Go to the ant thou sluggard; consider her ways, and be wise.

First explorations of a computational model of polymorphic ant caste ratio adaptation through environmental stimuli

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Abstract:

Swarm intelligence is the appearance of intelligent behaviour of a collective, which consists of relatively simple agents. Ants appear to utilize a mechanism similar to swarm intelligence as individual input from single ants is responsible for an adequate response by the colony as a whole. Worker to soldier ratio changes within an ant colony are an example of this type of swarm intelligence. The literature yielded two environmental factors which may contribute to a ratio change in ant colonies in the literature, namely food presentation and the detected presence of ants from another colony. In this paper we simulate ant colonies in different situations and environments through a mechanism based on swarm intelligence. We have tested our model in three separate condition sets, namely adaptation of the colony ratio through food presentation alone, through detected enemy presence alone and through a combination of both. Our results indicate that in our model only adaptation on the basis of a combination of the two factors leads to an improvement of the competitiveness of the colony as opposed to a colony with a fixed ratio.

1. Introduction

It has been said that God must love bugs more than he loves humans, as He created so many more of them. Insects are very, if not the most, successful organisms on this planet. Their diversity and ability to sustain themselves in the most diverse climates and environments are the main reasons for their abundance on the planet. Among the most successful insects are ants. Ants are not only capable insects individually through their great relative strength, but their ecological effectiveness lies in the fact that they work together. The ants are part of a colony, a *super organism*.

In nature, the colonies, and thus also indirectly the ants' main objective is the continuation of the colony. In order for the colony to survive it will sometimes be necessary to adapt to changing circumstances. Adaptation to ones surroundings greatly influences the effectiveness of said behavior. An ant colony is able to sustain very heavy damage: floods, drought or bored boys with magnifying glasses, but the ants will adapt their behavior to the extent that the colony as a whole reacts fittingly. This is remarkable because an ant colony may appear to act more intelligent than we would expect from single ants, but its behavior is a culmination of the separate, relatively simple behaviors of its ants.

Herein lays the crux of the matter. The information upon which to base the reaction of the colony, thus change the behavior of all members of the colony, is only available to the individual agents. This is complicated, as all agents only have a limited scope and ability to communicate and yet the colony systematically reacts as though its behavior is selected with complete overview over the situation. It seems the colony is more than the sum of its parts, and yet we know it to be just that.

Nature has always been an inspiration for research in artificial intelligence, as biological systems have a way doing incredible many and complex tasks, with relatively limited resources. Social insect structures are very interesting for AI tasks, as they show us a means to solve complex problems using simple agents. This paradoxical field of research was deemed so interesting that is has been given a special name in the field of artificial intelligence, namely *swarm intelligence* [1][2]. Swarm intelligence is the study of collective (intelligent) behavior, in decentralized, self-organizing multi-agent systems [3].

This paper seeks to computationally model swarm intelligence, and specifically its ability to react on the basis of decentralized input. Our model is based on ants, because in contrast to other social insects such as bees, wasps etc., certain types of ants have the characteristic of being *polymorphic*. *Polymorphism* is defined as discontinuous variation in a single population [3], which means that instances of the same species can have different appearances. In the case of ants, polymorphism means that in some species there are physically different castes. In most species of ants there is a varying physical disparity between different castes of ants[4], castes of ants who sustain the colony with food (workers), and those who defend the colony (soldiers/majors). These different castes both have vital, but very different, tasks within the colony. In some species the soldier ants have developed oversized jaws, to the extent that they are unable to bring any food to the colony, and since they are thus completely dependent on the workers for their food it would be costly on resources to have very many soldiers. However, colonies with too little soldiers could be vulnerable from attacks by other colonies and other animals. This suggests that the ratio between workers and soldiers might have an optimum considering different environmental circumstances. It was thought that this ratio between soldiers and workers was fixed, or only changed evolutionary. More recent studies have revealed that at least with certain species, colonies are able to change the ratio of their colony by influencing the development of the larvae. By giving a larva more or better food, the nursing worker ants will force it to puppate into a soldier ant [5].

It is not known how the information about the environment is communicated from one ant to the other, and how this leads to a change in the ratio. This paper presents our first attempts at modeling a mechanism for ratio change within an ant colony and its underlying factors.

There has been work done in the field of optimal caste ratio prediction in ant colonies. Hasegawa [6] empirically showed for a certain set of environmental factors that a colony functioned optimally at 20% majors. Walker and Stamps [7] applied a model created by Oster and Wilson [8] for social insects, to see whether it accurately predicted caste ratio in Camponotus Impressus ants. Given that ant colonies are able to attain (and thus change to) a certain optimal ratio given a number of environmental factors, there must exist some mechanism to guide this ratio change.

From the literature we have been able to find two distinct factors which influence the caste ratio. Firstly the presence of ants of another colony increases the number of soldier ants in the colony [5]. Secondly the manner in which food is presented can influence the caste ratio. McGlynn and Owen [9] found that in *Pheidole Flavens* food supplementation directly influenced the number of soldier pupae. Food was either presented as one clump, or spread over the area. In the clumped condition the number of soldier ants increased. The reason for this may be twofold; if food is clumped, then less workers are needed to find the food, and secondly, clumped food may lead to more competition for the one clump with other colonies.

It is reasonable to assume that both reasons for increasing the ratio are based on competition with other colonies. In other words, both the presence of another colony, as well as clumped food increase the probability of competition for food with another colony and the likelihood of a fight. If there may come a need to fight, soldiers are needed. In our model we will look at these two stimulants for an increased ratio separately and combined, and compare them to a fixed ratio colony.

Our hypothesis is that the colony which is most able to adapt to its surroundings, will have a better chance of survival. This adaptation will occur through individual input from the ants to the colony's nursery. In order to test this hypothesis three sets of simulations were performed. The first set merely tests our ratio adapting mechanism. The second set of simulations produces some additional information on the optimal weight of the input from a single ant to the colony, in order to determine how much the behavior of the whole colony should be adapted on the basis of input of a single ant. The third set of simulations tests the success of a colony adapting its ratio on the basis of two environmental factors separate as well as combined, compared to a fixed ratio colony.

2. Experiments and Simulations

2.1 Simulation 1

2.1.1 ***Introduction***

The first simulation we performed was a simple test to see whether our mechanism would function in the way we predict it will; namely that a colony in which our mechanism is implemented will be able to change its worker soldier ratio on the basis of the environment. We expect to see a rise in soldier ants because of the presentation of clumped food in the environment.

2.1.2 ***Method***

2.1.2.1 The world

A program was created in JAVA (see Figure 1). The program consists of a world in which a number of colonies can be placed. The world continually produces food for the ants. The world may contain one or more colonies of ants. Simulations with one colony were used to adjust parameters. In other runs two colonies were placed (a black colony with black ants and a red colony inhabited by red ants in order to visualize the competition). A colony consists out of a nest, and a number of worker and soldier ants. The nest is the originating point of new ants, and it is where the ants return to eat, or return food.

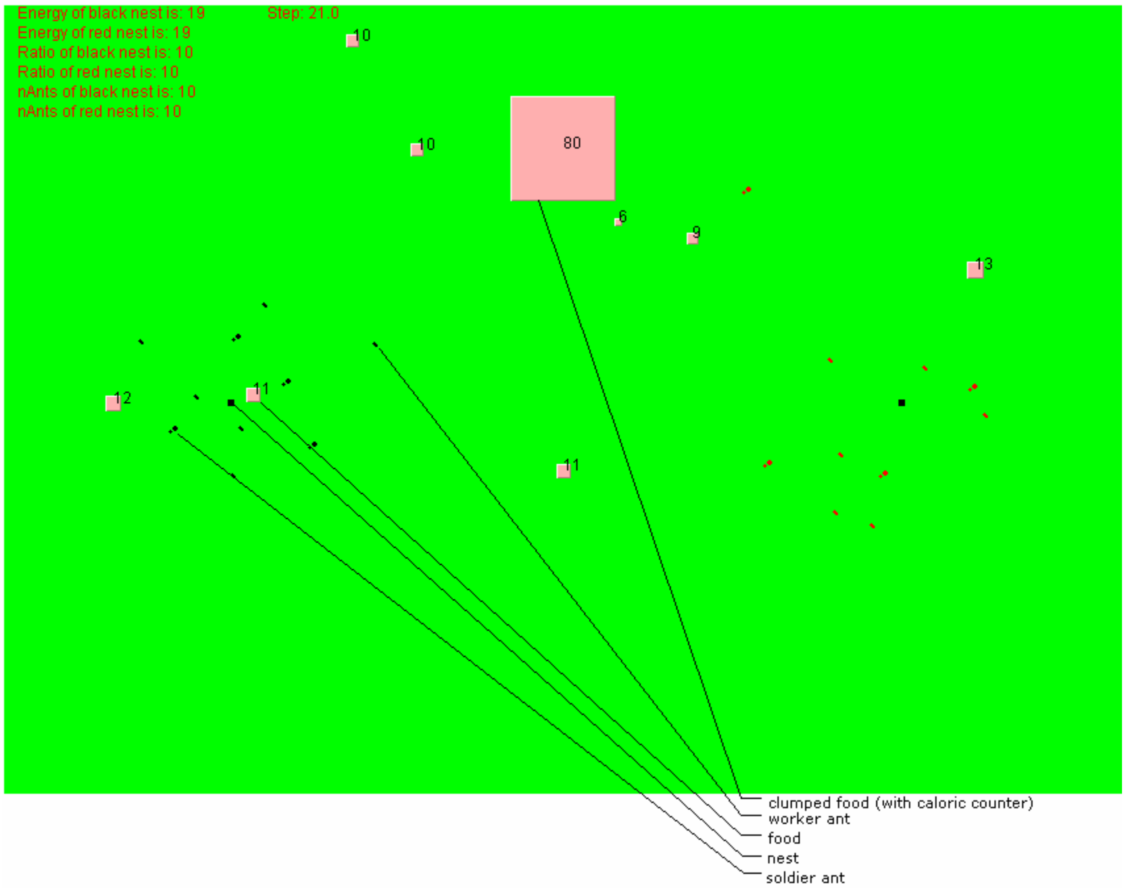

Figure 1 – JAVA Applet view of the 'World' in which the simulation takes place. In this view there are two colonies, a black colony on the left and a red colony on the right. Food is distributed randomly across the world, showing its nutritional value. There is one big clump of food (80 calories) which forces competition between the colonies. Further recorded information is shown in the left upper corner. The variables shown in the upper left corner are the number of units of stored food (energy), the ratio of the production of new ants (ratio), and the total number of ants (nAnts).

2.1.2.2 The food

Food in the simulation is either clumped or not clumped. Clumped means the caloric value is above 20 calories. All food is replenished as soon as it is eaten with roughly the same caloric value at a random location in the world. This forces the colonies to keep searching for food in different places, and allows for better competition as it also focuses the competition on which colony first finds the food; which is dependent on the number of ants. The Boolean information of whether a unit of food is clumped (> 20) is taken back to the nest by the worker who takes food from the unit of food.

2.1.2.3 The ants

The colony in our simulation can produce worker ants and soldier ants.

Worker ants are modeled after biological ants whose function is only to seek food. Their behavior is modeled by a general wander function through which they simply walk around away from the nest. Every time-step they lose energy, and when they get hungry (i.e. the distance to the nest is roughly equal to the amount of energy they have left), they return home to eat. Should they stumble into food during their wanderings, they take some of the food and immediately return home.

Part of ant communication takes place via pheromone traces. When ants come across a trace of pheromones, they follow the trace. If an ant has found food, communication of the location of the food takes place via a pheromone trail. Thus while returning home the ant leaves a pheromone trace from the food to their nest so that other members of the colony can also find the food.

If an ant comes across a pheromone trace while wandering, they follow the trace until it ends or they find food. The trace evaporates after a number of time steps. If they followed a trace to some food, they return home reinforcing the trace with their own pheromones.

Worker ants remember whether they took the food from a clumped or small food unit. Secondly they remember whether or not they've seen a worker from a different colony, and yield this information when they are home.

Soldier ants are similar to worker ants in every respect, other than the ability to carry food; they are not able to carry food. Soldier ants do follow the traces laid by the worker ants, but contrast to picking up the food and returning home, they start circling around the endpoint of the trace in order to 'defend' the food supply. Soldier ants also remember whether or not they have had contact with ants from another colony.

2.1.2.4 Colony

For our model it was not necessary to explicitly represent the colony queen and ant nursery. Since the model focuses on the competition outside of the nest, it was only necessary to represent the nest as the production point of new ants. There is a stack of ants waiting to become alive. These 'waiting ants' represent the larvae within a nest. These larvae become soldier ants or worker ants depending on the current ratio of the colony. If the nest has enough energy in reserve (to feed the whole colony), it produces new ants. The normal ratio is 10 workers for every soldier ant. When an ant brings back information which should lead to an increase in soldiers (see [4]), the ratio is brought down.

In pseudo code:

Per timestep:

```
{
        Update all values;
                If there is input to lower ratio from an ant →
                ratio becomes ratio minus 1 (minimum 1)
        Every ten timesteps:
                Ratio becomes ratio plus 1 (maximum 1)
                Create ant on the basis of ratio
}
```

The ratio automatically returns to normal over time (through the ten time-step updating of the ratio to normal.

The process of lowering the ratio represents the marking of a pupa by an ant to get additional food in order to become a soldier.

2.1.3 ***Results***

Data gathered from runs with one colony showed an increase of soldiers in the colonies with an adaptive ratio (Figure 2 and 3). These runs were performed in a single colony world. This means that the increase in soldiers is only attributed to the occurrence of clumped food. Not only the output of soldiers increases, but also the rate of the increase itself increased in the adaptive ratio condition. Thus the production of soldier ants increased more and more, because of a positive feedback loop from the clumped food items.

Our data also showed that the rate of growth of the colony as a whole is more gradual in a colony with an adaptive ratio (Figure 3). Compared to the graph in Figure 2 the colony grows less quickly, due to the relative decrease in food intake following from the production of soldiers.

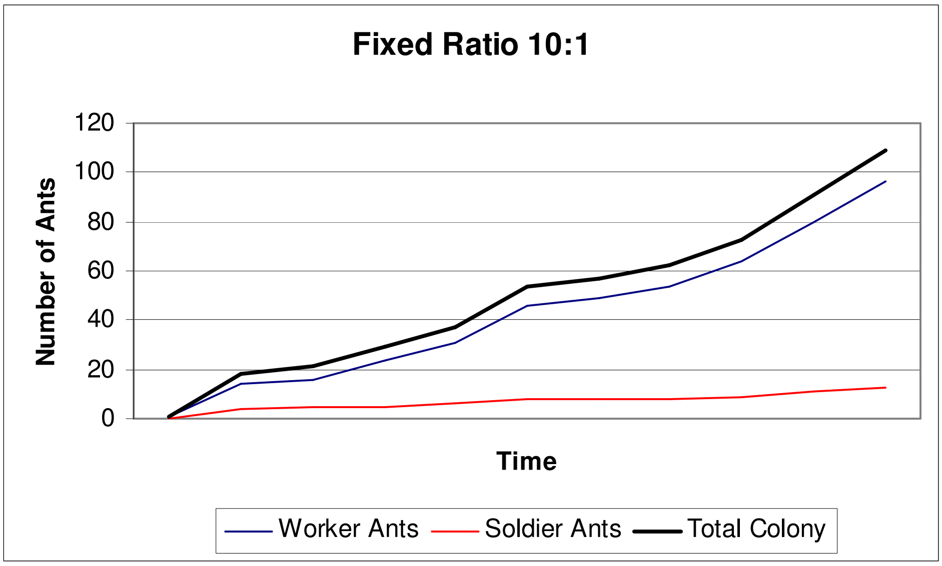

Figure 2 – Colony breakdown of workers and soldiers in a colony with a fixed ratio between soldiers and workers. The plateau in the middle of the run indicates pause in food intake.

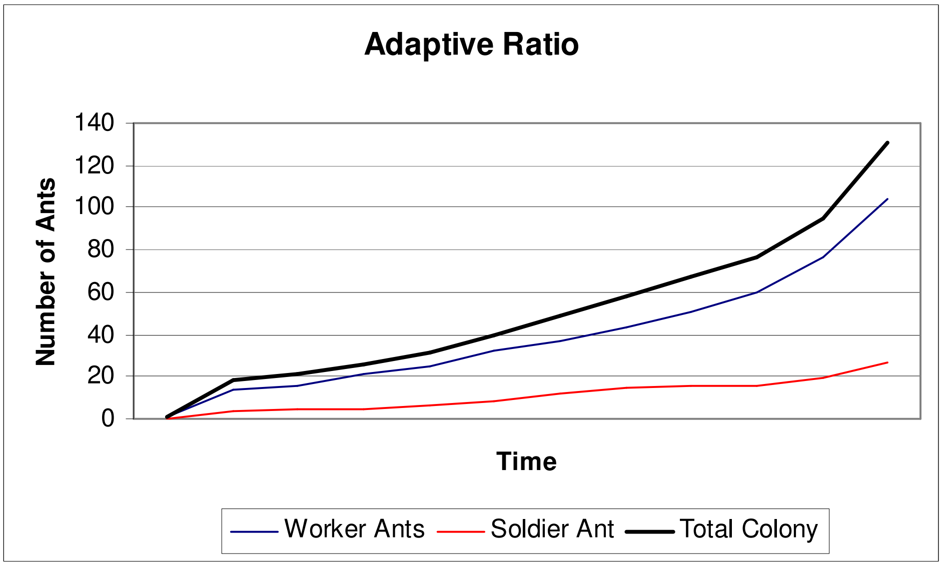

Figure 3 – Colony breakdown of workers and soldiers in a colony with an adaptive ratio between soldiers and workers.

2.1.4 ***Discussion***

Our model showed a direct relative increase of soldier ants, in a situation in which the environmental factors would indicate a rise in the ratio between soldier and worker ants. If success were measured by the number of ants of a colony, the data would show the fixed ratio colony to be more successful. The reason for this is that soldier ants do not bring back food, but they do cost energy. Since these were single colony world runs, there is no need for soldiers, and they essentially only hinder the growth of the colony. Thus energy which would otherwise be used for the production of energy producing workers is expended on the creation of soldiers by the colony with an adaptive ratio. This means the growth of those colonies is more gradual.

Our model does not incorporate threats to the colony other than alien ant colonies. But since soldier ants are of little use against other environmental threats this should not undermine their importance.

2.2 Simulation 2

2.2.1 ***Introduction***

In our second simulation we investigated how strongly the input of a single ant should influence the ratio adapting mechanism. We ran simulations with one and with two colonies. We performed simulations with competing colonies, with different settings for amount of ratio adaptation of the colony on per input. We expect to see which colony is the most successful, and thus see what settings are optimal.

2.2.2 ***Method***

2.2.2.1 Colony competition

Competition between colonies mostly ensues after both have found the same food item. There is no interaction between worker ants from different colonies. However, they do register encounters with alien ants. Soldier ants kill worker ants from other colonies, and soldier ants from different colonies kill each other (the one with the most energy survives). Fighting and killing expends energy more rapidly than wandering, and thus a soldier ant can kill only a certain number of other ants before needing to feed themselves.

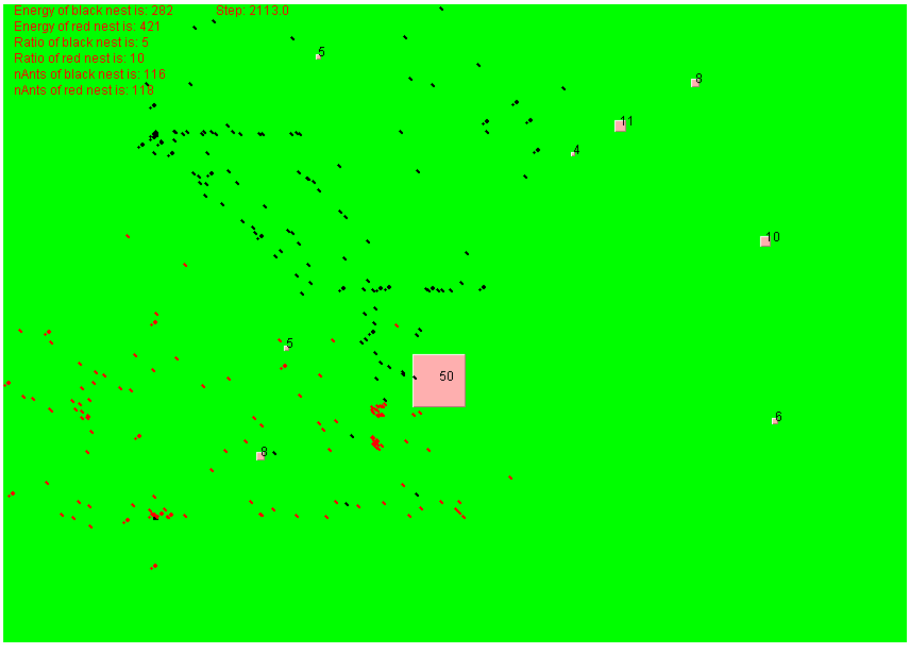

Figure 4 – An applet view showing competition over food. The colonies are positioned on the left side. Black at the top, red at the bottom. There is a clump of food of 50 calories, which both colonies have found. There are soldiers and workers from both colonies on the food.

2.2.2.2 Ratio adaptation

In order to see how the adaptation of the caste ratio can approach the optimum most effectively, we ran a simulation in order to see what the weight of the voice of a single ant should be. As mentioned above there is base ratio of ten workers for every soldier. In the first set of simulations, relevant information from a single ant lowers the ratio by 1. In order to see whether this actually provided an optimal representation of the relevant environmental factors we performed a number of runs. In these runs in one colony input from a single ant lowered the ratio by 2, thus leading to a more rapid adaptation of the ratio.

3.2 ***Results***

Data was gathered over 20 runs. The black colony lowered the ratio by 1, and the red colony by 2 at the input of every single ant.

20 runs	
Black wins	Red wins
17	**3**

Table 1 - Results simulation 2. The black colony lowers its ratio by 1 on the basis of the input from a single worker, the red colony lowers its ratio by 2. A victory is defined as one colony becoming dominant to the extent that the other colony has no more (worker) ants.

Overall, most runs were won by the black colony, but there were also runs in which the red colony became dominant. The data from a single run can show why the black colony is more successful (Figure 5). The red colony grows quickly from step 650 onwards. However, from step 930 onwards the growth stagnates. This is also the peak of the number soldiers in the red colony. The increase of soldiers on the side of the red colony leads to a decrease in worker ants in the black colony, as they are killed searching for food. Nevertheless, there is a relative decrease in food intake as the red colony relatively has less food searching workers (despite the overall increase in food intake caused by the overall increase in worker ants). The black colony grows more gradually, initially inhibited by the red colony, but at step 1000 starts a continuous stable growth. Because the black colony does not lose too many workers, relatively, in the beginning, its colony is able to settle in before creating an army to dispose of the red colony. This was the recurring pattern: in most cases the red colony lost so much of its momentum by producing too many soldiers too soon, so that it was over taken by the black colony which had built up more gradually.

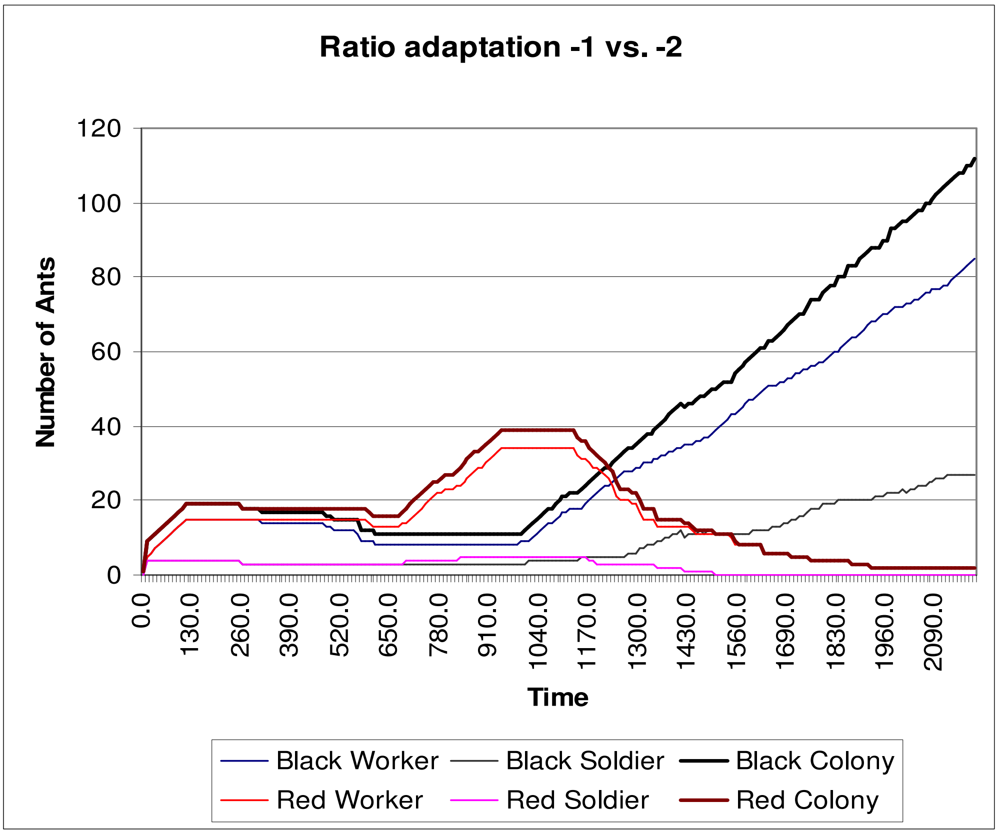

Figure 5 – Detailed look at both colonies during a single run, in which the black colony has a -1 input per worker ant, and the red colony has a -2 input per worker ant.

3.3 Discussion

Although the results did not show a complete dominance by the black colony, we could show that the -1 condition on average is better. It is apparent that the black colony built up more gradual, which leads to a bigger buffer in stored energy for the colony as compared to the less energy conserving red colony. This buffer allowed the black colony to sustain itself while the red colony initially has more soldiers. The red colony depletes its energy reserves so quickly because of its many soldiers that it is unable to sustain itself when the additional stress of competition over food ensues.

Because food is spread out through the world at random, there were certain runs in which the red colony was so 'lucky' in the initial allocation and redistribution of food that they were able to feed their big numbers of soldiers with their relatively few workers. In sum, our simulations showed that the parameters used for the black colony was on average more successful. Therefore, we used the -1 condition for further simulations.

2.4 Simulation 3

*2.4.1 **Introduction***

In the last simulation of our research we wanted to examine what factors can and should influence the worker soldier ratio of a colony. Empirical findings reported in the literature revealed two factors [5][7]: food presentation and the presence of an enemy colony. In this third simulation we will perform runs with competing colonies, in which one colony has a fixed ratio, and the other colony also has a fixed ratio, or an adaptive ratio.
The two factors will be investigated in isolation and in combination.

*2.4.2 **Method***

In order to evaluate both factors we performed four series of runs. In the first set of conditions, a baseline to compare to is created by performing a run with two colonies both with a fixed 10:1 ratio. In the other three trials the red colony has a fixed 10:1 ratio, and the black colony has an adaptive ratio. In each trial, the adaptation of the black colony's ratio is dependent on different environmental factors. In the first series of trials the black colony's ratio is only adapted on the basis of whether food that is found is clumped or not. In the second series the black colony adapts its ratio only on reports of alien ant encounters. In the last series of trials both factors are adapting the black colony's ratio.
The colonies are positioned in a way so that the clumped food can be distributed randomly, but is equally far from both colonies. This forces the colonies to compete over the clumps of food, while creating equal opportunities to find the clumps.

*2.4.3 **Results***

2.4.3.1 Fixed ratio baseline

The first run was performed with both colonies with fixed ratio. The data showed that both colonies in this situation grow to a certain balanced size and remain roughly the same size (Figure 6). Slight changes in colony growth speed occur, but these are caused by random changes in how fast food is found by a colony.

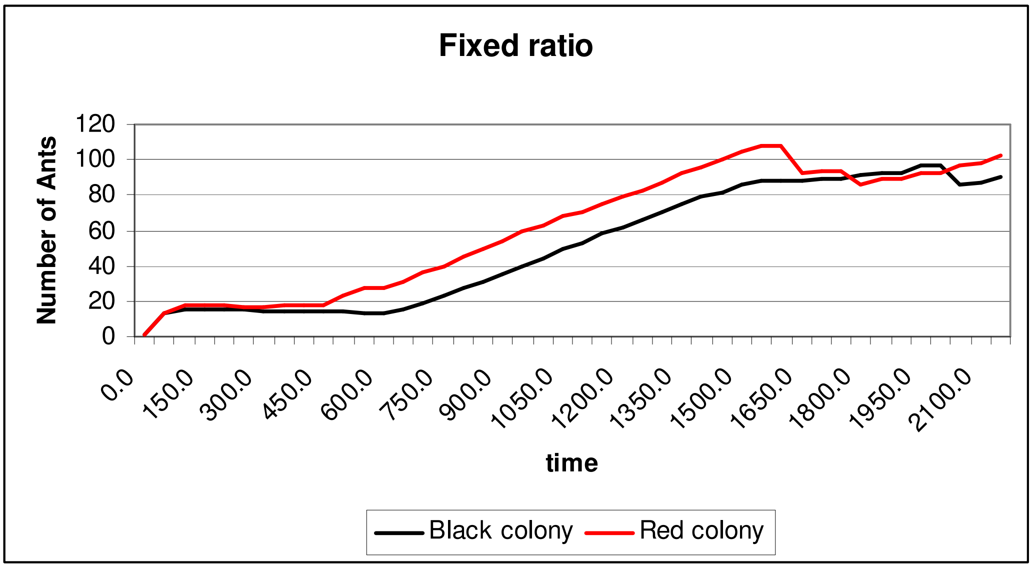

Figure 6 – Single run with black colony and red colony having a fixed ratio. The red colony found a clump of food earlier then the black colony, thereby having a little head start over the black colony. At time step 1600.0 the red colony dips as the maximum number of ants which can be sustained is reached. The colonies reach equilibrium and both oscillate around 90 ants indefinitely.

2.4.3.2 Food presentation

Ten runs were recorded in which the black colony adapts on basis of clumped food. The data showed a definite advantage in favor of the fixed ratio red colony, as they became dominant in all trials (Table 2).

10 runs	
Black wins	Red wins
0	**10**

Table 2 – Results of the ten runs in which the black colony adapts on basis of clumped food and red colony has a fixed ratio. In all recorded runs the red colony became dominating.

To properly understand why the odds are skewed so far in favor of the red colony it is necessary to look at the data of a single run showing the competition between the colonies in better detail, as shown in Figure 7. The reason for the erratic growth of the black colony is that when the black workers find a big clump of food, they start producing more soldiers, which leads to a greater disparity between the amount of food being delivered and the amount of food needed to sustain the colony. They do not produce enough soldiers, however, to seriously damage the red colony. The reds on the other hand create so many workers so rapidly, that they gain an enormous advantage in food intake. The fact that the red colony outnumbers the black colony keeps working to the red colony's advantage during the whole trial. More importantly, the black colony slightly revives every time they find a new clump of food (step 500, 700, 900 and 1400), but because they then put much of their energy into producing soldiers, the colony withers again. At step 1600 the red colony has become so big compared to the black colony that the black colony has no chance anymore, and the black colony dies. The data from the runs we performed follows this pattern, greatly to a similar extent. The average data over all the runs is shown in Figure 8.

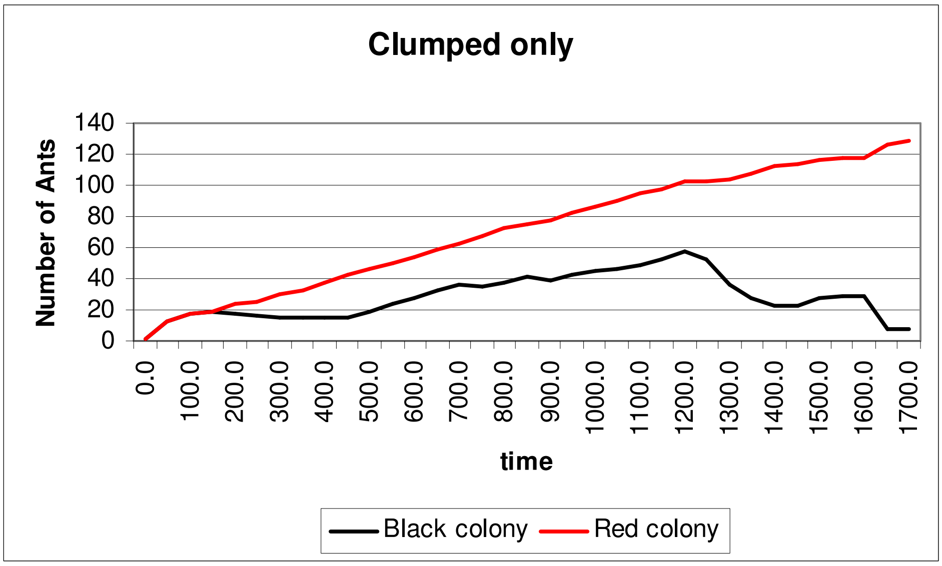

Figure 7 – Trial graph black colony adapts on basis of clumped food and red colony fixed ratio. In the graph we can see that the black colony is unable to keep up with the red colony.

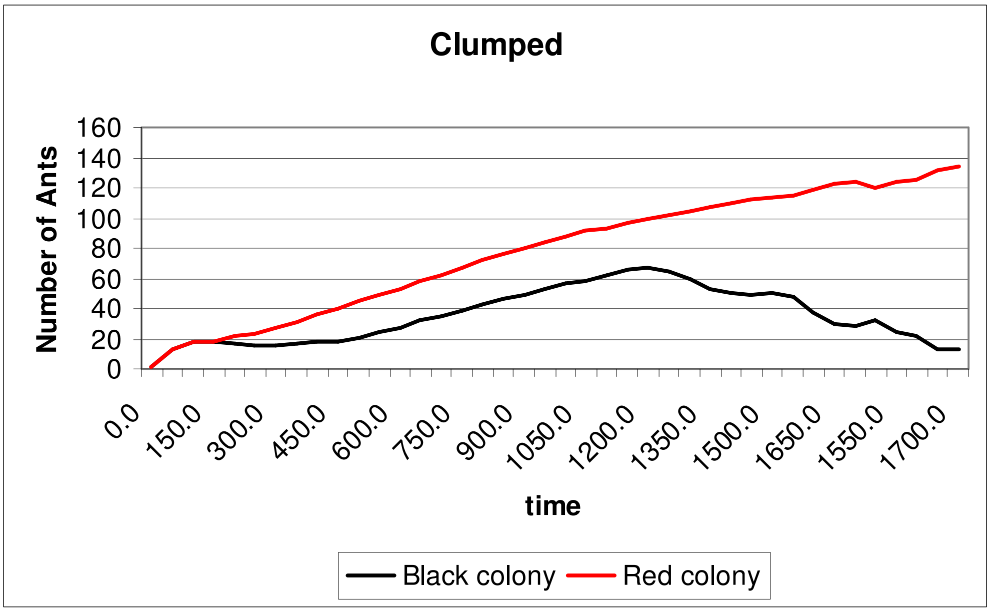

Figure 8 – Graph showing the average number of ants of both colonies over all ten runs. The graph shows that during the runs the black colony just does not grow enough to threaten the red colony.

2.4.3.3 Enemy ant presence

The second factor for which we performed runs was adaptation of the ratio based on the presence of enemies. In Table 3 the results of the 10 trials are shown.

10 runs	
Black wins	Red wins
Equilibrium: 10	

Table 3 – Results of the ten runs in which the black colony adapts on basis of enemy encounters and the red colony has a fixed ratio. In all recorded runs the colonies reached an equilibrium.

Interestingly enough, with these parameters the runs did not finish with either of the colonies becoming dominant. During the runs the colonies balanced out; obtain some dynamic equilibrium, occasionally losing a number of ants, but both colonies surviving in the end. A single exemplary run was analyzed (Figure 9), it can be seen that up to step 1200 the colonies are completely similar. At that point the colonies become so large that competition over food is unavoidable. After the confrontation both colonies have lost ants, but because there are then also fewer ants and most soldier ants have died, both colonies get some time to recuperate. From then on both colonies grow to the level where confrontation ensues again and the process repeats itself. Because the process is self-regulating, i.e. the confrontation leads to fewer soldier ants, which leads to less confrontation and so forth, no colony ever becomes dominant enough to lead to total victory.

The averaged data (Figure 10) shows an overall numerical advantage of the black colony in the graph from point 1200 onwards. This is caused by the higher number of soldiers on the black side, as the black soldiers are less likely to die.

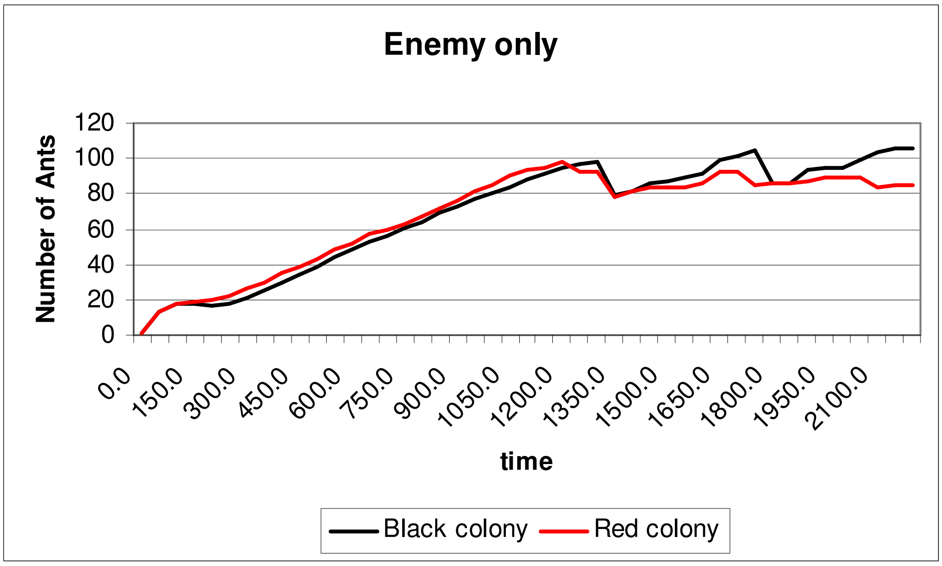

Figure 9 – Graph of a single run in which the black colony adapts on basis of enemy presence and the red colony has a fixed ratio. The balanced growth of the red colony and the black colony is visible.

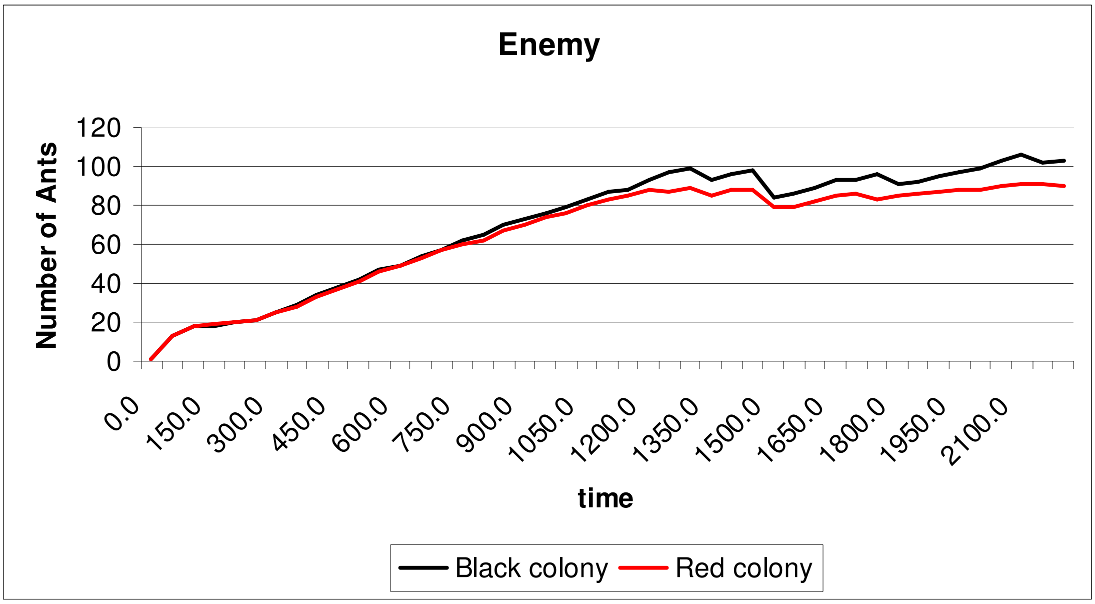

Figure 10 - Graph showing the average number of ants of both colonies over all ten runs. The graph shows that during the runs the colonies balance out.

2.4.3.4 Combined Factors (Food and Enemy Presence)

In the last series of trials the black colony adapted its ratio through both the presence of enemy ants and the presentation of food. The results of these trials can be viewed in Table 4.

15 runs	
Black wins (clumped & enemy)	Red wins (fixed)
13	**2**

Table 4 – Black colony adapts on basis of encountering enemy ants and encountering clumped food and the red colony has a fixed ratio.

The black colony becomes dominating in the vast majority of the runs, while the red colony still becomes dominant in some runs, usually through a very favorable food distribution.

From the data of a single run we are able to see when the black colony becomes dominant (Figure 11). We see that the colonies are relatively equal up to step 1500.0. At that point the difference also becomes apparent with the earlier simulations with the separate environmental factor. In this simulation the black colony does not only build up a substantially larger number of soldiers compared to the red colony (through the clumped food factor), but the confrontation itself also stimulates the creation of more soldiers, thereby making them more efficient in the rest of the run.

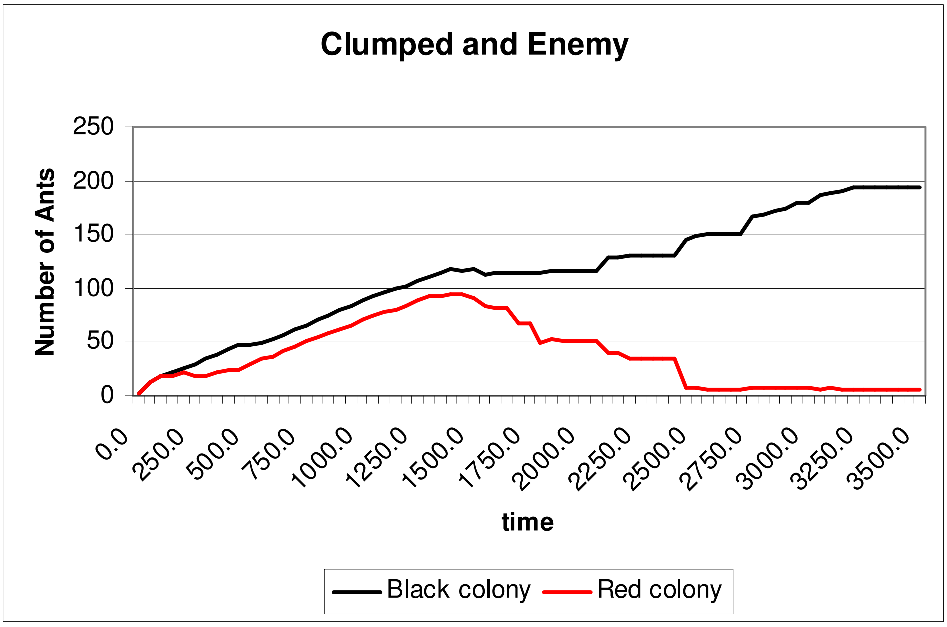

Figure 11 –Graph of a single run in which the black colony adapts on basis of enemy presence and the presentation of food and the red colony has a fixed ratio.

To further understand how the colonies interact in this run we can look at the data with a breakdown between soldiers and workers (Figure 12). Between step 1400.0 and 1800.0 we see a steep decline of the workers of the red colony, corresponding with an increase of soldiers on the side of the black colony. However, it is also important to note that the number of soldiers in the black colony is already significantly higher from step 800.0 onwards. The black colony created a beneficial worker soldier ratio before the first confrontation through information about the food situation, and then expanded on that advantage through the confrontation itself. Even though the black colony loses worker ants during the most intense competition (1400.0 – 1800.0); the black soldiers kill the red workers to such an extent that the black colony has the time to regenerate from 1900.0 onwards and grow dominant.

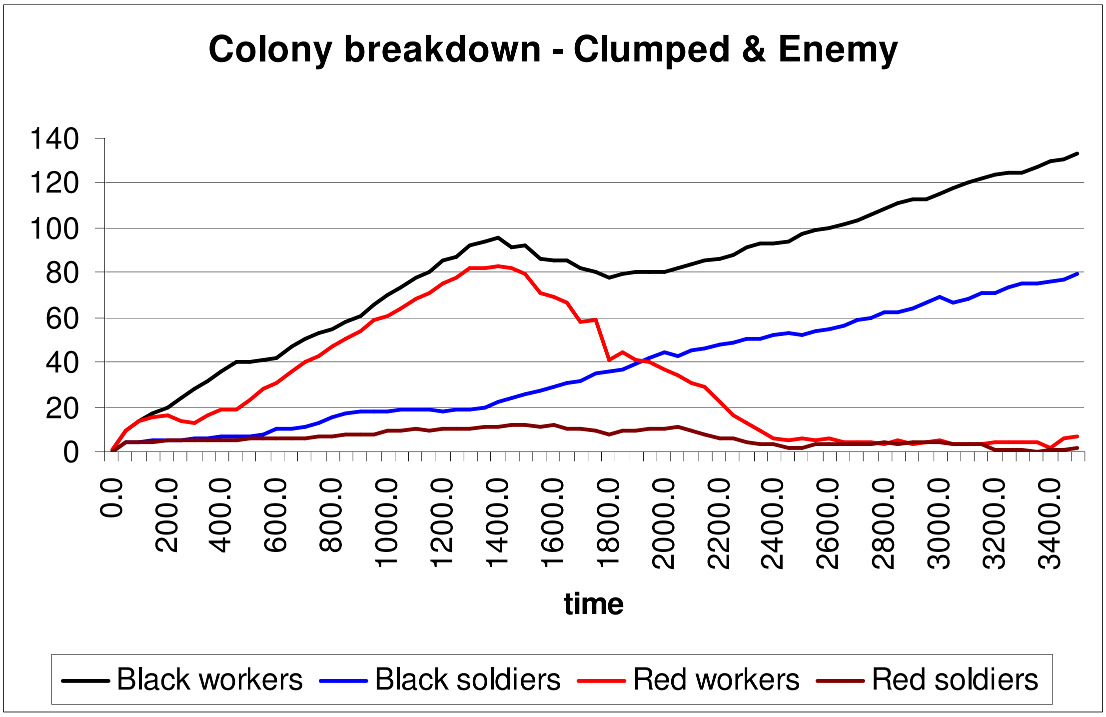

Figure 12 – Graph of the same run as shown in Figure 8 containing a breakdown between the soldiers and workers of both colonies on the same time scale.

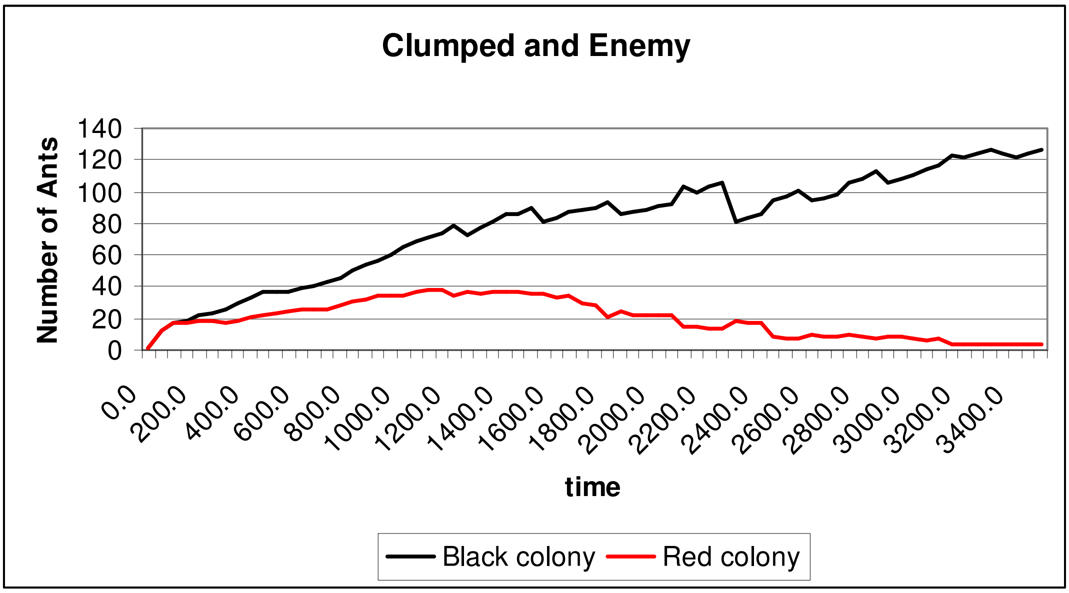

Figure 13 - Graph showing the average number of ants of both colonies over all fifteen runs.

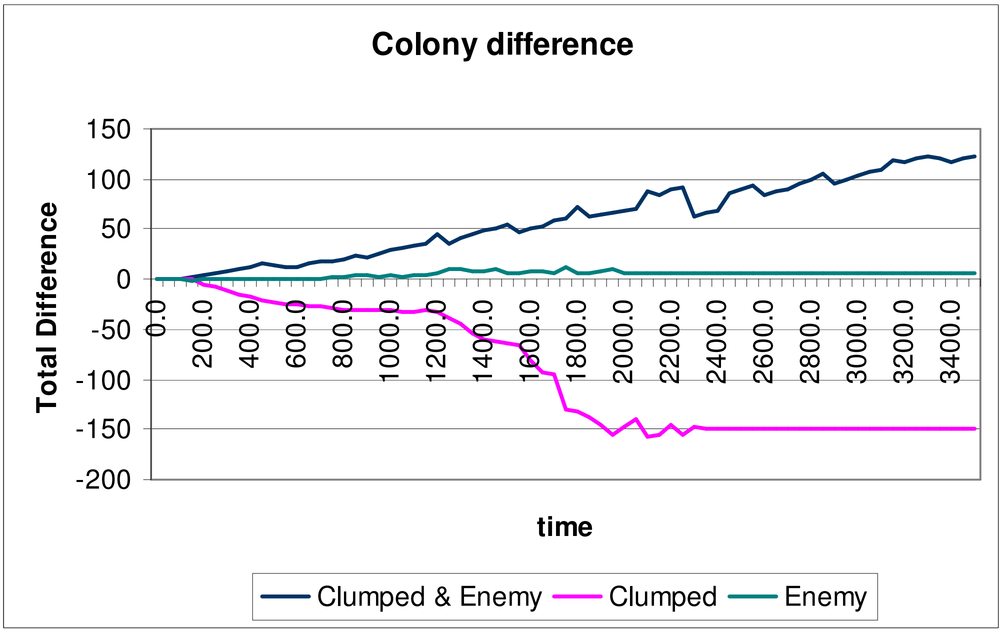

Figure 14 – Number of red ants subtracted from number of black ants for all three 15 run sets. It is very clear that using only food as a basis for ratio change is not beneficial for the colony, and that using enemy presence keeps everything completely balanced. Lastly it shows the enormous benefit of using both factors for ratio adaptation.

4.3 Discussion

In line with our hypothesis, our results indicate that using both food and enemy presence as factors for caste ratio adaptation benefits the competitiveness of the colony when compared to a colony with a fixed ratio. This is also biologically plausible, as a colony should need to adapt its ratio if competition is expected, and competition is expected in situation with clumped food and other colonies.

Even though the presentation of food is a factor in the adaptation of one of the colonies, the food was always presented as clumps, and never as a spread. The reason for this is that when food is presented in a spread, the two colonies would not behave differently, and thus the simulation would have little value.

It also appears that using only one of the two factors does not improve or may even worsen the competitiveness of the colony. It is not apparent whether this is biologically plausible, or caused by some unknown factor which was not included in our simulation. Further work on the model might shed some light on this matter.

It seems important for the black colony to fully commit to producing so many soldiers that they are able to stop the food intake of the red colony, to the extent that the black colony has time to feed their own colony. If the black colony does not fully commit to producing enough soldiers to seriously dent the red population, it actually is more vulnerable because its energy level is lower, and it thus is less able to cope with adversity.

3. General discussion

Our intention was to make some first explorations in the computational modeling of ant colony caste ratio changes. The model we designed includes a mechanism by which the colony reacts as a whole, based on decentralized input. This is an implementation of biologically inspired swarm intelligence, as the system's intelligence is based not on a single intelligent agent, but on the cumulative intelligent actions of a colony built from simple agents.

The results of our simulations show that our model is able to increase the ratio of soldier ants in the colony, on the basis of environmental factors. These factors were based on research of Passera et al [5] and Walker and Stamps [7] which showed that there are factors which can influence the ratio, namely the manner in which food is presented and the presence of ants from a different colony. Not only were we able to demonstrate that with our mechanism the colony was able to adapt its ratio, but also that such a colony is more successful than a colony with a fixed ratio when competing in the environment.

These findings may provide some indications of the underlying biological mechanism of which the existence was demonstrated by Hasegawa [6], who showed that the colony must regulate its ratio in some way.

One recurring conclusion we can draw from our data is that the increase in the ratio of soldier ants is most efficient in boosting the competitiveness when a colony has had some chance to settle in to its surroundings. The strain of nutritionally supporting a large group of soldiers is better to bare for a larger colony. Additionally, in a large colony the production of new ants put less strain on the food intake, and therefore a larger colony is more likely to have nutritional reserves. The fact that these settled colonies are better able to handle the adaptation of their ratios could be explained ecologically; as we would expect colonies to compete over food when they are at their largest and have the biggest chance of an overlap in their respective living area's. Considering that our simulations and data show that a well established colony would benefit most from the increase in soldier ants, this seems biologically plausible. In the future it would thus be interesting to perform simulations with well-established colonies, instead of growing colonies, to see whether this has any influence on the outcome. This could be implemented by creating a

bigger environment in which a colony can develop for a predetermined time without contact with other colonies before they require more food and therefore are forced to engage other colonies.
From our last simulation we concluded that a colony needs a vast army to actually damage the other colony enough, so that the benefit of the army, weighs up to the costs of having so many soldiers. It would be very interesting to see whether this conclusion is supported by biological reality. It could be that other mechanisms which are unknown regulate a maximum number of soldier ants.

In the research we have tried to include as many factors of ant biology and ecology in the model as possible, but of course the complexity of the real world can never fully be represented. Our model lacks any threats to the colonies apart from other ants. More importantly, our model generalizes over many different species of ants, all with individual caste differences and environments. Our model assumes a strict separation between castes, which is biologically plausible considering some species of ants, but in other species the differences are less pronounced as the soldier ants are simply big worker ants. In following research it would be interesting to include some additional nuances, to see if those change the outcomes.

Aside from the biological plausibility of our model, the mechanism we have implemented may be of future use in multi-agent systems. The model's ability to adequately respond on the basis of decentralized input could prove to be useful in developing more advanced multi-agent systems. Using biological studies of ant colonies and other social insects may lead to more flexible and efficient multi-agent systems, especially in solving complex problems but the agents are required to be simple and expendable.
Our research showed the colony very adept at finding food quickly, because as all ants seek food the chance of finding food increases with every ant. As a single ant leaves a pheromone trail from the food it found, the trail leads all other ants the food item. This mechanism was very effective. Because of its effectiveness this mechanism might be useful in path finding problems; specifically in unknown environments. Using ant-like

multi-agent systems would be beneficial because the individual agents are expendable, and the system as a whole is flexible.

In order to build such systems is can only be beneficial to have a better understanding of how ant colonies function, which was the initial aim of this research.

6. References

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Appendix I– Pseudo code

Worker Ant pseudo code:

```
Per time step:
    {
        if I'm hungry: return home
        if I've found food: return home and lay trace
        if I see a trace: follow it
        otherwise: wander around

        if I've seen a foreign ant: remember that
    }
```

Soldier Ant pseudo code:

```
Per time step:
    {
        if I'm hungry: return home
        if I see a trace: follow it
        if I'm at the end of a trace: circle around
        otherwise: wander around

        if I've seen a foreign ant: remember that
    }
```

Appendix II – The source code

```
/**
Code in mail bijgevoegd
**/
```