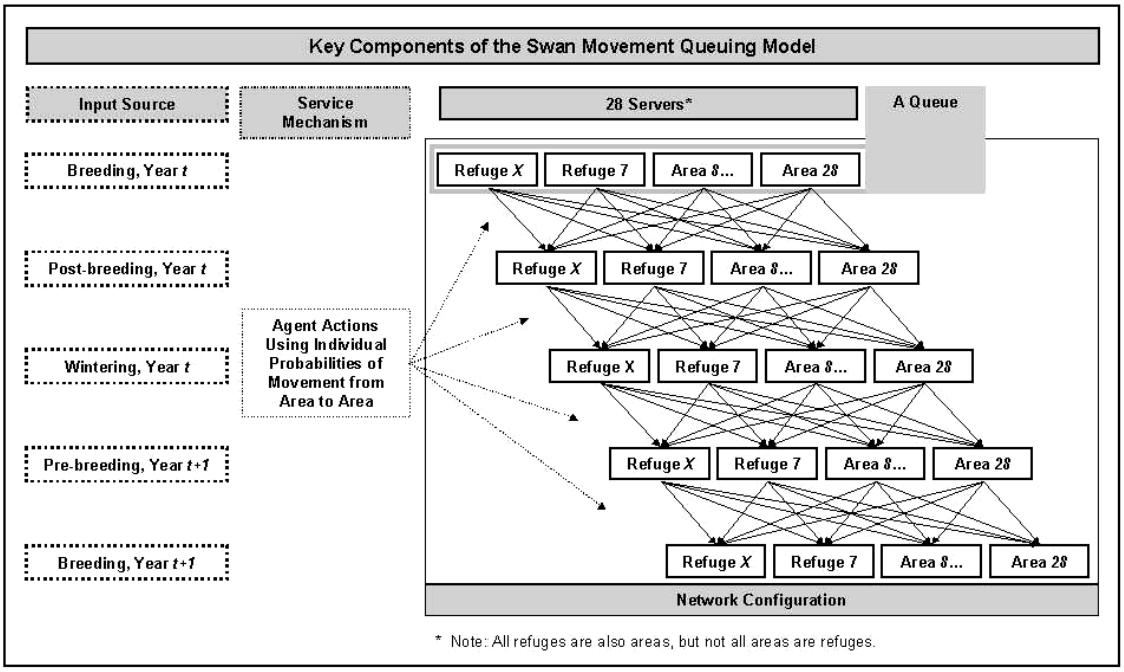

Figure 1. The D/DB/28 configuration of the queuing model.

I.e., all birds in a queue are processed simultaneously into the next queue and set of servers. And, because the service mechanism operates deterministically, the idle discipline is nonexistent for all practical, computing purposes. Each server governs, through a movement probability matrix, the number of birds allowed into itself. There are 28 servers in the system, corresponding to 27 geographic areas and one unknown buffer. The latter handles imprecise situations where the underlying movement likelihoods are undetermined. The network configuration is provided by the algorithm that uses the movement probability matrix to distribute swans among the 27 servers. The service mechanism is embedded within additional problem solving algorithms and iteratively steps through the seasons to provide a predicted distribution of swans for the subsequent breeding season. Additional complexity is modeled in the algorithm that is used to adjust the matrix of movement probabilities. The amount of interchange among Canadian breeding and U.S breeding trumpeter swans of the Rocky Mountain Population is unknown, but generally thought to be small. Therefore, the service mechanism tracks the broad breeding queue origin of birds. When entering subsequent intermediate queues, birds are allowed to mix among servers. However, via that tracking function, Canadian birds are not allowed to be serviced by U.S. servers, and vice versa, when entering the subsequent breeding queue.

3. A MULTIAGENT APPROACH

Waterfowl management represents a problem inherently distributed in time and space, and the very nature of multiagent systems methodology seemed appropriate to apply to such a domain [Sojda and Howe 1999.] Our overall decision support system (Figure 2) consists of a multiagent system [Weiss 1999] interacting with separate expert systems that provide specific ecological knowledge. Knowledge is incorporated for swan breeding habitat quality, ecology of palustrine wetlands, and principles of flyway management of migratory birds. From a software perspective, the expert systems exist independently of the multiagent system. The agents interact to determine the existence of appropriate expert system output, and they parse information in that output for eventual use in the queuing model.

The multiagent system consists of a minimum of three independent agents (facilitator, move, and refuge), but can include up to six more refuge agents depending on the geographical complexity of interest by the user. Additional agents also are embedded, somewhat transparently, within the DECAF software [Graham 2001; Graham and Decker 2000; Graham et al. 2001] that was used to implement the entire multiagent system. Our intent was to incorporate aspects of temporal and spatial distributed problem solving into the decision support system, and the specific agents were designed to do just that. It is the multiagent system that is the implementation of the queuing

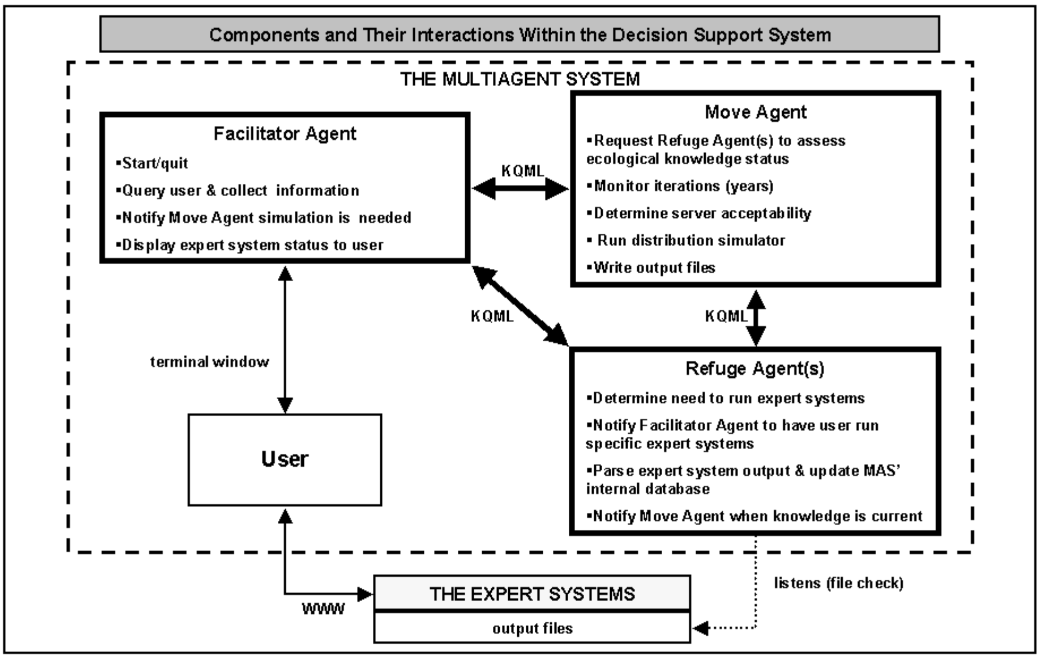

Figure 2. The decision support system consists of a multiagent system of 3-9 agents that interacts with three expert systems to implement the queuing model.

model. There is no central control mechanism, and agents autonomously share KQML [Labrou and Finin 1997] messages to provide the simulated distribution of swans.

The facilitator agent handles interaction with the user and notifies the move agent that the user wishes to proceed with a simulation. The facilitator agent also actively listens for knowledge about specific refuges that could be changing. If it is determined that additional knowledge is necessary, this agent then handles user interaction by requesting that specific expert systems be run. All communication with the user is via text I/O at the terminal window where the facilitator agent was started.

The purpose of each refuge agent is to determine the status of its own knowledge as needed for the particular consultation. If it is current, it reports this belief to the move agent. If not, this alternate belief is communicated to the facilitator agent so that the user can be prompted to run the needed expert systems. The refuge agent consists of three primary tasks, each one performing analogous sets of actions but gathering information and updating its beliefs about one of the three aspects of ecological knowledge.

The move agent contains the core of the queuing model and focuses on simulating the distribution of swans. It requests refuge agents to provide information, assembles all necessary system data, runs the queuing distribution simulator (an embedded C routine), and writes output files.

4. SERVICE MECHANISM: CONNECTING AGENTS AND EXPERT SYSTEMS

The queuing model's service mechanism is represented by an algorithm describing how swans move through the flyway and is embedded within the tasks of the agents themselves and their interaction within the multiagent system. Details of the work of the DECAF tasks and actions as they implement the service mechanism have been described by Sojda [2002]. Here, we describe the high level algorithm that constitutes the service mechanism of the queuing model.

For any transition stage, comprised of an input source and set of servers, swans potentially move from each server to every other server, including possibly staying in place (not moving). In the simplest of cases, i.e., the effect of using expert system input is not utilized; only the matrix of base probabilities of movement ($[M_{x,y}]$) is used to distribute birds to the next queue. As consultations increase in complexity, the refuge agents parse expert system output to determine whether a refuge (server) has conditions of acceptable or unacceptable quality for swans. When a refuge agent determines that a refuge has conditions of acceptable quality, that refuge accepts its base probability for that seasonal transition. If that is not the case (and conditions are unacceptable), that refuge accepts only 0.1 of the swans indicated by its base probability. The default value of 0.1 is arbitrary (and is set by editing the configuration file), but represents the relatively strong philopatry that is thought to exist in trumpeter swans. It has been known for some time that swans in the Greater Yellowstone Area tend to be philopatric under good habitat conditions [Banko 1960], although associated movements under varying habitat conditions have not been documented.

Obviously, the birds not accepted by a refuge must be redistributed. The remaining 0.9 of the swans are sent to the server that had the next highest base probability. For example, for server 1, this would be where $M_{1,y}$ is maximum; and the 0.9 of the swans would be sent to server y. Should there be more than one such server y (i.e., there is a tie), the 0.9 of the birds are sent to the server closest in straight line distance to the server not accepting all its swans (in this example, server 1). Because it was felt that there was no ecological, migratory significance among movement between some areas, some areas were grouped. This resulted in assigning the same distance from one area to more than one other area. Such grouping results in potential ties in straight line distance at this stage of the algorithm. When this occurs, the 0.9 of the birds are distributed equally among those corresponding servers. Migration parameters for the Rocky Mountain population of trumpeter swans have not been quantified, and the above algorithms are based on information gleaned during the knowledge engineering sessions

The expert system that assesses breeding quality provides a numeric rating from 0-100 [Sojda et al. in press] and affects servers in the breeding queue only. The threshold of breeding habitat rating to be used by the agents to determine refuge acceptability is arbitrary and can be set by editing the configuration file. A rating of 60 represents the conceptual value for minimally satisfactory habitat and was therefore used as the default.

Recommendations for water level management from the montane wetland expert system (Table 1) are used to determine server acceptability in all four queues based on an implementation of concepts generated during knowledge engineering sessions. Our experts stated that these relationships hold for all areas considered by our system. The relationships were elucidated by asking the experts to describe under what habitat conditions swans would expect to utilize or not utilize specific areas. A flowchart depicting this knowledge was developed by the knowledge engineers and critiqued by the experts. The system only considers the expected consequence on individual swans when alternate habitat is not available. From the table, a "+" and "o" allow a server to accept swans. A "-" results in a server accepting only 0.1 of the swans.

The expert system for assessing the contribution an area can make towards the flyway management plan for the Rocky Mountain Population of trumpeter swans determines whether a refuge can, or cannot, make such a contribution for the wintering and breeding queues.

5. KNOWLEDGE ENGINEERING FOR THE MOVEMENT PROBABILITIES

No quantitative information exists about trumpeter swan movements among seasons. Therefore, values for movement probabilities were gathered by conducting knowledge engineering sessions utilizing three experts working together for two days to arrive at consensus about those values. We provide details, here, because movement is so central to the queuing model's service mechanism. Two of the experts were waterfowl and refuge biologists with the U.S. Fish and Wildlife Service and one was a waterfowl biologist with the Idaho Department of Fish and Game. They were asked to provide their best estimates of these values using their own knowledge, informally consulting a database of neck collar resightings which one of them had designed, and using existing seasonal survey data. Data from the neck collar database was not directly used to estimate probabilities because it is thought to be biased, representing birds both marked opportunistically and resighted opportunistically. These data can be used, nonetheless, to verify the existence of certain migratory pathways. Ideally, movement information would have been collected for all Canadian breeding and staging areas. Although a request was made for such information from the Canadian Wildlife Service, it was not received. Independently providing such information was not a trivial task for them, and expanding the level of knowledge engineering was not feasible for us. Therefore, we did not pursue this and limited the information to that provided by the U.S. experts.

The experts were unable to provide direct probabilities of movement from area to area; but, they were willing to provide the likelihood that a bird in each of 27 areas would be seen in each area (including the starting area) during the subsequent season. Due to movement among areas within a season, however, the sum of these raw likelihoods for a particular season can exceed one. To overcome this, each likelihood value was weighted by dividing it by the sum of all likelihoods for the season. Such a weighted value was named a probability of movement from Area x to Area y (although it is not represented by an empirical probability distribution, per se) and is represented as:

$L_{x,y}$ = raw likelihood value of birds from area x being seen during the subsequent season in area y

$M_{x,y}$ = probability of swans moving from area x to area y

Season	Recommended Water Level	Alternate Habitat Available		Alternate Habitat Not Available	
		Individual Swans	Tri-State Segment	Individual Swans	Tri-State Segment
Breeding	Low	o	o	-	-
	Medium	+	+	+	+
	High - breeding habitat still exists	+	+	+	+
	High - breeding habitat eliminated	o	o	-	-
Post-breeding	Low	o	o	-	-
	Medium	+	+	+	+
	High	o	o	-	-
Wintering	Low	o	o	-	-
	Medium	+	+	+	+
	High	o	o	-	-
Pre-breeding	Low	o	o	-	-
	Medium	+	+	+	+
	High	o	o	-	-

Table 1. Expected consequences (degree of effect) of water levels on swans when water levels are those recommended by the management of montane wetlands expert system.

$$M_{x,y} = \frac{L_{x,y}}{\sum_{y=1}^{28} L_{x,y}}$$

This does assume that, during any one season, swans will be found in the same proportions among areas at the end of the season as represented by the likelihoods of movement into that area at the beginning of the season. At this time, no data exists to test this assumption. Areas to be represented in the queuing model were recommended by the experts as logical groupings of either traditional survey units or areas of management importance.

6. DISCUSSION AND CONCLUSIONS

6.1 General

The totality of the decision support system rests on a foundation of intelligent agents being used to implement and employ a queuing model to simulate the distribution of swans. The empirical evidence gathered on its performance [Sojda 2002] leads us to conclude that the base queuing model does accurately simulate swan distributions in the flyway. We have verified and validated the system but do not report on those specifics, here.

6.2 Queuing Models and Waterfowl Migration

Historically, land management decisions related to migratory birds typically were made on a small scale where a single national wildlife refuge or a complex of state, federal and private lands had objectives that were poorly linked with the objectives at other times and other areas that were used by the same migratory bird population. This historical condition for making decisions was understandable because the distribution of temporal and spatial data among management entities was compromised by the way in which data could be shared among managers in a timely manner. Without computer support, inferences were drawn after the fact when reports were shared within or among agencies or individual managers discussed the implications of the timing of movements and the distribution of migratory birds in relation to weather and habitat conditions. Based on the results from this study, multiagent systems incorporating queuing models appear to have the potential to enhance the use of spatial and temporal data related to migratory bird management challenges. By linking information from multiple areas and during different life cycle events from multiple areas, managers can take advantage of more comprehensive spatial and temporal data over a scale that has critical implications for maintaining migratory bird population viability. Time constraints and legal mandates require waterfowl managers to make decisions regardless of what modelling tools are available to them. Therefore, we have provided a simulation model based on the best available knowledge. We strongly agree with Clark and Schmitz [2001] that it is better to build a model constrained by existing information than wait until "all-encompassing data" becomes available.

Queuing theory had not been previously used as a modelling paradigm for waterfowl migration. The intrinsic character of queuing theory is to represent the spatial and temporal distribution of entities and how they move, are placed in queues, and are serviced. The parallel of queuing model servers and service mechanisms with waterfowl migration through management areas and annual life cycle events made the transfer of the theory to practical application straightforward. The modularity of DECAF agents provided us the opportunity to apply the internal agent tasks and actions to the specific elements of the queuing model. The nature of agents as independently responding to their environment allowed them to function as ideal entities for implementing the service mechanism in our model of waterfowl migration.

Twenty-seven areas sharing birds amongst each other, even if within somewhat structured migration parameters, across four seasonal changes, becomes a massively interconnected, multi-dimensional network. We obviously were able to represent this network algorithmically, but did not attempt to represent it mathematically. We do wonder whether a deeper understanding of the algebraic relationships, and any emergent behaviors from the complexity of the network, might not further elucidate a small aspect of ecological diversity as related to flyway management and migration of waterfowl. Alternatively, such a theoretical approach might elucidate thresholds where the service mechanism that we implemented begins to break down.

Managers of migratory bird populations have the responsibilities to use and test technologies and theories that address management issues over large spatial and temporal scales. This study focused on trumpeter swans, a remnant waterfowl population with strong family characteristics and strong philopatry, that use montane habitats within a relatively small area in the Pacific Flyway. This population provided an opportunity to test the use of queuing models for migratory populations that use similar mountain habitats throughout the annual cycle and move relatively short distances compared to most migratory birds. Thus, these results suggest that the value of queuing models should be tested with other migratory populations that move across many different geomorphic areas and have different life history strategies than swans.

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