



# Honey bee social foraging algorithms for resource allocation: Theory and application

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## ARTICLE INFO

### Article history:

Received 12 December 2008

Accepted 5 May 2010

Available online 1 June 2010

### Keywords:

Ideal free distribution

Honey bee social foraging

Evolutionarily stable strategy

Dynamic resource allocation

Temperature control

## ABSTRACT

A model of honey bee social foraging is introduced to create an algorithm that solves a class of dynamic resource allocation problems. We prove that if several such algorithms (“hives”) compete in the same problem domain, the strategy they use is a Nash equilibrium and an evolutionarily stable strategy. Moreover, for a single or multiple hives we prove that the allocation strategy is globally optimal. To illustrate the practical utility of the theoretical results and algorithm we show how it can solve a dynamic voltage allocation problem to achieve a maximum uniformly elevated temperature in an interconnected grid of temperature zones.

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## 1. Introduction

In the last two decades there has been an increasing interest in understanding how some organisms generate different patterns, and how some of them use collective behaviors to solve problems (Bonabeau et al., 1999). In engineering, this “bioinspired” design approach (Passino, 2005) has been used to exploit the evolved “tricks” of nature to construct robust high performance technological solutions. One of the most popular bioinspired design approaches is what is called “Swarm Intelligence” (SI) (Bonabeau et al., 1999; Kennedy and Eberhart, 2001). SI groups those techniques inspired by the collective behavior of social insect colonies, as well as other animal societies that are able to solve large-scale distributed problems. Some of the algorithms that have been developed are inspired on the collective foraging behavior of ants (Dorigo and Maniezzo, 1996), bees (Nakrani and Tovey, 2003; Teodorovic and Dell’orco, 2005; Walker, 2004), or the general social interaction of different animal societies (e.g., school of fishes) (Kennedy and Eberhart, 1995). For instance, the ant colony optimization (ACO) algorithms introduced by Dorigo and colleagues (e.g., see Dorigo and Blum, 2005; Bonabeau et al., 1999; Dorigo and Stützle, 2004; Dorigo et al., 2002) mimic ant foraging behavior and have been used in the solution to classical optimization problems (e.g., discrete combinatorial optimization problems, Dorigo et al., 1996) and in engineering applications (e.g., Schoonderwoerd et al., 1996; Reimann et al., 2004). Another approach that mimics the behavior of social

organisms is the particle swarm optimization (PSO) technique, where the behavior of different types of social interactions (e.g., flock of birds) is mimicked in order to create an optimization method that is able to solve continuous optimization problems (Poli et al., 2007). Many applications have applied this type of optimization method (see Poli, 2007 for an extensive literature review on the field). For instance, in Han et al. (2005) the authors use the PSO technique in order to optimally select the parameters of a PID controller, while in Juang and Hsu (2005) the PSO is used in order to design a recurrent fuzzy controller used to perform temperature control using a field-programmable gate array (FPGA). The primary goal of this paper is to show that another SI technique (i.e., honey bee social foraging) can be exploited in a bioinspired design approach to (i) solve a dynamic resource allocation problem (Ibaraki and Katoh, 1988) by viewing it from an evolutionary game-theoretic perspective, and (ii) provide novel strategies for multizone temperature control, an important industrial engineering application. It should be pointed out that the ACO is designed and successful for primarily static discrete optimization problems, like for shortest paths and hence is not directly applicable to dynamic continuous resource allocation problems. In the other hand, PSO has been used for continuous optimization problems. Even though we might be able to formulate our problem using an objective function and solve it with PSO, the main objective of this paper is not to compare with optimization methods as it has usually been in this area (Poli, 2007). In this paper, we aim to study the game-theoretic development of the honey bee social foraging (rather than optimization), and the implementation of those game-theoretic methods.

Our model of honey bee social foraging relies on experimental studies (Seeley, 1995) and some ideas from other mathematical models of the process. A differential equation model of functional

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aspects of dynamic labor force allocation of honey bees is developed and validated for one set of experimental conditions in Seeley et al. (1991) and Camazine and Sneyd (1991). The work in Cox and Myerscough (2003) extends this model (e.g., by adding details on energetics and currency) and Sumpter and Pratt (2003) introduced a generic nonlinear differential equation model that can represent social foraging processes in both bees and ants. Like in Sumpter and Pratt (2003) and Cox and Myerscough (2003), our model of recruitment uses the idea from Seeley et al. (1991) and Camazine and Sneyd (1991) that dance strength proportioning on the dance floor shares some characteristics with the evolutionary process (e.g., with fitness corresponding to forage site profitability and reproduction to recruitment as discussed in Seeley, 1995). Here we make such connections more concrete by modeling the bee recruitment process in an analogous manner to how survival of the fittest and natural selection are modeled in genetic algorithms using a stochastic process of fitness proportionate selection (Mitchell, 1996). The authors in de Vries and Biesmeijer (1998) introduce an “individual-oriented” model of social foraging and validate it against one set of experimental conditions as was done in Seeley et al. (1991) and Camazine and Sneyd (1991). More recently, in de Vries and Biesmeijer (2002) the authors expanded and improved the model in de Vries and Biesmeijer (1998) (e.g., taking into account the findings in Seeley and Tovey (1994) and by studying an equal harvest rate forager allocation distribution). The work in Bartholdi et al. (1993) studies the pattern of forager allocation and the optimality of it. The authors in Dukas and Edelman-Keshet (1998) study the spatial distribution of solitary and social food provisioners under different currency assumptions. The work in Bartholdi et al. (1993), Dukas and Edelman-Keshet (1998), and de Vries and Biesmeijer (2002) identifies connections to the concept of the “ideal free distribution” (IFD) (Fretwell and Lucas, 1970). Here, we do not use a detailed characterization of bee and nectar energetics and currency since there is not enough experimental evidence to justify whether or when a gathering rate or efficiency-based currency is used (Seeley, 1995); instead, we develop a *generic* measure of forage site profitability. This general profitability measure approach is the same one used in Passino and Seeley (2006) to represent the nest-site quality landscape for the honey bee nest-site selection process. Our general measure has the advantage of allowing us to easily represent a wide range of density-dependent foraging currencies via the classical “suitability function” approach to IFD studies (Fretwell and Lucas, 1970). Also, it eases the transition to the multizone temperature control problem since the temperature control objective can be easily characterized with our general profitability measure.

The IFD concept has been used to analyze how animals distribute themselves across different habitats or patches of food (Fretwell and Lucas, 1970). These habitats have different characteristics (e.g., one habitat might have a higher nutrient input rate than another), but animals tend to reach an equilibrium point where each has the same correlate of fitness (e.g., consumption rate). The term “ideal” means that the animals can perfectly sense the quality of all habitats and seek to maximize the suitability of the habitat they are in (by choosing which habitat to reside in), and the term “free” means that the animals can go to any habitat. In this paper, the IFD is a central unifying concept. The IFD will emerge for one hive as the foragers are *cooperatively* allocated across sites. Moreover, if  $n$  hives *compete* in the same environment for a resource the IFD will also emerge. Here, we create a mathematical representation of the  $n$ -hive game where each hive’s strategy choice entails picking the distribution of its foragers across the environment. Our analytical study starts by showing that the IFD is a strict Nash equilibrium (Başar and Olsder, 1999) in terms of the payoffs to each hive and a special

type of evolutionarily stable strategy (ESS). The original definition of an ESS is based on one important assumption: the population size has to be infinite. In Schaffer (1988) and Maynard Smith (1988) the authors define the conditions that must be satisfied in order to prove that a strategy is evolutionarily stable for a finite-population size. Using the ideas in Schaffer (1988) we state the conditions for what we call a *one-stable* ESS, and show that the IFD satisfies those conditions. This means that in an  $n$ -hive game, if a single hive’s strategy (forager allocation) mutates from the IFD it cannot survive when competing against a field of  $n-1$  hives that use the IFD strategy. While this means that the IFD is locally optimal in a game-theoretic sense (i.e., unilateral forager allocation deviations by a hive are not profitable), here we show that the achieved IFD is a global optimum point for both single hive and  $n$ -hive allocations. For the  $n$ -hive case, this means that if the forager allocation of all hives but one is at the IFD, then the remaining hive has to distribute its effort according to the IFD if it is to maximize its return.

Finally, it is important to highlight that other algorithms have been developed using honey bee social foraging. For instance, in Teodorovic and Dell’orco (2008) the authors introduce a bee colony optimization (BCO) algorithm, which is a generalization of the bee system (BS) tested in another combinatorial optimization problems, to solve a common problem in traffic congestion. Others have used different approaches to solve different optimization problems such as energy efficient mobile ad hoc networks (Wedde and Farooq, 2005), job shop scheduling (Chong et al., 2006), or Internet servers (Nakrani and Tovey, 2003; Walker, 2004). In general, all the articles that present a honey bee social foraging algorithm do not focus on trying to mimic the whole behavior of the foraging process. They tend to concentrate on the most important part of the foraging process, i.e., the waggle dance. Also, the problems that these algorithms are trying to solve can be grouped into continuous optimization problems. As it was pointed out before, our approach seeks to illustrate concepts from a game-theoretic perspective rather than the optimization one used in most of these algorithms (Pankiw, 2005; Pham et al., 2006; Teodorovic and Dell’orco, 2005; Chong et al., 2006; Karaboga, 2005). On the other hand, the utility of the theoretical concepts introduced in this paper, and the honey bee social foraging algorithm are illustrated by means of an engineering application. In general, most of the applications that use honey bee social foraging approaches use their algorithms in simulations, or in applications where the algorithm is not directly applied to solve a real engineering application. However, in our case, the technological challenge we confront is experimental multizone temperature control. Achievement of high performance multizone temperature control is very important in a range of commercial and industrial applications. For instance, recent work in this area includes distributed control of thermal processes (Jones et al., 2003; Zaheer-uddin et al., 1993; Emami-Naeini et al., 2003; Demetriou et al., 2003; Ross, 2004), and semiconductor processing (Alaeddine and Doumanidis, 2004a, b; Schaper et al., 1999b). Particularly relevant to our work is the study in Emami-Naeini et al. (2003), where the authors use multivariable distributed control in order to maintain a uniform temperature across a wafer during ramp-up (similar to the control objective we study here). In Schaper et al. (1999a) the authors describe a lithographical system that is heated by 49 independently controlled zones. Here, we use a multizone experimental setup that is similar to the one in Quijano et al. (2005) where dynamic resource allocation methods are studied. In Quijano and Passino (2007) a multizone temperature control experiment is also used, but the dynamics are based on a replicator dynamics model. Our experiments demonstrate how one hive can achieve an IFD that corresponds to maximum uniform temperatures on the

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