Collective decision-making in an agent-based model: Nest-site choice by honeybees swarms

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Abstract: Honeybees use communication to decide for the nest-site they are moving to. In this paper, we are going to implement a model to study how the balance between independence and interdependence affects the decision process of the bees and see if a consensus can emerge. After introducing the definition of consensus, we analyze the effect of the interdependence parameter λ and the quality factor assigned to the competing choices. High values of λ promote the consensus, but reduce the system performance by increasing the convergence time.

I. INTRODUCTION

Collective decision-making plays a central role in social animals behavior[1]. This mechanism provides the animal group with a tool that increments its survival and reproduction probabilities. Collective mechanisms have a large range of applications across different species. For example, groups have to decide where or when they are going to migrate, where to invest time looking for food or choose a shelter among different places.

Information polling is fundamental in this process, but instead of voting, they communicate. Communication can create interdependence between the different members of the community. On one hand, this can optimize and facilitate the decision-making process, but on the other hand, this can increment the noise effects and increase the error in it. So, it's important that the system has the right amount of independence and interdependence.

In this paper, we will discuss the decision-making process of honeybees (*Apis Mellifera*) swarms on the nest-site choice [2]. It is an empirical fact that, in late spring or early summer, when the swarm population is big enough, the place where they live is not capable of host them, then the swarm separates in two. A committee, formed for several hundreds of called scout bees is organized to search for possible nest-sites for the new swarm.

The decision-making mechanism works in the following way: Once a scout bee finds a possible nest-site, it returns to the swarm and transmits this information to the other bees. The information transmission is done through a process called "waggle dance", the bee dances for the possible nest-site and tries to convince the others to investigate and dance for it. If the quality of the possible nest-site is high, the bee will dance more vigorously and more time for this site. Initially, the bees inspect randomly sites, but when a certain time has passed, some places will get more attention, especially the sites with more quality, and eventually, they will arrive at a consensus. In our case, the decision is made by comparing the number of bees dancing for each possible nest-site.

We consider an agent-based model, so each scout bee behavior's is dictated by and stochastic process. It is an important fact, that the honeybees always choose the best site to move. Our goal is to study a semi-realistic model based on this process, understand the underlying mechanism of this phenomena and make possible predictions on the bees behavior's.

II. CONDORCET'S JURY THEOREM

Marquis de Condorcet's theorem [3] demonstrates that, when a group has to make a dichotomous choice and each member has a competence (probability of choosing the best option) bigger than 1/2, under majority rule, the probability of the group taking the best choice tend to 1 as the group size increases. This theorem assumes that each member has an independent probability of choosing the best option. In other words, democratic decisions tend to outperform dictatorial ones. If we put this into numbers, the competence of the group is equal $\sum_{i=m}^{n} \binom{n}{i} p^i (1-p)^{n-i}$. Where n is the number of group individuals, $m = (n+1)/2$ is a bare majority, assuming n is odd, and p is the competence of each individual.

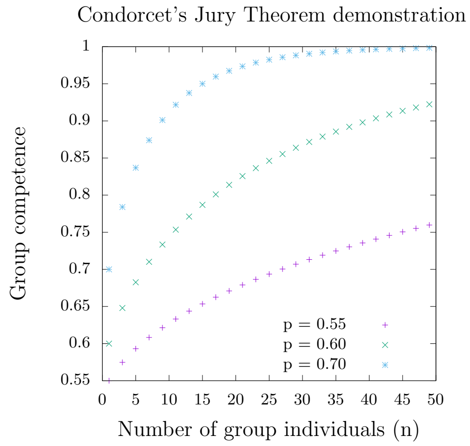

FIG. 1: Group competence under simple majority rule vs the number of group individuals.

This theorem has an impact on social animals and their decision-making mechanism. On the FIG.1 we can observe that as the competence of each individual increases, the group competence is bigger for a lower number of group members.

III. MODEL

The model used to simulate the bees' decision process tries to grasp the intrinsic behavior of the scout swarm in the easiest possible way.

There are n scout bees numerated $1, 2, .., n$ who participate in the decision-making process and k potential nest-sites labeled as $1, 2, ..., k$, where each site j has an objective quality $q_j \geq 0$. Each bee can be at two different states: dancing for a possible nest-site, and so spreading information, either not dancing for any particular site. In this last case, the bee may be resting, searching for a site or observing the other bees. The state at a time t for each bee i is characterized by a two-component vector: $x_{i,t} = (s_{i,t}, d_{i,t})$, where:

- $s_{i,t} \in 0, 1, 2, ..., k$: Indicates the nest-site the bee is dancing for. If $s_{i,t} = 0$ the bee is not dancing for any nest-site.
- $d_{i,t} \geq 0$: Indicates the remaining duration of the waggle dance.

Initially, we suppose all the bees are at the state $x_{i,t} = (0, 0)$. The evolution of the system depends on the state of each bee, as explained above, we have to distinguish two different cases:

1. The bee is not dancing for any nest-site, $s_i = 0$

In this case, the bee is susceptible to fly to a possible nest-site and dance for it. Also, the bee can remain not dancing. We define a probability for the bee to find a site j at a time $t+1$ and dance for it as $p_{j,t+1}$, where $p_{0,t+1}$ is the probability that the bee remains at rest. These probabilities are normalized over all the possible states.

$$p_{j,t+1} = (1 - \lambda)\pi_j + \lambda f_{j,t} \tag{1}$$

The term π_j indicates the *a priori* probability for the bee to find the possible nest-site without any advertisement, this probability depends on environmental factors, such as the site location and distance from the swarm. The term π_0 ($j = 0$, no site) is included and decodes the probability of the bee staying at rest. These probabilities also are normalized to 1. The factor $f_{j,t}$ denotes the fraction of bees dancing for each site at a time t.Finally, but not less important, λ is the interdependence parameter, and as its name says, it captures the amount of interdependence between the bees. The two limiting cases are:

- $\lambda = 0$: The probability of the bee finding and dancing for a site remains on the *a priori* probability, and the bees do not influence each other by communication.
- $\lambda = 1$: The probability of the bee finding and dancing for a site are proportional to the number of bees dancing for this site. In this case, the bees dancing completely determinate the decision-making process.

It is needed to remark two characteristics of the bees: First, they are independent, so they individually inspect possible nest sites before dancing for it. Also, they assign each site a quality independently of the other bees dance duration. This case is represented by low values of λ. Second, the bees are interdependent, so they are more likely to inspects the nest sites that get more attention from the other bees. This case is represented by high values of λ. Now, we have to define the waggle dance duration which is directly proportional to the nest-site quality (q_j).

$$d_{j,t+1} = \begin{cases} q_j & j \neq 0 \\ 0 & j = 0 \end{cases} \tag{2}$$

2. The bee is dancing for a nest-site, $s_i \neq 0$

The bee will continue to dance for the same nest-site it was dancing but the dance duration will be reduced one time period. If the dance duration is over the bee will return the the no-dancing state.

$$d_{j,t+1} = \begin{cases} (s_j, d_{j,t} - 1) & d_{j,t} \neq 0 \\ (0, 0) & d_{j,t} = 0 \end{cases} \tag{3}$$

Field studies suggest that is not necessary that all the bees performing waggle dance are advertising just one site to reach a consensus [4], when a site is advertised by a sufficiently large number of bees it can emerge. In this paper, we will use a strict consensus statement to ensure that the bees' decision is strongly made:

- $n_i > 2n_j$: The number of bees dancing for a nest-site has to be more than the double in the second most advertised site.
- $n_0 < 0.5n$: More than the 50% of bees are dancing for a nest-site.

A different and more relaxed statement can change quantitative but not qualitatively the results. We have also introduced an order parameter to characterize the consensus

$$Q = (n_i - 2n_j)/n \quad \text{if} \quad n_i > n_j \tag{4}$$

If $Q > 0$ the bees have arrived at a consensus, and if $Q = 1$, all the bees are dancing for one nest-site.

IV. SIMULATION RESULTS

The structure of the study is the following: First, to get a more and simple vision of how the model works, we study the case of five possible nest-sites and evaluate the bees distribution for different interdependence parameters, then analyze the cases for two equal and different nest-sites and finally consider how the "distances" between the qualities of the two nest-sites affect the decision process. It's important to remark that in this paper we are going to study the two more relevant parameters of the model λ and Q, this is a reasonable hypothesis based on previous studies.

A. Five nest-sites

The five possible nest-sites ($k = 5$), have fixed qualities $q_i(i = 1, ..., 5) = 3, 4, 7, 9, 10$, so it's difficult for the bees to distinguish between the two best sites. We consider that the *a priori* probabilities are equally distributed over the five sites $\pi_i(i = 1, ..., 5) = 5\%$, whereas the *a priori* probability of staying at rest is $\pi_0 = 75\%$. We fix these parameters so it's not so easy for the bees to find a site without following any other bees advertisement. Minor and reasonable changes in these probabilities do not change the final results of the system.

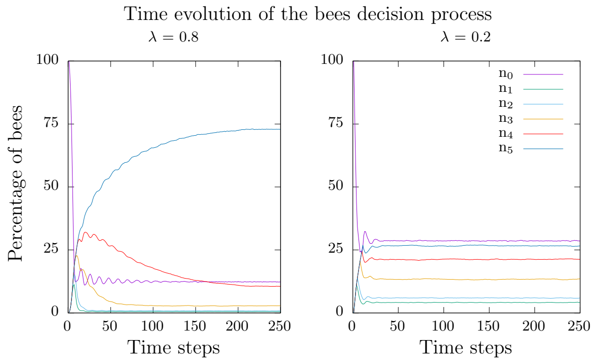

FIG. 2: Time evolution of the proportion of bees dancing for each possible nest site for $n = 500$ bees and two different interdependence parameters. The results correspond to 500 different simulations, where we averaged the number of bees at each time step.

In the case of high interdependence ($\lambda = 0.8$), we can appreciate that the best nest-site tends to accumulate the major number of bees as the time increases, also there is an important difference in the percentage of bees dancing for the best two nest-sites. However, on the low interdependence illustration ($\lambda = 0.2$), the best nest-site still accumulates the major number of bees, but the difference in the percentage of bees between the best two sites is low. Note that the time needed to arrive at the stationary state is much lower in this last case. We can state that for a higher interdependence parameter, the bees are more likely to dance for the more advertised nest-sites and thus the ones with more quality.

B. Two equal nest-sites

Now we study the scenario where there are two possible equal nest-sites, which means they both have the same quality. We consider $q_1 = q_2 = 3$, $\pi_0 = 70\%$ and $\pi_1 = \pi_2 = 15\%$. We want to analyze the population of bees behavior for different interdependence parameters, study its impact on the consensus and discuss how the density of the system, in our model, the number of scout bees, affects the results.

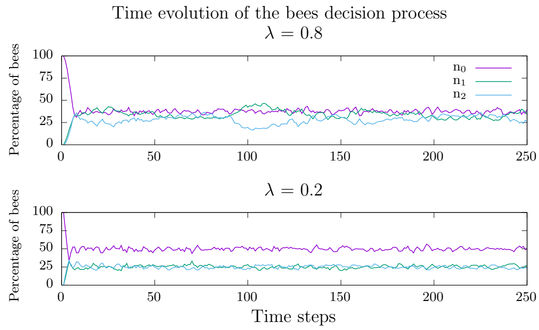

FIG. 3: Time evolution of the proportion of bees dancing for each possible nest site for $n = 500$ bees and qualities $q_1 = q_2 = 3$ for two different interdependence parameters. The results correspond to only one simulation.

If the interdependence is low, the system is more stable and the number of bees that don't dance for any particular site is bigger than in the case of high interdependence. To analyze if the system arrives at a consensus we have to study the order parameter Q. The fluctuations can make the system arrive at a consensus but in a transitory manner (FIG. 4) especially for high λ and it is more difficult to achieve as the density of the system increases due to the decrease of the fluctuations.

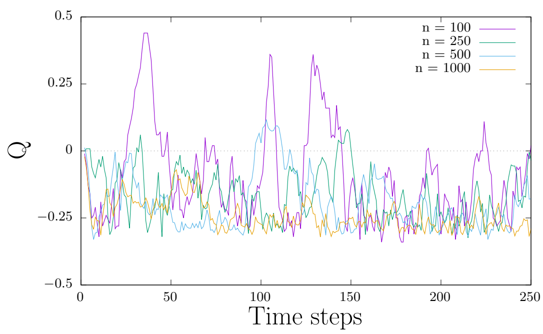

FIG. 4: Order parameter Q vs time steps for $\lambda = 0.8$ and different number of bees. The results correspond to only one simulation.

The number of bees (FIG.5) not dancing for any nest-site decreases whereas the percentage of bees dancing for each of the two possible sites increases both linearly as λ grows. Note that n_1 and n_2 are practically superposed and this distribution of the bees is independent of the density of the system.

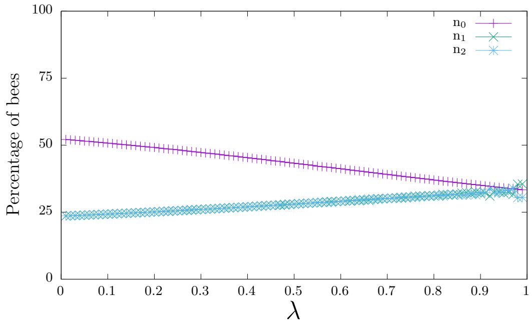

FIG. 5: Percentage of bees dancing for each nest-site and not dancing for any particular site vs the interdependence parameter at the stationary state. The results are averaged over 500 different simulations and correspond to the case $n = 500$. The final oscillations for high values of λ are due to the strong fluctuations of the system.

It's important to conclude, that in the context of decision-making, a group faced with a decision between two possible nest sites can spontaneously choose one of them but only in a transitory state, especially for high values of the interdependence parameter and low number of bees, but overall the bees can't reach a consensus

C. Two different nest-sites

We suppose there are two possible nest-sites with different fixed qualities $q_1 = 3$ and $q_2 = 4$.

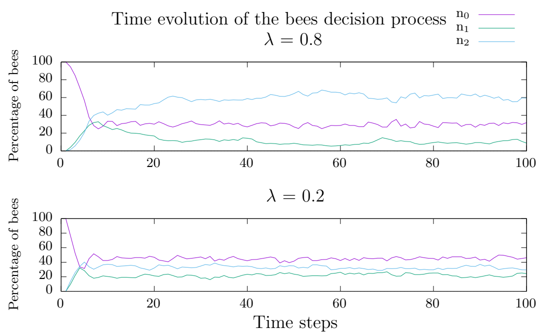

FIG. 6: Time evolution of the proportion of bees dancing for each possible nest site for $n = 500$ bees and qualities $q_1 = 3$ and $q_2 = 4$ for two different interdependence parameters. The results correspond to only one simulation.

The interdependence factor (λ) has the same impact as the case of two equal nest-sties, but now on the majority of simulations the site with bigger quality will prevail on the decision process.

We can appreciate that order parameter Q (FIG.7) values fluctuate around positive values and more vigorously for lower densities of the system for a high interdependence. If we analyze the average of this other parameter for different λ (FIG.8), we can observe that for λ>0.43 the system always arrives at a consensus independently of the density of the system.

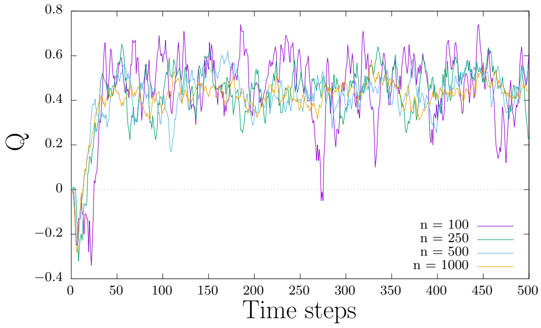

FIG. 7: Order parameter Q vs time steps for $\lambda = 0.8$. The results correspond to only one simulation.

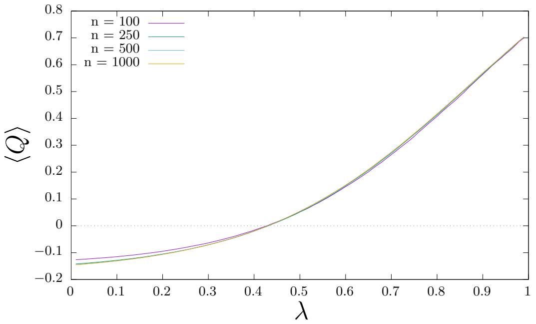

FIG. 8: Order parameter Q averaged over 500 different simulations for each λ.

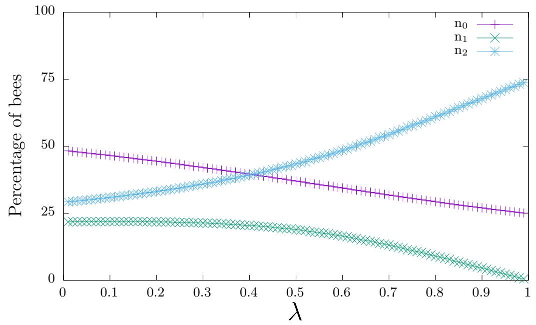

FIG. 9: Percentage of bees dancing for each nest-site and not dancing for any particular site vs the interdependence parameter at the stationary state. The results are averaged over 500 different simulations and correspond to the case $n = 500$. These results are independent of the density of the system.

The percentage of bees dancing for the best-nest site at the stationary state increases while the second nest site percentage decreases as λ increases. For high values of λ the fluctuations can lead the bees to chose the wrong nest site, especially for low densities of the system and at early stages of the decision process. So, independence without interdependence can eventually lead to a temporally wrong decision, but, at the stationary state the bees will always choose the best nest-site.

It's important to mention that the time needed to reach the stationary state (FIG.10) increases as the interdependence factor increases, so in this case, the optimal λ for the decision process is the one slightly bigger than 0.43.

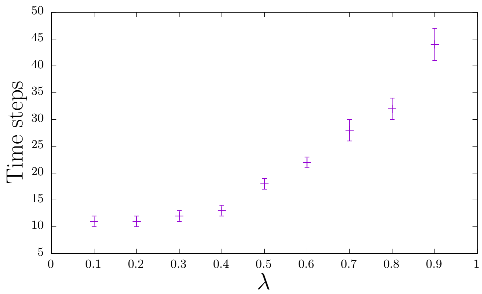

FIG. 10: Time necessary to reach the stationary state for different interdependence parameters λ. These results are independent of the density of the system.

D. Quality distances

In this section, we are going to analyze how the "distances" between the two possible nest-sites qualities affect the bees population distribution and the consensus at the stationary state.

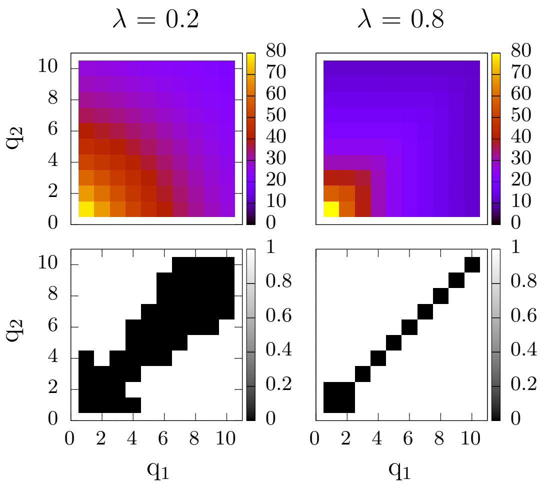

FIG. 11: Up - Percentage of bees not dancing for any particular nest-site. Down - The black dots indicate that there is no consensus at the stationary state, whereas the white ones show the opposite. The results correspond to $n = 100$ and 100 different simulations for each pair of two different qualities and two different interdependence parameters.

The percentage of bees not dancing for any site decreases as the quality of the two nest-sites and λ increases. For low values of λ and similar qualities there won't be consensus, whereas high values promote it.

If the two qualities are alike and bigger, the interdependence parameter (FIG. 12) needed to reach the consensus has to be also bigger. Note that if the distance is large, λ tends to zero, so it will be more easy to reach consensus. For further research, it will be interesting to study continuous quality distributions characterized by its diferent momenta.

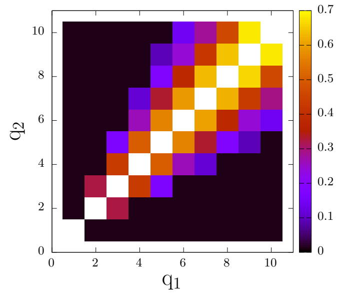

FIG. 12: First interdependence parameter for which $\langle Q \rangle > 0$ for two different qualities. Consensus is not achieved when both qualities are equal

V. CONCLUSIONS

We have analyzed a model for the determination of the nest-site by honeybees based and consistent with empirical work. In the case of two equal nest-sites, the system can reach a transitory consensus state, but it breaks rapidly and overall there is no consensus. If one site is better than the other, in a wide range of interdependence parameter values, the bees will choose the best one to move. Only if they are strongly interdependent, they can transitorily choose the wrong site at the early stages of the process. High values of λ promote consensus; however, the time needed to arrive at the stationary state is bigger, so to increase the performance of the process, bees need to have the right balance between independence and interdependence. To conclude, nature has given the bees a very strong mechanism to chose for the best possible nest-site.

In the following months, we will use a robot swarm [5] to study experimentally more general situations, for example, the influence of spacial fluctuations.

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