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# Agent-Based Modeling and Simulation of Species Formation Processes

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## 1. Introduction

Agent-based modeling and simulation becomes increasingly popular in social and biological sciences. It is due to the fact that agent-based models allow to elegant and explicitly represent entities, environment, and relations between them Gilbert (2008). Scientist can develop agent-based-model (agents, environment, and relations between them), directly observe interactions and emergent phenomena resulting from them, and experiment with the model. Agent-based approach also allows for very intuitive modeling—entities from the real world can be directly represented in the model. It is also possible to represent heterogeneous entities and environment in the model, as well as model intelligent behavior of entities. Also, the very important mechanism is environment with potentially spatial/geographical structure—agents can be located within such environment, migrate from one place to another, and one can model obstacles, barriers, and geographical elements Gilbert (2008).

The notions *agent* and *multi-agent system* have many different meanings in the literature of the field—in this chapter the following meaning of these terms will be used. *Agent* is considered physical of virtual entity capable of acting within environment, capable of communicating with other agents, its activities are driven by individual goals, it possesses some resources, it may observe the environment (but only local part of it), it possesses only partial knowledge about the environment (or no knowledge about it at all), it has some abilities and may offer some services, and it may be able to reproduce Ferber (1999).

*Multi-agent system* is a system composed of environment, objects (passive elements of the system), agents (active elements of the system), relations between different elements, set of operations which allow agents to observe and interact with other elements of the system (including other agents), and operators which aim is to represent agent's actions and reactions of the other elements of the system Ferber (1999).

Agent systems become popular in different areas, such as distributed problem solving, collective robotics, construction of distributed computer systems which easily adapt to changing conditions. The applications in the area of modeling and simulation include models of complex biological, social, and economical systems Epstein (2006); Epstein & Axtell (1996); Gilbert (2008); Gilbert & Troitzsch (2005); Uhrmacher & Weyns (2009).

Evolutionary algorithms are heuristic techniques which can be used for finding approximate solutions of global optimization problems Bäck, Fogel & Michalewicz (1997). Co-evolutionary algorithms are particular branch of the evolutionary algorithms Paredis (1998). Co-evolutionary algorithms allow for solving problems for which it is impossible to formulate explicit fitness function because of their specific property—the fitness of the given individual is estimated on the basis of its interactions with other individuals existing in the population. The form of these interactions serves as the basic way of classifying co-evolutionary algorithms. There are two types of co-evolutionary algorithms: co-operative and competitive.

Agent-based evolutionary algorithms are the result of merging evolutionary computations and multi-agent systems paradigms Cetnarowicz et al. (1996). In fact two approaches to constructing agent-based evolutionary algorithms are possible. In the first one the multi-agent layer of the system serves as a "manager" for decentralized evolutionary computations. In the second approach individuals are agents, which "live" within the environment, posses the ability to reproduce, compete for limited resources, die when they run out of resources, and make independently all their decisions concerning reproduction, migration, etc., taking into consideration conditions of the environment, other agents present within the neighborhood, and resources possessed. Hybrid systems, which mix these two approaches are also possible.

The example of the second approach is the model of co-evolutionary multi-agent system (CoEMAS) Dreżewski (2003), which results from the realization of co-evolutionary processes in multi-agent system. Agent-based co-evolutionary systems have some interesting features, among which the most interesting seems to be the possibility of constructing hybrid systems, in which many different computational intelligence techniques are used together within one coherent agent-based computational model, and the possibility of introducing new evolutionary operators and social relations, which were hard or impossible to introduce in the case of "classical" evolutionary computations.

Co-evolutionary multi-agent systems (CoEMAS) utilizing mentioned above second kind of approach to merging evolutionary computations and multi-agent systems have already been applied with good results to multi-modal optimization Dreżewski (2006), multi-objective optimization Dreżewski & Siwik (2008), generating investment strategies Dreżewski, Sepielak & Siwik (2009), and solving Traveling Salesman Problem Dreżewski, Woźniak & Siwik (2009).

Agent-based systems with evolutionary mechanisms can also be used in the area of modeling and simulation. Agent-based modeling and simulation is particularly suited for exploring biological, social, economic, and emergent phenomena. Agent-based systems with evolutionary mechanisms give us the possibility of constructing agent-based models with integrated mechanisms of biological evolution and social interactions. This approach can be especially suitable for modeling biological ecosystems and socio-economical systems. With the use of mentioned approach we have all necessary tools to create models and of such systems: environment, agents, agent-agent and agent-environment relations, resources, evolution mechanisms (competing for limited resources, reproduction), possibility of defining species, sexes, co-evolutionary interactions between species and sexes, social relations, formation of social structures, organizations, teams, etc.

In this chapter we will mainly focus on processes of species formation and agent-based modeling and simulation of such phenomena. The understanding of species formation processes (*speciation*) still remains the greatest challenge for evolutionary biology. The biological models of speciation include *allopatric models* (which require geographical separation of sub-populations) and *sympatric models* (where speciation takes place within one population without physical barriers) Gavrilets (2003). Sympatric speciation may be caused by different kinds of co-evolutionary interactions between species and sexes (*sexual selection*). Allopatric speciation can take place when sub-populations of original species become geographically separated. They live and evolve in different conditions (adapt to conditions of different environments), and eventually become reproductively isolated even after the disappearance of physical barriers. Reproductive isolation causes that natural selection works on each sub-population independently and there is no exchange of gene sequences what can lead to formation of new species. The separation of sub-populations can result not only from the existence of geographical barriers but also from different habits, preferences concerning particular part of the nest, low mobility of individuals, etc.

Sexual selection is the result of co-evolution of interacting sexes. Usually one of the sexes evolves to attract the second one to mating and the second one tries to keep the rate of reproduction (and costs associated with it) on optimal level (what leads to *sexual conflict*) Gavrilets (2003). The proportion of two sexes (females and males) in population is almost always 1 : 1. This fact combined with higher females' reproduction costs causes, that in the majority of cases, females choose males in the reproduction process according to some males' features. In fact, different variants of sexual conflict are possible. For example there can be higher females' reproduction costs, equal reproduction costs (no sexual conflict), equal number of females and males in population, higher number of males in population (when the costs of producing a female are higher than producing a male), higher number of females in population (when the costs of producing a male are higher than producing a female) Krebs & Davies (1993).

The main goal of this chapter is to introduce new coherent model of multi-agent system with biological and social layers and to demonstrate that systems based on such model can be used as agent-based modeling and simulation tools.

It will be demonstrated that using proposed approach it is possible to model complex biological phenomena—species formation caused by different mechanisms. Spatial separation of sub-populations (based on geographical barriers and resulting from forming flocks) and sexual selection mechanisms will be modeled.

In the first part of the chapter we will describe formally bio-social multi-agent system (BSMAS) model. Then using introduced notions we will show that it is possible to define three models of species formation: two based on isolation of sub-populations, and one based on co-evolutionary interactions between sexes (sexual selection). In the experimental part of the chapter selected results of experiments showing that speciation takes place in all constructed models, however the course of evolution of sub-populations is different will be presented.

## 2. General model of multi-agent system with biological and social mechanisms

In this section the general model of multi-agent system with two layers: biological and social is presented. On the basis of such abstract model concrete simulation and computational systems can be constructed. In the following sections I will present examples of such systems. The model presented in this section includes all elements required in agent-based modeling of biological and social mechanisms: environment, objects, agents, relations between environment, objects, and agents, actions and attributes.

### 2.1 Bio-Social Multi-Agent System (BSMAS)

The *BSMAS* in time $t$ is described as 8-tuple:

$$\begin{aligned} BSMAS(t) = \langle & EnvT(t), Env(t), ElT(t) = VertT(t) \cup ObjT(t) \cup AgT(t), \\ & ResT(t), InfT(t), Rel(t), Attr(t), Act(t) \rangle \end{aligned} \tag{1}$$

where:

- $EnvT(t)$ is the set of environment types in the time $t$;
- $Env(t)$ is the set of environments of the $BSMAS$ in the time $t$;
- $ElT(t)$ is the set of types of elements that can exist within the system in time $t$;
- $VertT(t)$ is the set of vertice types that can exist within the system in time $t$;
- $ObjT(t)$ is the set of object (not an object in the sense of object-oriented programming but object as an element of the simulation model) types that may exist within the system in time $t$;
- $AgT(t)$ is the set of agent types that may exist within the system in time $t$;
- $ResT(t)$ is the set of resource types that exist in the system in time $t$, the amount of resource of type $rest(t) \in ResT(t)$ will be denoted by $res^{rest}(t)$;
- $InfT(t)$ is the set of information types that exist in the system, the information of type $inft(t) \in InfT(t)$ will be denoted by $inf^{inft}(t)$;
- $Rel(t)$ is the set of relations between sets of agents, objects, and vertices;
- $Attr(t)$ is the set of attributes of agents, objects, and vertices;
- $Act(t)$ is the set of actions that can be performed by agents, objects, and vertices.

In the rest of this chapter, for the sake of notation clarity, all symbols related to time will be omitted until it is necessary to indicate time relations between elements.

### 2.2 Environment

The environment type $envt \in EnvT$ of $BSMAS$ may be described as 4-tuple:

$$envt = \langle EnvT^{envt}, VertT^{envt}, ResT^{envt}, InfT^{envt} \rangle \tag{2}$$

$EnvT^{envt} \subseteq EnvT$ is the set of environment types that may be connected with the $envt$ environment at the beginning of its existence. $VertT^{envt} \subseteq VerT$ is the set of vertice types that may exist within the environment of type $envt$. $ResT^{envt} \subseteq ResT$ is the set of resource types that may exist within the environment of type $envt$. $InfT^{envt} \subseteq InfT$ is the set of information types that may exist within the environment of type $envt$.
The environment $env \in Env$ of type $envt$ is defined as 2-tuple:

$$env = \langle gr^{env}, Env^{env} \rangle \tag{3}$$

where $gr^{env}$ is directed graph with the $cost$ function defined: $gr^{env} = \langle Vert, Arch, cost \rangle$, $Vert$ is the set of vertices, $Arch$ is the set of arches. The distance between two nodes is defined as the length of the shortest path between them in graph $gr^{env}$. $Env^{env} \subseteq Env$ is the set of environments of types from $EnvT$ connected with the environment $env$.
Vertice type $vertt \in VertT^{env}$ is defined as follows:

$$vertt = \langle Attr^{vertt}, Act^{vertt}, ResT^{vertt}, InfT^{vertt}, VertT^{vertt}, ObjT^{vertt}, AgT^{vertt} \rangle \tag{4}$$

where:

- $Attr^{vertt} \subseteq Attr$ is the set of attributes of $vertt$ vertice at the beginning of its existence;
- $Act^{vertt} \subseteq Act$ is the set of actions, which $vertt$ vertice can perform at the beginning of its existence, when asked for it;

- $ResT^{vertt} \subseteq ResT$ is the set of resource types, which can exist within *vertt* vertice at the beginning of its existence;
- $InfT^{vertt} \subseteq InfT$ is the set of information, which can exist within *vertt* vertice at the beginning of its existence;
- $VertT^{vertt}$ is the set of types of vertices that can be connected with the *vertt* vertice at the beginning of its existence;
- $ObjT^{vertt} \subseteq ObjT$ is the set of types of objects that can be located within the *vertt* vertice at the beginning of its existence;
- $AgT^{vertt} \subseteq AgT$ is the set of types of agents that can be located within the *vertt* vertice at the beginning of its existence.

Element of the structure of system's environment (vertice) $vert \in Vert$ of type $vertt \in VertT^{env}$ is given by:

$$vert = \langle Attr^{vert}, Act^{vert}, Res^{vert}, Inf^{vert}, Vert^{vert}, Obj^{vert}, Ag^{vert} \rangle \tag{5}$$

where:

- $Attr^{vert} \subseteq Attr$ is the set of attributes of vertice *vert*—it can change during its lifetime;
- $Act^{vert} \subseteq Act$ is the set of actions, which vertice *vert* can perform when asked for it—it can change during its lifetime;
- $Res^{vert}$ is the set of resources of types from $ResT$ that exist within the *vert*;
- $Inf^{vert}$ is the set of information of types from $InfT$ that exist within the *vert*;
- $Vert^{vert}$ is the set of vertices of types from $VertT$ connected with the vertice *vert*;
- $Obj^{vert}$ is the set of objects of types from $ObjT$ that are located in the vertice *vert*;
- $Ag^{vert}$ is the set of agents of types from $AgT$ that are located in the vertice *vert*.

Each object and agent is located within one of the vertices. The set of all objects that exist within the system $Obj = \bigcup_{vert \in Vert} Obj^{vert}$, and the set of all agents that exist within the system $Ag = \bigcup_{vert \in Vert} Ag^{vert}$. $El = Vert \cup Obj \cup Ag$ is the set of all elements (vertices, objects, and agents) that exist within the system.

#### 2.3 Objects

Object type $ot \in ObjT$ is defined as follows:

$$objt = \langle Attr^{objt}, Act^{objt}, ResT^{objt}, InfT^{objt}, ObjT^{objt}, AgT^{objt} \rangle \tag{6}$$

where:

- $Attr^{objt} \subseteq Attr$ is the set of attributes of *objt* object at the beginning of its existence;
- $Act^{objt} \subseteq Act$ is the set of actions, which *objt* object can perform when asked for it at the beginning of its existence;
- $ResT^{objt} \subseteq ResT$ is the set of resource types, which can be used by *objt* object at the beginning of its existence;
- $InfT^{objt} \subseteq InfT$ is the set of information, which can be used by *objt* object at the beginning of its existence;

- $ObjT^{objt} \subseteq ObjT$ is the set of types of objects that can be located within the $objt$ object at the beginning of its existence;
- $AgT^{objt} \subseteq AgT$ is the set of types of agents that can be located within the $objt$ object at the beginning of its existence.

Passive element of the system (object) $obj \in Obj$ of type $objt \in ObjT$ is defined in the following way:

$$obj = \langle Attr^{obj}, Act^{obj}, Res^{obj}, Inf^{obj}, Obj^{obj}, Ag^{obj} \rangle \quad (7)$$

where:

- $Attr^{obj} \subseteq Attr$ is the set of attributes of object $obj$—it can change during its lifetime;
- $Act^{obj} \subseteq Act$ is the set of actions, which object $obj$ can perform when asked for it—it can change during its lifetime;
- $Res^{obj}$ is the set of resources of types from $ResT$, which exist within object $obj$;
- $Inf^{obj}$ is the set of information of types from $InfT$, which exist within object $obj$;
- $Obj^{obj}$ is the set of objects of types from $ObjT$ that are located within the object $obj$;
- $Ag^{obj}$ is the set of agents of types from $AgT$ that are located within the object $obj$.

### 2.4 Agents

Agent type $agt \in AgT$ is defined as follows:

$$agt = \langle Gl^{agt}, Attr^{agt}, Act^{agt}, ResT^{agt}, InfT^{agt}, ObjT^{agt}, AgT^{agt} \rangle \quad (8)$$

where:

- $Gl^{agt}$ is the set of goals of $agt$ agent at the beginning of its existence;
- $Attr^{agt} \subseteq Attr$ is the set of attributes of $agt$ agent at the beginning of its existence;
- $Act^{agt} \subseteq Act$ is the set of actions, which $agt$ agent can perform at the beginning of its existence;
- $ResT^{agt} \subseteq ResT$ is the set of resource types, which can be used by $agt$ agent at the beginning of its existence;
- $InfT^{agt} \subseteq InfT$ is the set of information, which can be used by $agt$ agent at the beginning of its existence;
- $ObjT^{agt} \subseteq ObjT$ is the set of types of objects that can be located within the $agt$ agent at the beginning of its existence;
- $AgT^{agt} \subseteq AgT$ is the set of types of agents that can be located within the $agt$ agent at the beginning of its existence.

Active element of the system (agent) $ag$ of type $agt \in AgT$ is defined as follows:

$$ag = \langle Gl^{ag}, Attr^{ag}, Act^{ag}, Res^{ag}, Inf^{ag}, Obj^{ag}, Ag^{ag} \rangle \quad (9)$$

where:

- $Gl^{ag}$ is the set of goals, which agent $ag$ tries to realize—it can change during its lifetime;
- $Attr^{ag} \subseteq Attr$ is the set of attributes of agent $ag$—it can change during its lifetime;

- $Act^{ag} \subseteq Act$ is the set of actions, which agent $ag$ can perform in order to realize its goals—it can change during its lifetime;
- $Res^{ag}$ is the set of resources of types from $ResT$, which are used by agent $ag$;
- $Inf^{ag}$ is the set of information of types from $InfT$, which agent $ag$ can possess and use;
- $Obj^{ag}$ is the set of objects of types from $ObjT$ that are located within the agent $ag$;
- $Ag^{ag}$ is the set of agents of types from $AgT$ that are located within the agent $ag$.

### 2.5 Relations

The set of relations contains all types of relations between sets of elements of the system that can perform particular actions. The set of all relations that exist in the system is defined as follows:

$$Rel = \left\{ \xrightarrow[Act2]{Act1} : Act1, Act2 \subseteq \bigcup_{el \in El} Act^{el} \right\} \tag{10}$$

where $el$ is an element (vertice, object, or agent) of the system, $El$ is the set of all elements of the system, and $Act^{el}$ is the set of actions that $el$ can perform.

Relation $\xrightarrow[Act2]{Act1}$ is defined as follows:

$$\xrightarrow[Act2]{Act1} = \left\{ \left\langle El^{Act1}, El^{Act2} \right\rangle \in 2^{El} \times 2^{El} \right\} \tag{11}$$

$El^{Act1}$ is the set of elements of the system (vertices, objects, and agents) that can perform all actions from the set $Act1 \subseteq Act$, and $El^{Act2}$ is the set of elements of the system (vertices, objects, and agents) that can perform all actions from the set $Act2 \subseteq Act$.

## 3. Multi-agent systems for species formation simulation

In this part of the chapter three systems used during simulation experiments we will be formally described with the use of notation introduced in section 2. First of the presented systems uses mechanism of allopatric speciation in which species formation is a result of existing geographical barriers between sub-populations. The second one uses flock forming mechanisms. The third one uses sexual selection mechanism. In all systems competition for limited resources takes place.

### 3.1 Multi-agent system with geographical barriers

Multi-agent system with geographical barriers (aBSMAS) is the model of allopatric speciation. In allopatric speciation the eventual new species is born as a result of splitting the origin species into sub-populations, which are separated with some kind of physical (geographical) barrier. In the case of aBSMAS there exist environment composed of vertices which are connected with paths (see fig. 1). Agents can migrate between vertices but the cost of migration is very high and in fact such a migration takes place very rarely. Within each vertice agents compete for limited resources—there is no competition for resources between sub-populations located within different vertices.

Agents reproduce when they have enough resource. Agent which is ready for reproduction tries to find another agent that can reproduce and that is located within the same vertice of the environment. Reproduction takes place with the use of recombination and mutation operators—operators from evolution strategies were used: intermediate

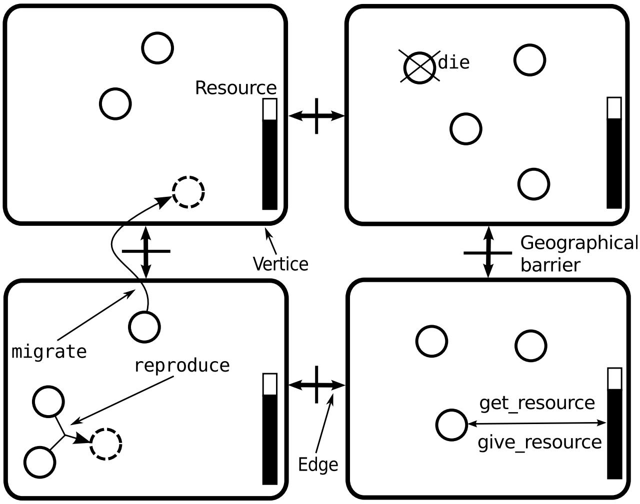



Fig. 1. Multi-Agent System with Geographical Barriers

recombination Booker et al. (1997), and mutation with self-adaptation Bäck, Fogel, Whitley & Angeline (1997). The offspring receives some resource from parents.
The multi-agent system with geographical barriers is defined as follows (compare eq. (1)):

$$\begin{aligned} aBSMAS(t) =& \langle EnvT(t) = \{et\}, Env(t) = \{env\}, ElT(t) = VertT(t) \cup ObjT(t) \cup \\ & AgT(t), ResT(t) = \{rt\}, InfT(t) = \emptyset, \\ & Rel(t), Attr(t) = \{genotype\}, Act(t) \rangle \end{aligned} \tag{12}$$

where $VertT = \{vt\}$, $ObjT = \emptyset$, and $AgT = \{ind\}$.
The set of actions is defined as follows:

$$Act = \{die, reproduce, get\_resource, give\_resource, migrate, \} \tag{13}$$

Environment type $et$:

$$et = \langle EnvT^{et} = \emptyset, VertT^{et} = VertT, ResT^{et} = ResT, InfT^{et} = \emptyset \rangle \tag{14}$$

Environment $env$ of type $et$ is defined as follows:

$$env = \langle gr^{env}, Env^{env} = \emptyset \rangle \tag{15}$$

Vertice type $vt$ is defined in the following way:

$$\begin{aligned} vt = \langle & Attr^{vt} = \emptyset, Act^{vt} = \{give\_resource\}, ResT^{vt} = ResT, \\ & InfT^{vt} = \emptyset, VertT^{vt} = VertT, ObjT^{vt} = \emptyset, AgT^{vt} = AgT \rangle \end{aligned} \tag{16}$$

where $give\_resource$ is the action of giving resource to agent of type $ind$.
Each $vert \in Vert$ is defined as follows:

$$\begin{aligned} vert = \langle & Attr^{vert} = \emptyset, Act^{vert} = Act^{vt}, Res^{vert} = \{res^{vert}\}, Inf^{vert} = \emptyset, \\ & Vert^{vert}, Obj^{vert} = \emptyset, Ag^{vert} \rangle \end{aligned} \tag{17}$$

$res^{vert}$ is the amount of resource of type $rt$ that is possessed by the $vert$. $Vert^{vert}$ is the set of nine (for Michalewicz fitness landscape—see sec. 4.1), thirty (for Rastrigin fitness landscape), sixty three (for Schwefel fitness landscape), or sixteen (for Waves fitness landscape) vertices connected with the vertice $vert$. $Ag^{vert}$ is the set of agents located within the vertice $vert$.
There is one type of agents in the system ($ind$):

$$ind = \langle Gl^{ind} = \{gl_1, gl_2, gl_3\}, Attr^{ind} = \{genotype\}, Act^{ind} = \{die, reproduce, get\_resource, migrate\}, ResT^{ind} = ResT, InfT^{ind} = \emptyset, ObjT^{ind} = \emptyset, AgT^{ind} = \emptyset\rangle \tag{18}$$

where $gl_1$ is the goal "get resource from environment", $gl_2$ is the goal "reproduce", and $gl_3$ is the goal "migrate to other vertice". *die* is the action of death—agent dies when it runs out of resources, *reproduce* is the action of reproducing (with the use of recombination and mutation operators), *get_resource* is the action of getting resource from environment, and *migrate* is the action of migrating to other vertice.
Agent $ag^{ind}$ (of type $ind$) is defined as follows:

$$ag^{ind} = \langle Gl^{ag,ind} = Gl^{ind}, Attr^{ag,ind} = Attr^{ind}, Act^{ag,ind} = Act^{ind}, Res^{ag,ind} = \{r^{ag,ind}\}, Inf^{ag,ind} = \emptyset, Obj^{ag,ind} = \emptyset, Ag^{ag,ind} = \emptyset\rangle \tag{19}$$

Notation $Gl^{ag,ind}$ means "the set of goals of agent $ag$ of type $ind$". $r^{ag,ind}$ is the amount of resource of type $rt$ that is possessed by the agent $ag^{ind}$.
The set of relations is defined as follows:

$$Rel = \left\{ \xrightarrow[\{get\_resource\}]{\{get\_resource\}} \right\} \tag{20}$$

The relation is defined as follows:

$$\xrightarrow[\{get\_resource\}]{\{get\_resource\}} = \left\{ \left\langle Ag^{ind,\{get\_resource\}}, Ag^{ind,\{get\_resource\}} \right\rangle \right\} \tag{21}$$

$Ag^{ind,\{get\_resource\}}$ is the set of agents of type $ind$ capable of performing action *get_resource*. This relation represents competition for limited resources between $ind$ agents.

### 3.2 Multi-agent system with flock formation mechanisms

In multi-agent system with flock formation mechanisms (fBSMAS) speciation takes place as a result of flock formation (see fig. 2). Each agent (individual) can reproduce, die and migrate between flocks—it searches for flock that occupies the same ecological niche. Agents can mate only with agents from the same flock. Reproduction is initiated by the agent that has enough resources to reproduce. Such agent searches for ready for reproduction partner from the same flock. When the partner is chosen then the reproduction takes place. Offspring is generated with the use of intermediate recombination Booker et al. (1997), and mutation with self-adaptation Bäck, Fogel, Whitley & Angeline (1997).
Flocks can merge and split. Merging takes place when two flocks are located within the same ecological niche (basin of attraction of some local minima in the multi-modal fitness landscape—see section 4). Flock splits into two flocks when there exists an agent within the flock which in fact occupies different ecological niche than other agents in the flock and there is

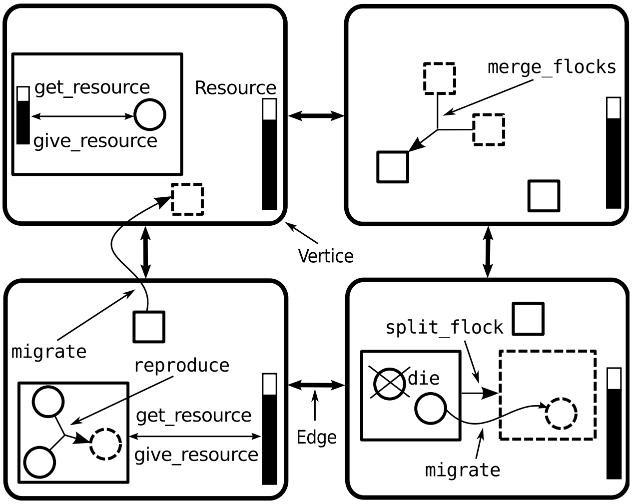



Fig. 2. Multi-Agent System with Flock Formation Mechanisms

no existing flock that such agent can migrate to. Flocks compete for limited resources located within the environment, and agents compete for limited resources located within their flocks. Flocks can migrate within environment.
The multi-agent system with flocks is defined as follows (compare eq. (2)):

$$\begin{aligned} fBSMAS(t) = \langle & EnvT(t) = \{et\}, Env(t) = \{env\}, ElT(t) = VertT(t) \cup ObjT(t) \cup \\ & AgT(t), ResT(t) = \{rt\}, InfT(t) = \emptyset, \\ & Rel(t), Attr(t) = \{genotype\}, Act(t) \rangle \end{aligned} \tag{22}$$

where $VertT = \{vt\}$, $ObjT = \emptyset$, and $AgT = \{flock, ind\}$.
The set of actions is defined as follows:

$$\begin{aligned} Act = \{ & die, reproduce, get\_resource, give\_resource, migrate, search\_flock, \\ & merge\_flocks, split\_flock\} \end{aligned} \tag{23}$$

Environment type *et*:

$$et = \langle EnvT^{et} = \emptyset, VertT^{et} = VertT, ResT^{et} = ResT, InfT^{et} = \emptyset \rangle \tag{24}$$

Environment *env* of type *et* is defined as follows:

$$env = \langle gr^{env}, Env^{env} = \emptyset \rangle \tag{25}$$

Vertice type *vt* is defined in the following way:

$$\begin{aligned} vt = \langle & Attr^{vt} = \emptyset, Act^{vt} = \{give\_resource\}, ResT^{vt} = ResT, \\ & InfT^{vt} = \emptyset, VertT^{vt} = VertT, ObjT^{vt} = \emptyset, AgT^{vt} = \{flock\} \rangle \end{aligned} \tag{26}$$

where *give_resource* is the action of giving resource to flock.

Each $vert \in Vert$ is defined as follows:

$$vert = \langle Attr^{vert} = \emptyset, Act^{vert} = Act^{vt}, Res^{vert} = \{res^{vert}\}, \\ Inf^{vert} = \emptyset, Vert^{vert}, Obj^{vert} = \emptyset, Ag^{vert}\rangle \tag{27}$$

$res^{vert}$ is the amount of resource that is possessed by the $vert$. $Vert^{vert}$ is the set of four vertices connected with the vertice $vert$ (see fig. 2). $Ag^{vert}$ is the set of agents of type $flock$ located within the vertice $vert$.

There are two types of agents in the system: $flock$ and $ind$. $flock$ type of agent is defined in the following way:

$$flock = \langle Gl^{flock} = \{gl_1, gl_2, gl_3\}, Attr^{flock} = \emptyset, Act^{flock} = \{get\_resource, give\_resource, \\ migrate, merge\_flocks\}, ResT^{flock} = ResT, InfT^{flock} = \emptyset, \\ ObjT^{flock} = \emptyset, AgT^{flock} = \{ind\}\rangle \tag{28}$$

where $gl_1$ is the goal "get resource from environment", $gl_2$ is the goal "merge with other flock", and $gl_3$ is the goal "migrate to other vertice". *get_resource* is the action of getting resource from environment, *give_resource* is the action of giving resource to *ind* type agent, *migrate* is the action of migrating to other vertice, and *merge_flocks* is the action of merging with other flock.

*ind* type of agent is defined in the following way:

$$ind = \langle Gl^{ind} = \{gl_4, gl_5, gl_6, gl_7\}, Attr^{ind} = \{genotype\}, Act^{ind} = \{die, reproduce, \\ get\_resource, migrate, search\_flock, split\_flock\}, ResT^{ind} = ResT, \\ InfT^{ind} = \emptyset, ObjT^{ind} = \emptyset, AgT^{ind} = \emptyset\rangle \tag{29}$$

where $gl_4$ is the goal "get resource from flock agent", $gl_5$ is the goal "reproduce", $gl_6$ is the goal "migrate to other flock", and $gl_7$ is the goal "split flock". *die* is the action of death—agent dies when it runs out of resources, *reproduce* is the action of reproducing (with the use of recombination and mutation operators), *get_resource* is the action of getting resource from $flock$ type agent, *migrate* is the action of migrating to other flock, *search_flock* is the action of searching for another flock—located within the same ecological niche, and $split\_flock$ is the action of creating a new flock.

Agent $ag^{flock}$ (of type $flock$) is defined as follows:

$$ag^{flock} = \langle Gl^{ag,flock} = Gl^{flock}, Attr^{ag,flock} = \emptyset, Act^{ag,flock} = Act^{flock}, \\ Res^{ag,flock} = \{r^{ag,flock}\}, Inf^{ag,flock} = \emptyset, Obj^{ag,flock} = \emptyset, Ag^{ag,flock}\rangle \tag{30}$$

Notation $Gl^{ag,flock}$ means "the set of goals of agent $ag$ of type $flock$". $r^{ag,flock}$ is the amount of resource of type $rt$ that is possessed by the agent $ag^{flock}$. $Ag^{ag,flock}$ is the set of agents of type *ind* that currently belong to the flock agent.

Agent $ag^{ind}$ (of type *ind*) is defined as follows:

$$ag^{ind} = \langle Gl^{ag,ind} = Gl^{ind}, Attr^{ag,ind} = Attr^{ind}, Act^{ag,ind} = Act^{ind}, Res^{ag,ind} = \{r^{ag,ind}\}, \\ Inf^{ag,ind} = \emptyset, Obj^{ag,ind} = \emptyset, Ag^{ag,ind} = \emptyset\rangle \tag{31}$$

$r^{ag,ind}$ is the amount of resource of type $rt$ that is possessed by the agent $ag^{ind}$.

The set of relations is defined as follows:

$$Rel = \left\{ \xrightarrow[\{get\_resource\}]{\{get\_resource\}} \right\} \tag{32}$$

The relation is defined as follows:

$$\xrightarrow[\{get\_resource\}]{\{get\_resource\}} = \left\{ \left\langle Ag^{flock,\{get\_resource\}}, Ag^{flock,\{get\_resource\}} \right\rangle, \left\langle Ag^{ind,\{get\_resource\}}, Ag^{ind,\{get\_resource\}} \right\rangle \right\} \tag{33}$$

$Ag^{flock,\{get\_resource\}}$ is the set of agents of type $flock$ capable of performing action $get\_resource$. $Ag^{ind,\{get\_resource\}}$ is the set of agents of type $ind$ capable of performing action $get\_resource$. This relation represents competition for limited resources between agents of the same type.

### 3.3 Multi-agent system with sexual selection

In multi-agent system with sexual selection (sBSMAS) speciation takes place as a result of sexual selection. There exist two sexes (see fig. 3). Agents compete for limited resources, can reproduce and die. Reproduction takes place when pair is formed composed of agents from opposite sexes. Reproduction process is initiated by a female agent (when it has enough resources to reproduce). Then it searches for the partner in such a way that it chooses one male agent from all male agents that are ready for reproduction in the given vertice. The partner is chosen on the basis of genotype similarity—the more similar are two agents from opposite sexes the more probable is that female agent will choose that male agent. The offspring is generated with the use of mutation and recombination operators (intermediate recombination Booker et al. (1997), and mutation with self-adaptation Bäck, Fogel, Whitley & Angeline (1997)). The offspring receives some of the resources from parents.

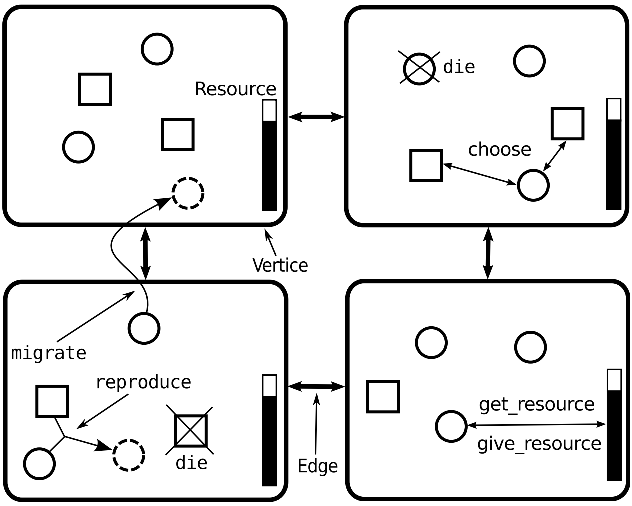



Fig. 3. Multi-Agent System with Sexual Selection

The multi-agent system with sexual selection is defined as follows (compare eq. (2)):

$$\begin{aligned}BSMAS(t) = \langle & EnvT(t) = \{et\}, Env(t) = \{env\}, ElT(t) = VertT(t) \cup ObjT(t) \cup \\ & AgT(t), ResT(t) = \{rt\}, InfT(t) = \emptyset, Rel(t), \\ & Attr(t) = \{genotype\}, Act(t) \rangle\end{aligned} \tag{34}$$

where $VertT = \{vt\}$, $ObjT = \emptyset$, and $AgT = \{female, male\}$.
The set of actions is defined as follows:

$$Act = \{die, reproduce, get\_resource, give\_resource, migrate, choose\} \tag{35}$$

Environment type $et$ is defined in the following way:

$$et = \langle EnvT^{et} = \emptyset, VertT^{et} = VertT, ResT^{et} = ResT, InfT^{et} = \emptyset \rangle \tag{36}$$

Environment $env$ of type $et$ is defined as follows:

$$env = \langle gr^{env}, Env^{env} = \emptyset \rangle \tag{37}$$

Vertice type $vt$ is defined in the following way:

$$\begin{aligned}vt = \langle & Attr^{vt} = \emptyset, Act^{vt} = \{give\_resource\}, ResT^{vt} = ResT, \\ & InfT^{vt} = \emptyset, VertT^{vt} = VertT, ObjT^{vt} = \emptyset, AgT^{vt} = AgT \rangle\end{aligned} \tag{38}$$

where $give\_resource$ is the action of giving resource to agents.
Each $vert \in Vert$ is defined as follows:

$$\begin{aligned}vert = \langle & Attr^{vert} = \emptyset, Act^{vert} = Act^{vt}, Res^{vert} = \{res^{vert}\}, Inf^{vert} = \emptyset, \\ & Vert^{vert}, Obj^{vert} = \emptyset, Ag^{vert} \rangle\end{aligned} \tag{39}$$

$res^{vert}$ is the amount of resource of type $rt$ that is possessed by the $vert$. $Vert^{vert}$ is the set of four vertices connected with the vertice $vert$ (see fig. 3). $Ag^{vert}$ is the set of agents located within the vertice $vert$.
There are two types of agents in the system: $female$ and $male$. $female$ agent type is defined in the following way:

$$\begin{aligned}female = \langle & Gl^{female} = \{gl_1, gl_2, gl_3\}, Attr^{female} = \{genotype\}, \\ & Act^{female} = \{die, reproduce, choose, get\_resource, migrate, \}, \\ & ResT^{female} = ResT, InfT^{female} = \emptyset, ObjT^{female} = \emptyset, AgT^{female} = \emptyset \rangle\end{aligned} \tag{40}$$

where $gl_1$ is the goal "get resource from environment", $gl_2$ is the goal "reproduce", and $gl_3$ is the goal "migrate to other vertice". *die* is the action of death—agent dies when it runs out of resources, *reproduce* is the action of reproducing (with the use of recombination and mutation operators), *choose* is the action of choosing partner for reproduction from the set of *male* agents that are located within the same vertice and are ready for reproduction, *get_resource* is the action of getting resource from environment, and *migrate* is the action of migrating to other vertice.

*male* agent type is defined in the following way:

$$\begin{aligned} male = \big\langle Gl^{male} &= \{gl_1, gl_2, gl_3\}, Attr^{male} = \{genotype\}, \\ Act^{male} &= \{die, reproduce, get\_resource, migrate, \}, \\ ResT^{male} &= ResT, InfT^{male} = \emptyset, ObjT^{male} = \emptyset, AgT^{male} = \emptyset \big\rangle \end{aligned} \tag{41}$$

where $gl_1$ is the goal "get resource from environment", $gl_2$ is the goal "reproduce", and $gl_3$ is the goal "migrate to other vertice". *die* is the action of death—agent dies when it runs out of resources, *reproduce* is the action of reproducing (with the use of recombination and mutation operators), *get_resource* is the action of getting resource from environment, and *migrate* is the action of migrating to other vertice.
Agent $ag^{female}$ (of type $female$) is defined in the following way:

$$\begin{aligned} ag^{female} = \big\langle & Gl^{ag,female} = Gl^{female}, Attr^{ag,female} = Attr^{female}, Act^{ag,female} = Act^{female}, \\ & Res^{ag,female} = \{r^{ag,female}\}, Inf^{ag,female} = \emptyset, \\ & Obj^{ag,female} = \emptyset, Ag^{ag,female} = \emptyset \big\rangle \end{aligned} \tag{42}$$

Notation $Gl^{ag,female}$ means "the set of goals of agent $ag$ of type $female$". $r^{ag,female}$ is the amount of resource of type $rt$ that is possessed by the agent $ag^{female}$.
Agent $ag^{male}$ (of type $male$) is defined in the following way:

$$\begin{aligned} ag^{male} = \big\langle & Gl^{ag,male} = Gl^{male}, Attr^{ag,male} = Attr^{male}, Act^{ag,male} = Act^{male}, \\ & Res^{ag,male} = \{r^{ag,male}\}, Inf^{ag,male} = \emptyset, Obj^{ag,male} = \emptyset, Ag^{ag,male} = \emptyset \big\rangle \end{aligned} \tag{43}$$

Notation $Gl^{ag,male}$ means "the set of goals of agent $ag$ of type $male$". $r^{ag,male}$ is the amount of resource of type $rt$ that is possessed by the agent $ag^{male}$.
The set of relations is defined as follows:

$$Rel = \left\{ \xrightarrow[\{get\_resource\}]{\{get\_resource\}}, \xrightarrow[\{reproduce\}]{\{choose,reproduce\}} \right\} \tag{44}$$

The relation $\xrightarrow[\{get\_resource\}]{\{get\_resource\}}$ is defined as follows:

$$\xrightarrow[\{get\_resource\}]{\{get\_resource\}} = \left\{ \left\langle Ag^{\{get\_resource\}}, Ag^{\{get\_resource\}} \right\rangle \right\} \tag{45}$$

$Ag^{\{get\_resource\}}$ is the set of agents capable of performing action *get_resource*. This relation represents competition for limited resources between agents.
The relation $\xrightarrow[\{reproduce\}]{\{choose,reproduce\}}$ is defined as follows:

$$\xrightarrow[\{reproduce\}]{\{choose,reproduce\}} = \left\{ \left\langle Ag^{female,\{choose,reproduce\}}, Ag^{male,\{reproduce\}} \right\rangle \right\} \tag{46}$$

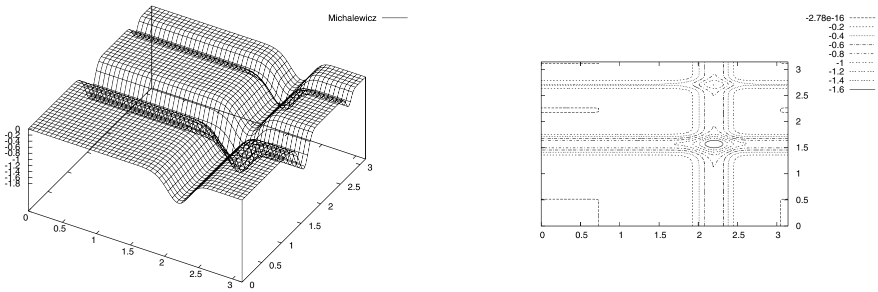
$Ag^{female,\{choose,reproduce\}}$ is the set of agents of type $female$ capable of performing actions *choose* and *reproduce*. $Ag^{male,\{reproduce\}}$ is the set of agents of type *male* capable of performing action *reproduce*. This relation represents sexual selection mechanism—$female$ agents choose partners for reproduction form *male* agents and then reproduction takes place.

## 4. Experimental results

The main goal of experiments was to investigate whether the speciation takes place in the case of all three simulation models: aBSMAS (allopatric speciation), fBSMAS (sub-populations isolation resulting from flock formation behavior), and sBSMAS (speciation resulting from the existence of sexual selection). Four multimodal fitness landscapes were used—Michalewicz, Rastrigin, Schwefel, and Waves. Presented results include illustration of species formation processes, as well as changes of the population size during speciation processes.

### 4.1 Fitness landscapes

As it was said, four multimodal fitness landscapes were used during experiments. Each minima of the fitness function is considered as "ecological niche" which should be populated by distinct species during experiments.




(a) (b)

Fig. 4. Michalewicz fitness landscape

Michalewicz fitness landscape is given by (Michalewicz (1996)):

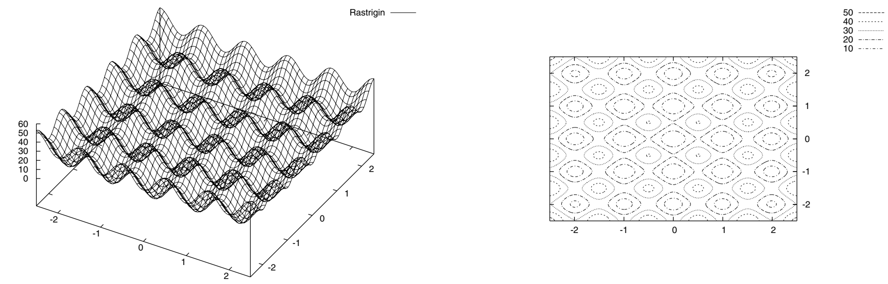
$$f_1(\vec{x}) = -\sum_{i=1}^{n} \left( \sin(x_i) * \left( \sin(i * x_i^2/\pi) \right)^{2*m} \right) \quad x_i \in [0;\pi] \text{ for } i = 1,\ldots,n \tag{47}$$

This function has $n!$ local minima, where $n$ is the number of dimensions. $m$ parameter regulates the steepness of "valleys". During experiments the values of parameters were $m = 10$ and $n = 2$ (see fig. 4).
Rastrigin multimodal fitness landscape is defined as follows (Potter (1997)):

$$f_2(\vec{x}) = 10 * n + \sum_{i=1}^{n} \left( x_i^2 - 10 * \cos(2 * \pi * x_i) \right) \quad x_i \in [-2.5;2.5] \text{ for } i = 1,\ldots,n \tag{48}$$

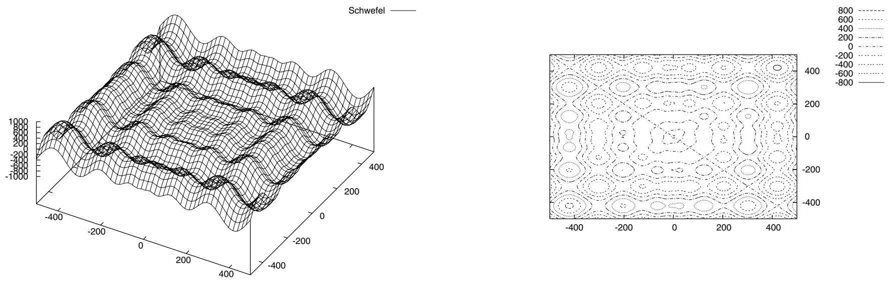
This function has many regularly placed local minima. During experiments $n = 2$ was assumed (see fig. 5).
Schwefel fitness landscape is defined as follows (Potter (1997)):

$$f_3(\vec{x}) = \sum_{i=1}^{n} \left( -x_i * \sin\left( \sqrt{|x_i|} \right) \right) \quad x_i \in [-500.0;500.0] \text{ for } i = 1,\ldots,n \tag{49}$$



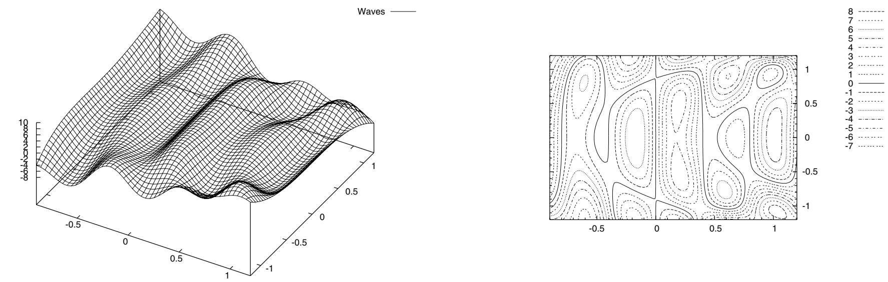

(a) (b)

Fig. 5. Rastrigin fitness landscape




(a) (b)

Fig. 6. Schwefel fitness landscape




(a) (b)

Fig. 7. Waves fitness landscape

This function has many irregularly placed local minima. During experiments $n = 2$ was assumed (see fig. 6).

Waves fitness landscape is defined as follows (Ursem (1999)):

$$f_4(\vec{x}) = -\big(\,(0.3 * x_1)^3 - \left(x_2^2 - 4.5 * x_2^2\right) * x_1 * x_2 - \\ 4.7 * \cos\left(3 * x_1 - x_2^2 * (2 + x_1)\right) * \sin(2.5 * \pi * x_1)\big) \\ x_1 \in [-0.9; 1.2],\ x_2 \in [-1.2; 1.2] \tag{50}$$

This function has many irregularly placed local minima (see fig. 7).

### 4.2 Species formation processes

In this section species formation processes are illustrated. Fig. 8– 19 show the course of evolution and speciation processes for all three models of speciation and for four mentioned above fitness landscapes. Experiments' results show location of agents after 0, 50, 500, and 5000 simulation steps.

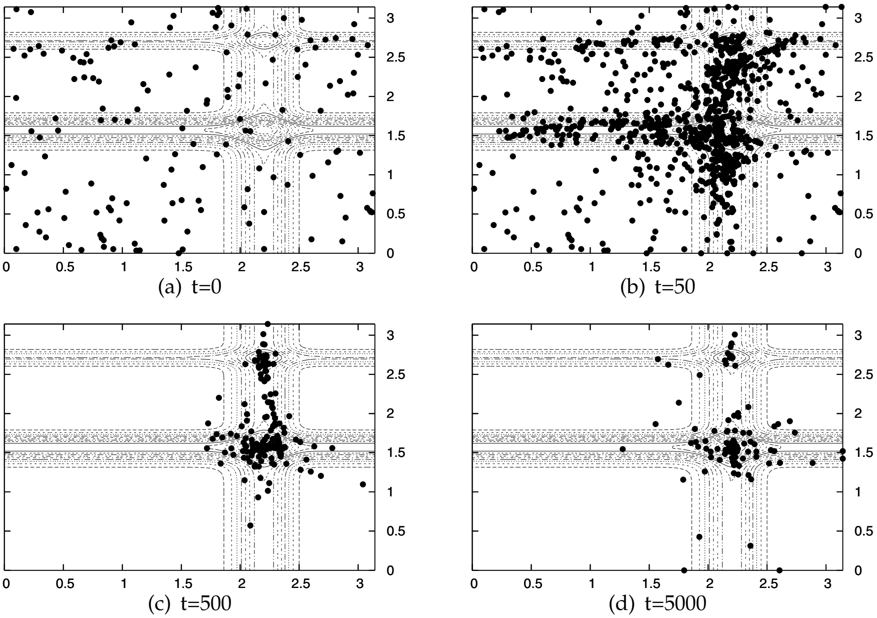



Fig. 8. Species formation processes in aBSMAS with Michalewicz fitness landscape

Fig. 8–11 show the course of speciation in model with geographical barriers. In the case of all fitness landscapes speciation takes place—it can be seen that distinct species are formed. Species are located within the basins of attraction of local minima which are "ecological niches" for species. However not in all of the niches there exist some species, for example see fig. 9, 10, and 11. Also, it can be seen that rather high level of population diversity within species is maintained—agents are spread over rather large areas of fitness landscape.
Fig. 12– 15 show speciation processes taking place under second model—multi-agent system with flocks. As it can be seen in the figures, the speciation takes place and the diversity within the species is rather low, as compared to aBSMAS model, and especially sBSMAS model. Also,

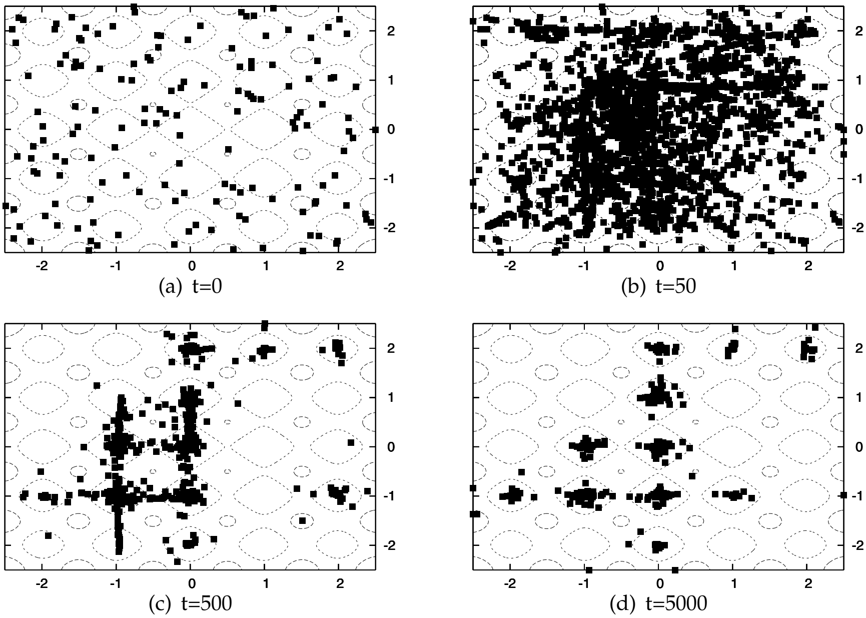



Fig. 9. Species formation processes in aBSMAS with Rastrigin fitness landscape

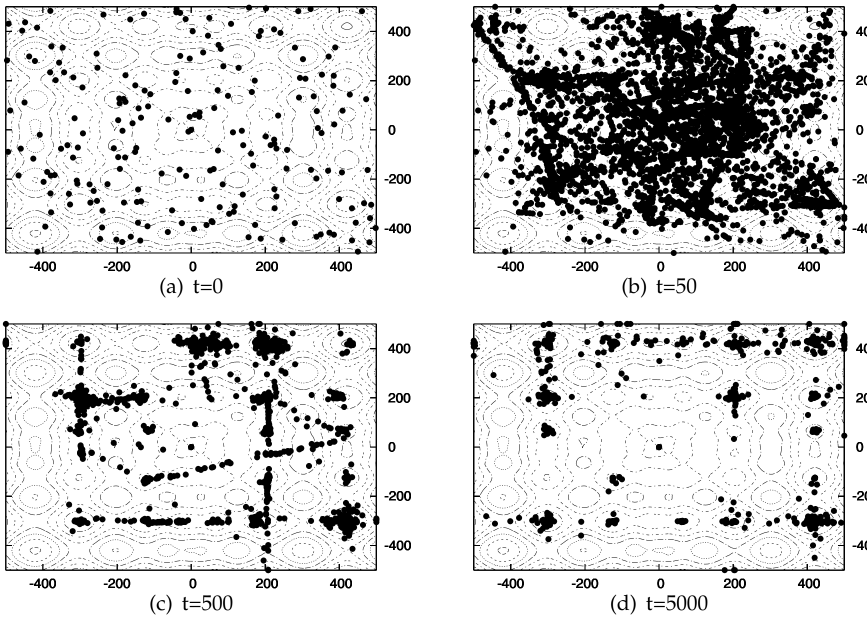



Fig. 10. Species formation processes in aBSMAS with Schwefel fitness landscape

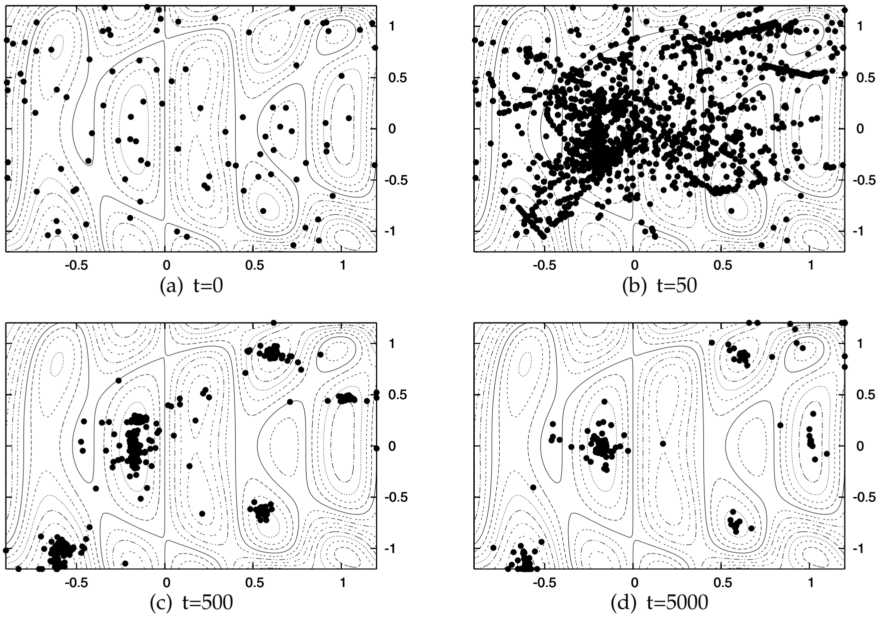



Fig. 11. Species formation processes in aBSMAS with Waves fitness landscape

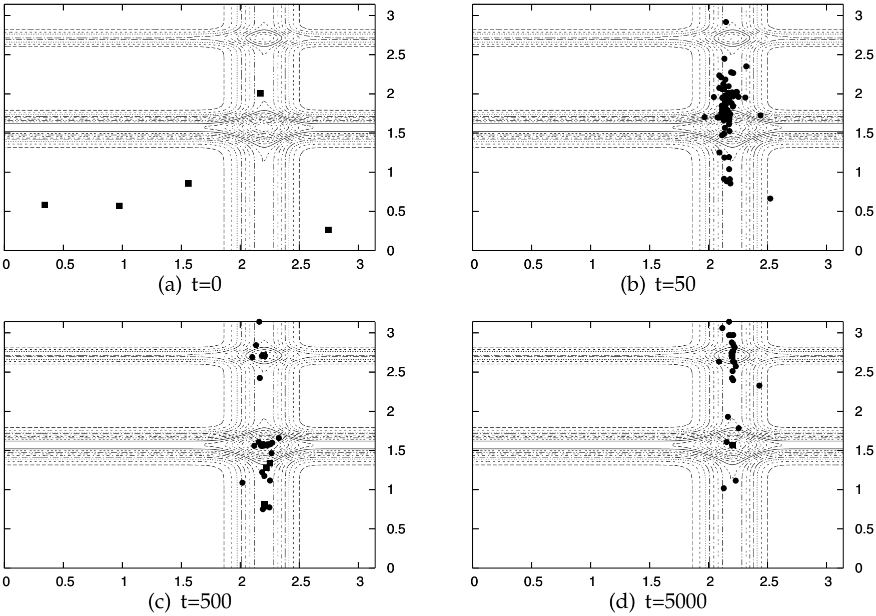



Fig. 12. Species formation processes in fBSMAS with Michalewicz fitness landscape

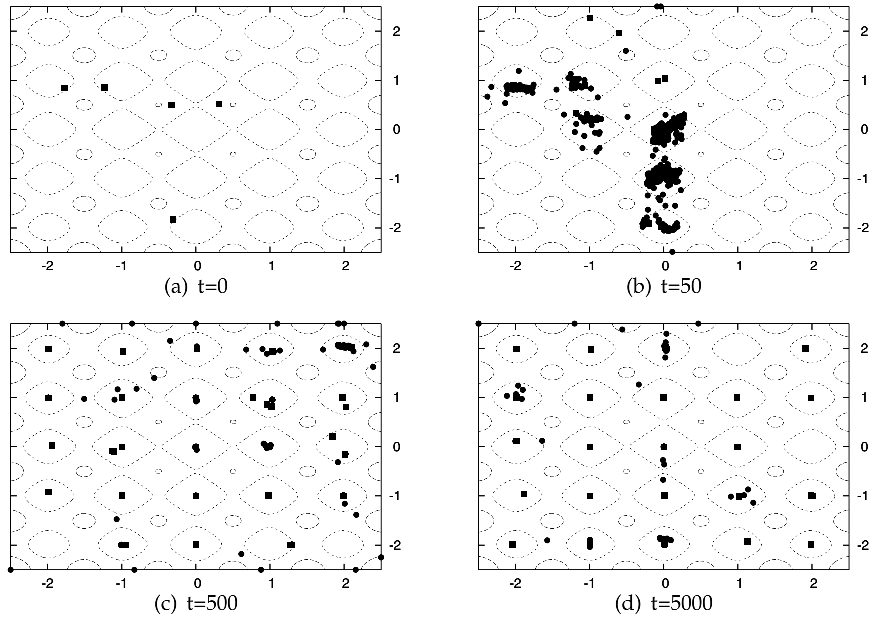



Fig. 13. Species formation processes in fBSMAS with Rastrigin fitness landscape

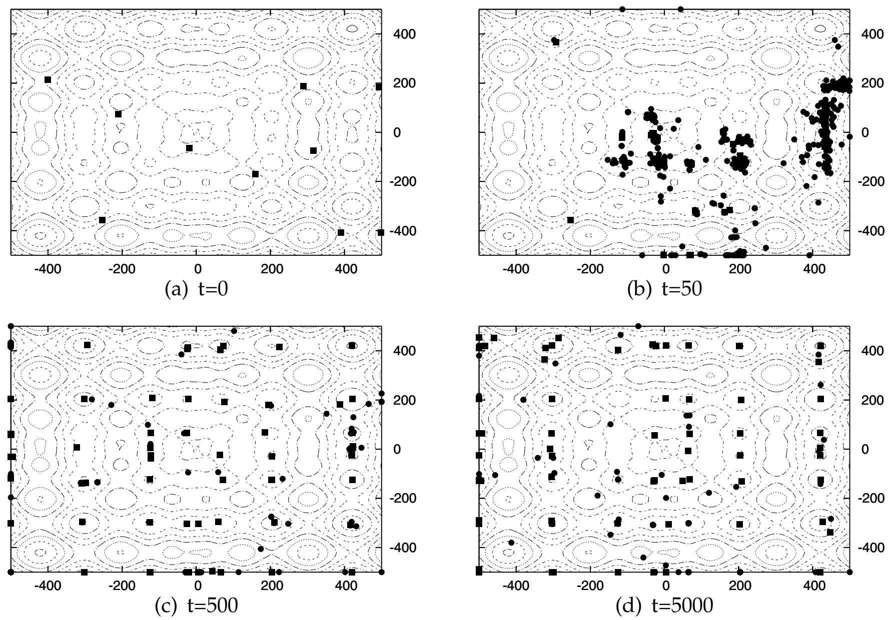



Fig. 14. Species formation processes in fBSMAS with Schwefel fitness landscape

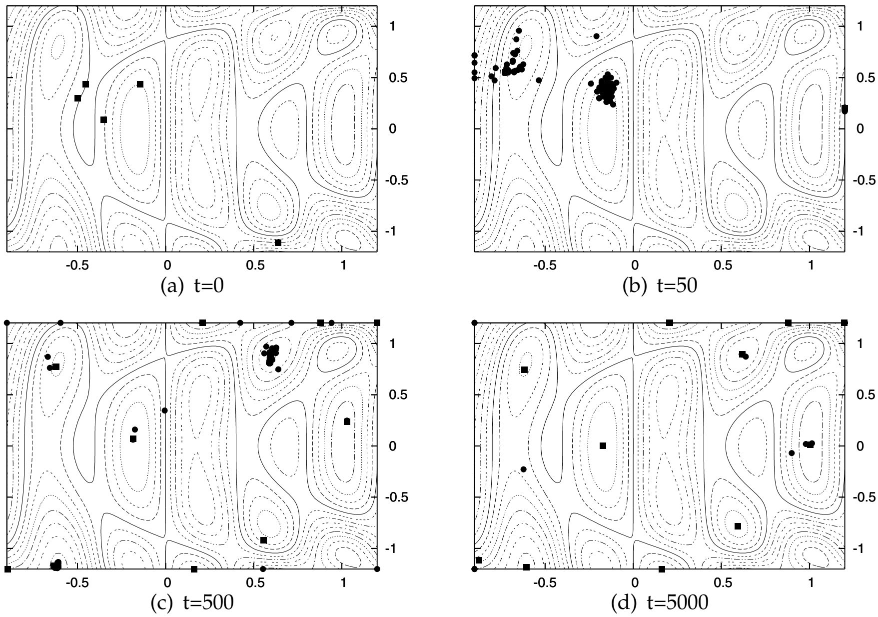



Fig. 15. Species formation processes in fBSMAS with Waves fitness landscape

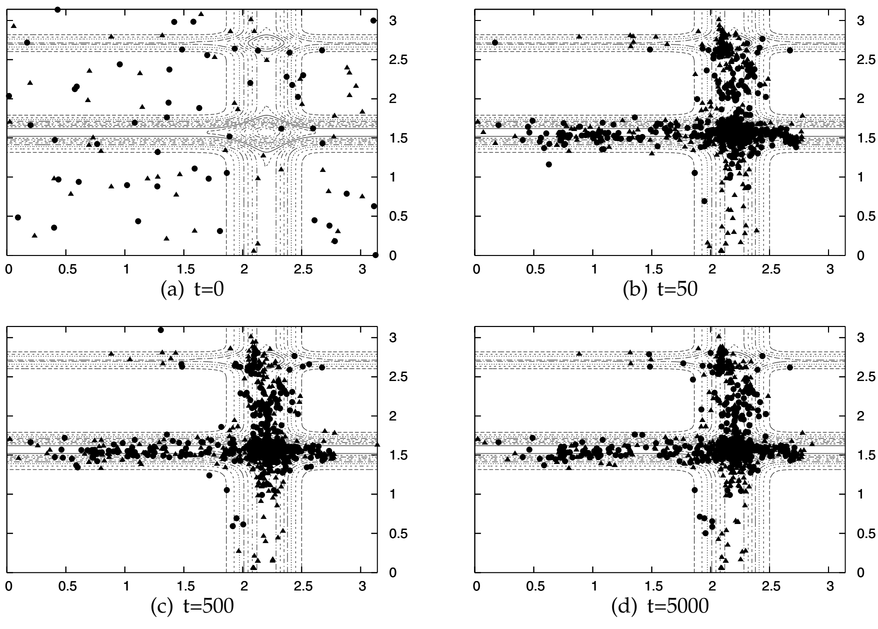



Fig. 16. Species formation processes in sBSMAS with Michalewicz fitness landscape

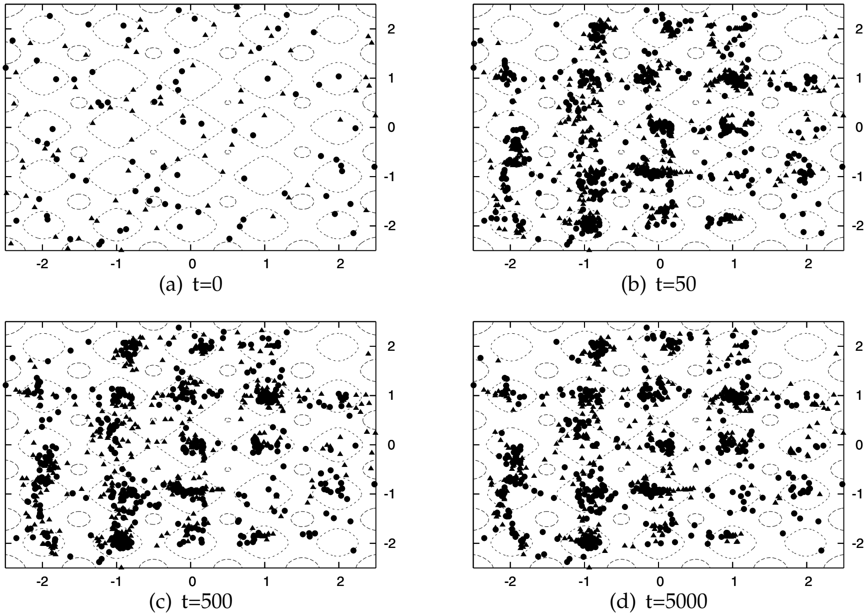



Fig. 17. Species formation processes in sBSMAS with Rastrigin fitness landscape

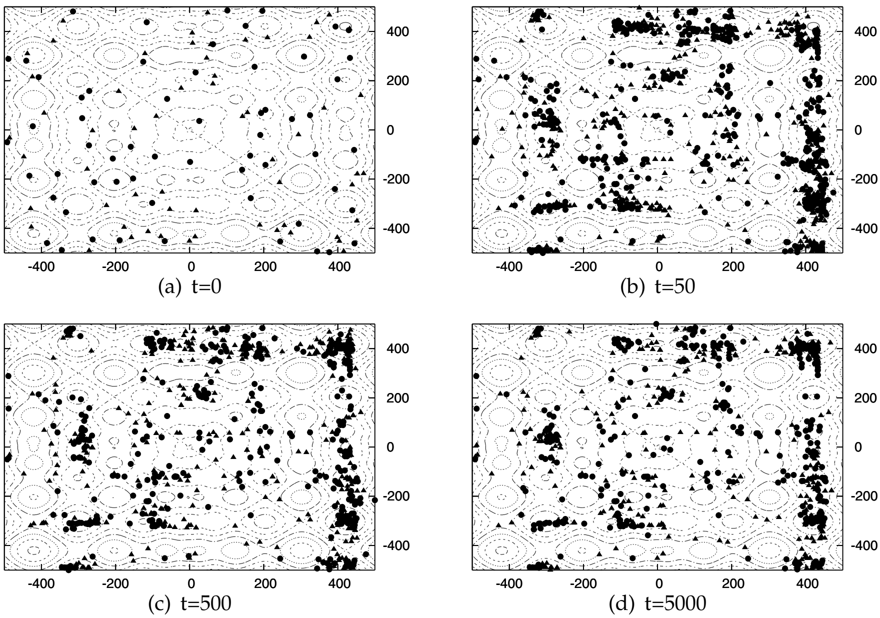
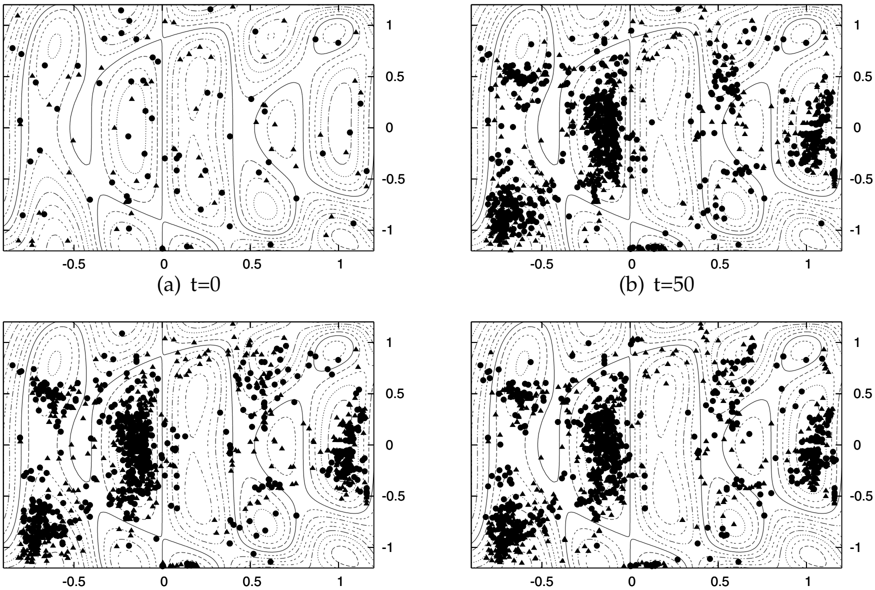



Fig. 18. Species formation processes in sBSMAS with Schwefel fitness landscape




(a) t=0 (b) t=50

(c) t=500 (d) t=5000

Fig. 19. Species formation processes in sBSMAS with Waves fitness landscape

there are generally more species formed—in most cases, in 5000 step almost in all niches there exist some species.

In the case of third model—multi-agent system with sexual selection—the population diversity within species is very high (see fig. 16– 19). Species are formed, but the boundaries between them are not clear in most cases (see fig. 16 and 18).

### 4.3 Population size during experiments

In fig. 20 and 21 changes of the population size during experiments in the three systems are shown. In all cases the number of agents changes rapidly during initial steps of the simulation but stabilizes after some time.

In the case of fBSMAS model after the rapid increase in the number of agents, there can be observed the tendency to slightly decrease the population size—it appears after the intensive epoch of species formation and populating environmental niches and it results from the existence of mechanism of merging flocks located within the same ecological niche.

In aBSMAS model the population is much more numerous than in the case of other two models. This is caused by the fact that aBSMAS model uses much more vertices in the environment and also more agents are needed to populate these vertices and maintain evolutionary processes.

## 5. Summary and conclusions

In this paper the model of bio-social multi-agent system (BSMAS) was introduced. Presented model is based on CoEMAS approach Dreżewski (2003), which has already been applied in several computational systems. The BSMAS approach allows for agent-based modeling of biological and social phenomena due to the possibility of defining in a very natural way of all

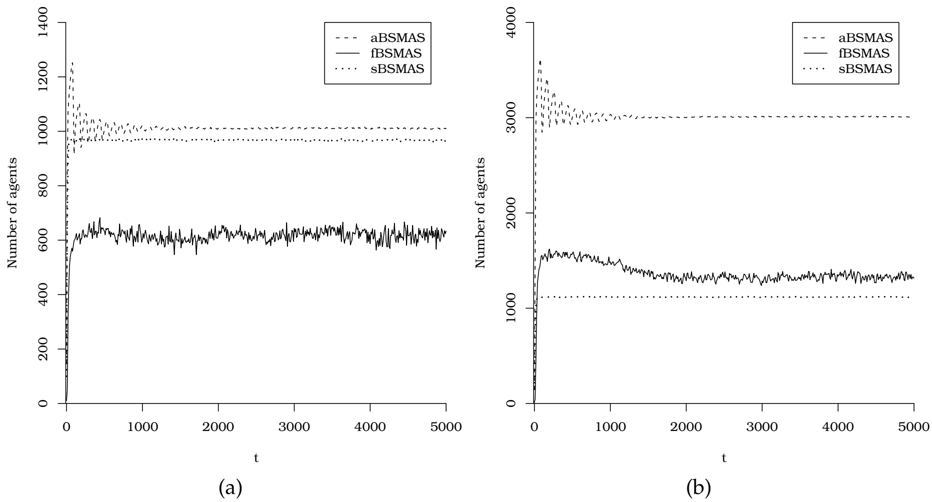



Fig. 20. Number of agents in the aBSMAS, fBSMAS, and sBSMAS during experiments with Michalewicz (a) and Rastrigin (b) landscapes

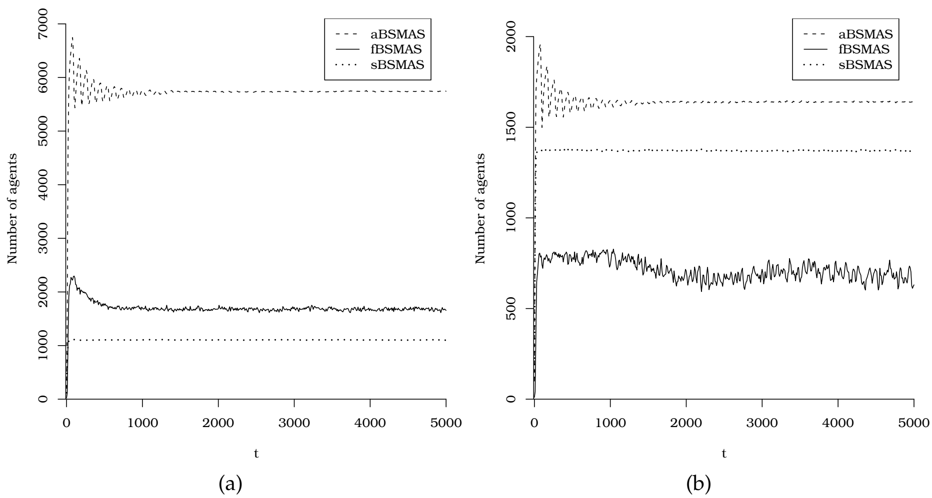



Fig. 21. Number of agents in the aBSMAS, fBSMAS, and sBSMAS during experiments with Schwefel (a) and Waves (b) landscapes

elements of multi-agent simulation: heterogeneous environment, passive elements (objects), active elements (agents), relations between them, resources, actions and attributes.
With the use of BSMAS model three systems with speciation were defined: system with allopatric speciation, system with speciation resulting from flock formation, and system with sexual selection. Presented results show that in all three cases speciation takes place, however the course of the evolution is in each case different, there are differences in the number of

formed species and population diversity within species. Also, in each model the population size changes in a different way during experiments.
Future work will include the application of BSMAS model to different areas—mainly social and economical simulations. Also the implementation of dedicated simulation system is included in future plans.

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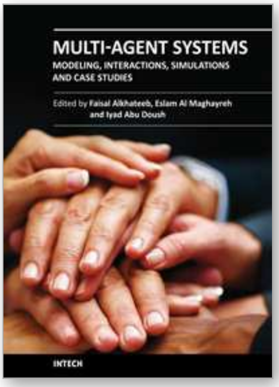


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A multi-agent system (MAS) is a system composed of multiple interacting intelligent agents. Multi-agent systems can be used to solve problems which are difficult or impossible for an individual agent or monolithic system to solve. Agent systems are open and extensible systems that allow for the deployment of autonomous and proactive software components. Multi-agent systems have been brought up and used in several application domains.



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