Simulation of Bee Foraging Behavior using Biroi Preference Algorithm

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Abstract

Visualization using a multi-agent-based software, Netlogo, was employed in the simulation and replication of the foraging behavior of bees. The simulation model is based on the Biroi Preference Algorithm, which is named after the stingless bees *Trigona biroi*. The algorithm uses Analytic Hierarchy Process (AHP) to rank various criteria, such as distance, direction, height and food quality. From the results of AHP, probabilities are derived and assigned to the different feeding sites. Bee scouts look for food randomly, but foragers choose from the different feeding sites, as communicated by the scouts. Foragers choose feeding sites based on the assigned probabilities following the Optimal Foraging Theory. If the food source is depleted, bees tend to choose another feeding site by observing the Ideal Free Distribution and the Marginal Value Theorem. The simulation model can be extended to include more factors and complicated activities.

Keywords: foraging behavior, multi-agent simulation, bee foraging algorithm, *Trigona biroi*

1 Introduction

Different bee species have different criteria in choosing food sites and food quality. Stingless bees (Hymenoptera, Apidae, Meliponini) use various information from different sources for individual and collective decision-making (Biesmeijer & Slaa, 2004). *Trigona corvina*, *Plebeia tica* and *Trigona* (*Tetragonisca*) *angustula* have different behaviors of recruitment and communication of food source location (Aguilar et al., 2005). Stingless bees *Melipona scutellaris* and *M. quadrifasciata* communicate direction of food sources more accurately than communicating the distance (Jarau et al., 2000), thus affect their choice of food sites. *Trigona carbonaria* generally choose a food site with the closer distance to the hive (Nieh et al., 2000). In short distances, bees tend to search for food at certain angles from the hive opening before searching for food from other places. Some bees prefer certain levels of sucrose concentration of nectars (Roubik et al., 1995; Scheiner et al., 2004; Schmidt et al., 2006); and some prefer only few groups of flower species (Ramalho, 1989). Honeybees, *Apis mellifera* L, choose and discriminate natural odors, such as floral scents (Masson et al., 1993). Several studies showed that in different bee species, foragers deposit olfactory cues near the food sources to communicate their food preference, and these cues attract the other foragers (Villa & Weiss, 1990; Aguilar & Sommeijer, 2001; Schmidt et al., 2003; Hrncir et al., 2004; Schmidt et al., 2005; Boogert et al., 2006; Witjes & Eltz, 2007; Contrera & Nieh, 2007). The presence of nestmates in a feeding site attracts foragers (Sánchez et al., 2008), and this affects choice of feeding site. Sound signals from the scouts give information about the distance and sucrose concentration of the food sources (Aguilar & Briceño, 2002), and foragers choose among these information. Honeybees also choose food sources based on visuals, such as colors (Backhaus, 1993). Honeybees have the capacity to learn by association; and they can learn the colors, odors, shapes and structures of food sources (Scheiner et. al, 2004). Bumblebees have the capacity to distinguish patterns based on experiences (Seguin & Plowright, 2008). Because bees have different, possibly conflicting, preferences, visualizing their foraging behavior, e.g. determining to what food source most of the bees would go, is a challenge.

There are already multiple evolutionary algorithms that exist, such as Ant Colony Algorithm, Particle Swarm Algorithm and Honeybee Algorithm (Jones & Bouffet, 2008; Lemmens et al.,2007). There is also Marriage in Honeybees Optimization Algorithm, which is a variation of the Honeybee Algorithm that is based on bee reproduction (Abbass, 2001). The simplified pseudo-code for the Honeybee Algorithm (Jones & Bouffet, 2008) is shown below.

Algorithm 1 ***Procedure*** *Honeybee Algorithm*

Initialize *population with random solutions.*

Do until *termination condition is not met*

Select best sites for neighbourhood search.

Place x bees in each selected site within a defined radius about the best bee at the site.

Assign remaining bees in population to search randomly.

Evaluate fitness of population and rank.

end do

end

The main focus of Honeybee Algorithm and its variations are on solving non-ecological problems, such as optimization (Quijano & Passino, 2007; Baig & Rashid, 2007) and scheduling (Chong et al., 2007), rather than on replicating the behavior of bee foraging. Thomas Schmickl (n.d.) wrote a simulation model aiming to replicate and visualize the foraging behavior of *Apis mellifera* L. Independent from the simulation model of Schmickl, a generic simulation model is presented in this paper. The simulation model is written in a multi-agent-based software, Netlogo. The model bases its algorithm on the Biroi Preference Algorithm, which is named after the inspiration from the stingless bees, *Trigona biroi*.

The Biroi Preference Algorithm assumes that bees follow the Optimal Foraging Theory (OFT), Ideal Free Distribution (IFD) and the Marginal Value Theorem (MVT). Following the OFT means that bees are maximizing the benefits that can be obtained from the food vis-á-vis the costs needed in foraging. Benefits may include calories that can be acquired and taste of the food; while costs may include time needed in foraging, distance and height to be travelled, and competitors present near the food. In IFD, the number of bees foraging a food source should be proportional to the amount of the food and to the area of the feeding site at a certain time. In MVT, bees find another food source when the profitability of the food is diminishing or when the amount of food is depleting. A bee colony build a list of food sources using the information communicated by the scouts; and from this list, the foragers will know the profitability of each food source.

2 The Biroi Preference Algorithm

2.1 The Generic Steps

The following pseudo-code shows the generic steps of the algorithm.

Algorithm 2 ***Procedure*** *Biroi Preference Algorithm*

Setup *bee hive and* ***n*** *food sources.*

Input $C_1, C_2, ..., C_m$ *(%criteria to be considered)*

Input $A_{i,j}$ *where i=1,2,...n; j=1,2,...m (%values of each criteria per food source;* $A_{i,j} \in \mathbb{R}^{\oplus}$ *with usual notion of order)*

Compute $W_1, W_2, ..., W_m$ *using Analytic Hierarchy Process.*

Do until *i=n*

Do until *j=m*

$Sum_j = \sum_{i=1}^{n} A_{i,j}$

$Norm_{i,j} = \frac{A_{i,j}}{Sum_j}$

end do

$Weight_i = \sum_{j=1}^{m}(Norm_{i,j} \times W_j)$

end do

Do until *i=n*

$Probability_i = \frac{Weight_i}{\sum_{d=1}^{n} Weight_d}$

end do

Assign $Probability_i$ *to food source* ***i****.*

♠*Foragers randomly choose among the food sources based on the probabilities (%Example: If there are two food sources, say* F_1 *and* F_2*; and* F_1 *has* $Probability_1$*=0.34 and F2 has* $Probability_2$ *=0.66, then random numbers* ***s*** *will be assigned to* F_1 *where 0<s≤34, and random numbers* ***t*** *will be assigned to* F_2 *where 34<t≤100)*

Do *the Simulation.*

Compute $B_1, B_2, ..., B_n$ *(%number of bees in each food source per simulation tick)*

Determine $E_1, E_2, ..., E_n$ *amounts of food source 1, 2, ..., n, respectively; and* $F_1, F_2, ..., F_n$ *areas of food source 1, 2, ..., n, respectively (%per simulation tick)*

★***If*** $\frac{B_i}{E_i} > constant_1$ *or* $\frac{B_i}{F_i} > constant_2$*,* ***then*** *do not allow new foragers to forage at food source* ***i****, and decrease number of bees to attain* $\frac{B_i}{E_i} \leq constant_1$ *or* $\frac{B_i}{F_i} \leq constant_2$*, for i=1, 2, ..., n (%*E_i*'s deplete as* B_i*'s increase; food replenishment is optional)*

The non-accepted or subtracted foragers transfer to other food source using the assigned probabilities. (%IFD and MVT assumption)

end if
end

2.2 Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) assumes that preferences of the bees are deterministic or certain. AHP also assumes that bees are rational in selecting the best of the food sources, which is the idea of OFT. The values needed in AHP can be derived using the results from laboratory experiments. The following steps show how to compute W_1, W_2, ..., W_m using AHP (Taha, 2003).

Algorithm 3 ***Procedure*** *AHP*

Rank the criteria C_1, C_2, ..., C_m by comparing each of the criteria in an $m \times m$ Pairwise Comparison Matrix.

*The elements $q_{a,b}$, for a=1, 2,..., m and b=1, 2,..., m, represent the relative ranking of criterion **a** and criterion **b**.*

Comparison factors should be discrete from 1 to 9.

*$q_{a,b}$=1 means criteria **a** and **b** are equally preferred.*

*$q_{a,b}$=5 means criterion **a** is strongly more preferred than criterion **b**.*

*$q_{a,b}$=9 means criterion **a** is extremely more preferred than criterion **b**.*

Other intermediate values between 1 to 9 are interpreted correspondingly.

If *$q_{a,b}=k$, **then** $q_{b,a}=\frac{1}{k}$.*

If *a=b **then** $q_{a,b}$=1.*

The Pairwise Comparison Matrix:

$$Mat_o = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \ldots & C_m \end{array} \\ \begin{bmatrix} q_{1,1} & q_{1,2} & \cdots & q_{1,m} \\ q_{2,1} & q_{2,2} & \cdots & q_{2,m} \\ \vdots & \vdots & & \vdots \\ q_{m,1} & q_{m,2} & \cdots & q_{m,m} \end{bmatrix} \end{array}$$

Normalize the Pairwise Comparison Matrix.

$CSum_b = \sum_{a=1}^{m} q_{a,b}$ *, for b=1, 2, ..., m (%sum of column elements)*

Do until *a=m*

Do until *b=m*

$newq_{a,b} = \frac{q_{a,b}}{CSum_b}$ *(%normalized $q_{a,b}$'s)*

end do

$W_a = \frac{\sum_{b=1}^{m} newq_{a,b}}{m}$ *(%average of $newq_{a,b}$'s per row)*

end do

$$Vectorw = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_m \end{bmatrix}$$

Check for consistency (%optional)

$Mat_o \times Vectorw = H$

$$H = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_m \end{bmatrix} \text{ (\%assumed notation)}$$

$Nmax = \sum_{a=1}^{m} h_a$

$ConsistencyIndex = \frac{(Nmax-m)}{m-1}$

$RandomConsistency = \frac{1.98\times(m-2)}{m}$

$ConsistencyRatio = \frac{ConsistencyIndex}{RandomConsistency}$

If *ConsistencyRatio $\geq$ 0.1, **then** the Pairwise Compariosn Matrix has a high level of inconsistency*

end if

end

2.3 Simulation-specific Codes

The following pseudo-codes vary and depend upon the programmer. Algorithm 4 shows how the scouts work, and Algorithm 5 shows how the foragers work. In this simulation model, it is assumed that the forager-scout communication is global, i.e. information are stored not by individual bees, but by the hive. Possible criteria are distance from the hive, direction (angle from the entrance of the hive), height of the food source with respect to the hive, and food quality (sucrose concentration).

Algorithm 4 ***Procedure*** *Scouting*

Assign x-y coordinate to each food source.

Initialize *list of food sources with the corresponding assigned values of random numbers; and store the list in the hive. Deactivate the names of the food sources in the list.*

Input *number of scouts (%population)*

Do until *stopped by the user*

Release scouts and search food randomly (%rate of release is optional)

If *food source is found, **then** get x-y coordinate of the food source and go back to hive.*

Scout communicate the x-y coordinate inside the hive and the corresponding food source is activated in the list.

(%After the communication process, scouts will randomly search for food again)

Else *continue searching for food.*

end if

end do

end

Algorithm 5 ***Procedure*** *Foraging*

  Input *number of foragers (%population)*
  Input *number of lost bees and/or probability of being lost (%optional)*
  Do until *stopped by the user*
    From the activated food sources in the list, individual foragers choose among the food sources using the assigned random numbers (%refer to ♠ in the generic steps; the program may recompute the probabilities and the assigned random numbers based only on the activated food sources)
    Release foragers (%rate of release is optional)
    Foragers travel back-and-forth from the hive to the assigned x-y coordinate of the chosen food source
      Foragers feed on the chosen food source
        If *food source is depleting,* ***then*** *follow ★ in the generic steps*
        end if
    If *food is depleted,* ***then*** *foragers go back to the food source* ***p*** *times before transferring to other food source (%unlearning behavior; optional) (%rate of forgetting is optional)*
    end if
  end do
  Plot *amount of food consumed per food source (%optional)*
  Plot *amount of collected and stored food in the hive (%optional)*
  end

3 Simulation Implementation in NetLogo

3.1 Netlogo

The simulation of the model was implemented in NetLogo 4.0.3 (Wilensky, 1999), a cross-platform environment for developing models of complex systems using the multi-agent systems paradigm. NetLogo is both a modeling environment and a programming language.

3.2 Hive and Food Sources

The simulation involves two types of bees – the scouts and the foragers. Patches, which represent environment data, are mainly classified into food patches (of which there are presumed three types), hive patches, and wall patches. These patches are colored to signify their distinction from each other and from the white normal patches that contain no data. The three food patches are placed variably distanced from the nest (cyan, green, and blue respectively), while the hive patches (purple) are surrounded by the wall patches (pink). The screen shot on figure 1 shows the different patches and their color assignments.

3.3 Scouts and Foragers

The outline of each bee is colored to represent its current state. Scouts that are outlined with red signify that they have not found any food yet, while those that are outlined with pink have successfully found food. White outlined foragers are those that are going to the communicated location of food source to collect food. Upon returning, the foragers are outlined with green, cyan, or blue to signify which food they have collected. The foragers can also be colored yellow if they have been to an already empty food source. Examples of colored bees are also shown in figure 1.

3.4 AHP and Categories

As seen in figure 2, the controls at the right portion of the model are set up sliders and drop-down lists for the computation of AHP. The first three rows, which are drop-down lists represent the upper-triangular of the Pairwise Comparison Matrix. The next four rows are the value sliders of the parameters for each food source. The first of the four parameters is implemented as the distance from each food source to the hive. This is done to test the accuracy of the AHP model. When all parameters except distance are equal in value and equal in terms of their ranks in the upper triangular matrix, the model should show that if distance is given the top priority by foragers, then the closest food source to the hive will have the most number of visits from the foragers. Furthermore, on the left side are switches and sliders that can alter the population of scouts and foragers, the length of delay before each bee leaves after another has left, the loyalty of bees to a tree, the wiggle rate of bees, the learning curve or memory of bees, the probability of food being replenished and its delay, and other debugging related variables for programmers and modelers. The two buttons, "Setup" and "Go" respectively resets the model, and starts the simulation.

3.5 Plots and Monitors

A plot can also be seen at the bottom-right corner of the model where the number of food collected from each source is plotted per tick (the unit of measurement for time used in NetLogo). Monitors of bees in a certain state are also recorded per tick. A screen shot of the plot and monitors are illustrated in figure 3.

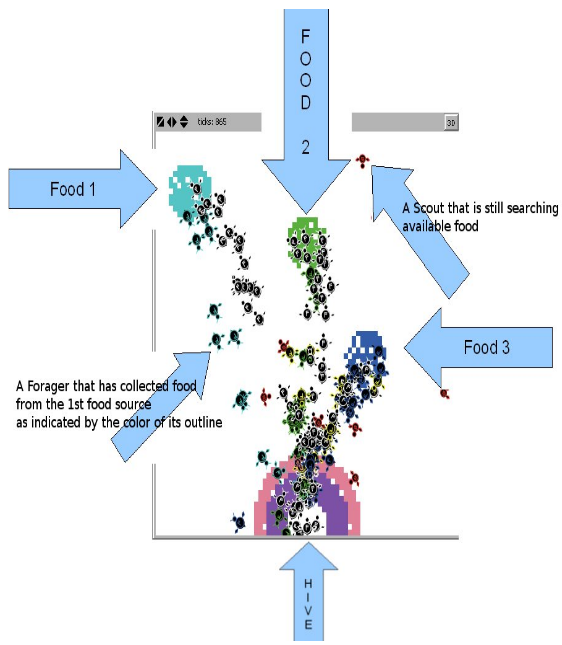

Figure 1: The Simulation Panel: Bees and Patches

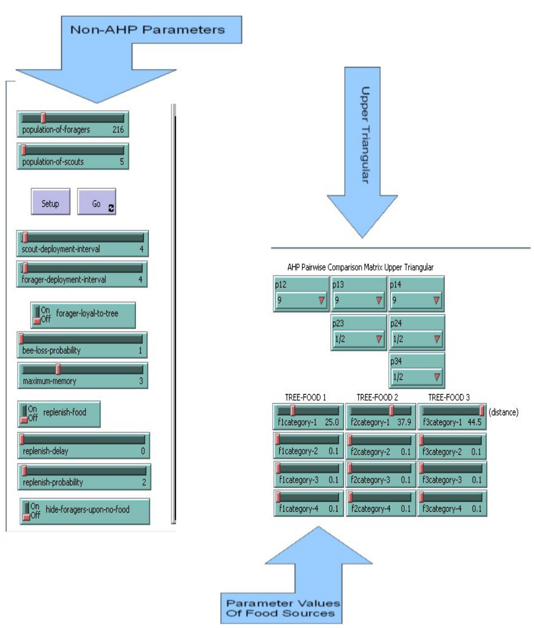

Figure 2: Sliders and Switches

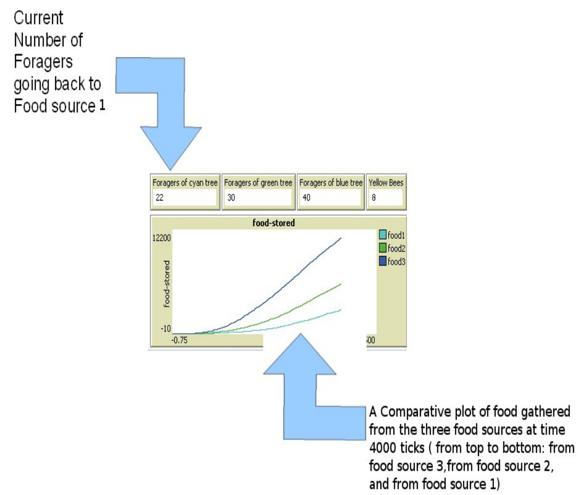

Figure 3: The Plot and Monitors

4 Concluding Remarks

It is hard to analyze the behavior of complex systems, such as bee colonies; but it is still possible to approximate their behavior using simulation. Simulation of bee foraging behavior helps academicians in teaching ecological principles. It also helps beekeepers in visualizing the possible behavior of individual bees and the colonies.

The simulation done in NetLogo validates the strength of Biroi Preference Algorithm to mimic bee foraging. However, the capabilities of NetLogo are limited, and an improved software is needed to model more sophisticated multi-agent-based systems. Moreover, AHP is used for decision-making under certainty, but the algorithm can be extended to include fuzzy and probabilistic values in future researches.

The inputs and outputs of the Biroi Preference Algorithm and of the simulation model can be validated by real experiments. The entries in the Pairwise Comparison Matrix can be determined using experimental results. The algorithm can be extended to include other factors to accurately model the real foraging behavior of bees. Moreover, the user has the ability to change inputs in the simulation model. Sensitivity Analysis can be done by simulating the behavior of bees using different inputs.

The Biroi Preference Algorithm can be used not only for bees but also for species with related behavior. The algorithm can be used for modeling human behavior, such as the behavior of customers during queues. The applications of the algorithm are not confined with Ecology, and it can benefit other fields such as Operations Research, Business Management, Computer Science and Social Psychology.

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