University of Camerino

School of Science and Technology

Performance Analysis and Simulation Course

Ant Colony Simulation:
Temperature and Food fluctuations

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AY 2021/2022

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Introduction

The ant colony, known as a self-organised system, can adapt to the environment through negative and positive feedback; however, it is not clear how ants coordinate. Some studies show that the ant colony is not a hierarchical system (the queen does not command), but each ant has its own task, and moreover the communication between ants is limited to an exchange of deeds (by means of antennas) through which an ant specifies its role.

The ants are really important for the ecosystem because they:

- aerate the soil, allowing water and oxygen to reach plant roots;
- take seeds down into their tunnel to eat the nutritious elaiosomes that are part of the seed; These seeds often sprout and grow new plants (seed dispersal);
- eat a wide variety of organic material and provide food for many different organisms.

So, we literally can't live without them.

Goal

The aim of the project is to define and simulate a population model of an ant colony (a new colony or an already defined colony), paying attention to the effects of the variation of the temperature and of the food present in the environment, and see how the ant colony responds to these changes. Indeed, studies show that these variations have effects on the speed of workers, on the development of immature ants and on the reproduction of the queen; the consequences of the effects of the changes can be summarised as follows:

- There is no effect of temperature and food on the ant's energy and dynamics of the colony population.
- Temperature elevations (or diminutions) will increase the risk of ant colonies dying out because they need to consume more energy to sustain themselves.
- Changes of food availability will affect energy and population dynamics of ant colonies.

Assumptions

A lot of factors are involved in the dynamics of an Ant Colony, and since we are going to define a model and simulate it, we need to consider only the major aspect of the ant colony scenario.

We will focus on the work of the ants and the influence of temperature and food availability, without taking into account this factors:

1. The temperature inside the nest and outside is the same and does not change during the time;
2. The mass of the ant and the pheromones are abstracted away by using the rates;
3. There is no distinction between water and food; they are both considered $Food$;
4. It does not exist the season cycle as well as the day-night cycle;
5. The queen will lay a constant number of eggs each time;
6. The simulation considers only the part of the year when the ant colony is active.

Moreover, we consider an ant colony of *Black Garden Ant* or *Common Balck Ant* (species *Lasius Niger*), that is monogynous, meaning that the colonies contain a single queen, and can reach in size up to 2000 - 7000 ants on average during the years. The ant colony will be active from May to October and will hibernate the other part of the year. In this type of ant colony there are different kinds of ants, each with a particular role: the queen, the males, the workers, the soldiers. Since the males are alive only 1 or 2 days after the mating, and then they die, we can not take them into account.

Also the soldiers are not represented because we are studying the temperature/food influence of a single ant colony; this means that there are no conflicts between colonies.

The model

To perform the simulation and provide results, we define a population model representing the rules and behaviours of the system. Since this is a model, and to maintain it simpler, different properties of the real word are abstracted away, like the place, the time (day/night cycle), the change of season… as mentioned before.

We first focus on the agents that interact in the environment and the dynamics inside the colony, and then we will see the influence of temperature and food, and finally we will take a look at the relative population model considering a Population Continuous Time Markov Chain (PCTMC).

Description and dynamics of the colony

Given a colony of *Black Garden Ants* it is possible to identify and consider four main different ants (or roles):

1. The **queen**: there is only one queen per colony (future queens are not taken in consideration), and her purpose is to lay eggs; the growth of the colony depends mainly on the fertility of the queen and on the efficiency of the worker ants.
2. The **nurses**: they are a particular kind of worker ants who take care of feeding the larvae and the queen, as well as cleaning the nest; these ants always work inside the nest.
3. The **foragers**: they are the second type of worker ants that take care of looking for and collecting food outside the nest and making it available to the whole colony; these ants always work outside the nest.

4. The **larvae**: with larvae we mean immature ants (egg, larva, and pupa); the larvae require food to grow and become adult ants; once adult, they will become nurses or foragers based on the request in the colony.

Each ant has a basal metabolic rate which specifies how much energy is consumed; furthermore, doing work (gathering food, or giving to eat, or laying eggs) consumes energy. Of course, an ant dies based on the energies it has: the more tired and hungry the ant is, the less energy it will be, the greater the probability of death.

During its life, a nurse ant can change role and become a forager (or vice versa) according to the needs present in the nest.

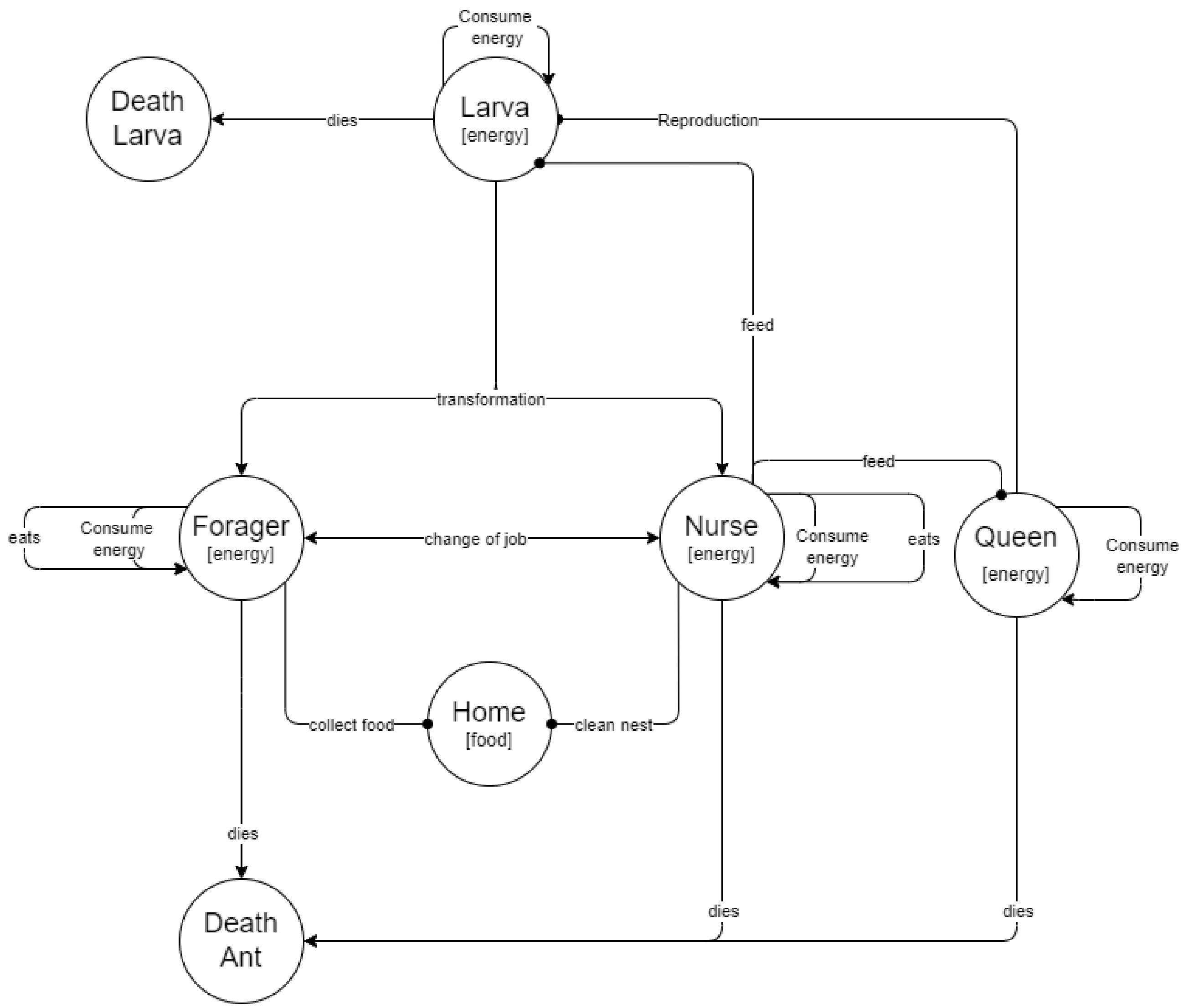
Introducing the model

In order to define a model, and use it in a simulator, we have to specify the agents and states, the actions they can perform and the rates of the rules.

In particular, the model contains the following agents: *Queen*, *Nurse*, *Forager* and *Larva*. These represent the main ants in the colony and each of them have an energy variable (e) that represents the hungry level of the ant: the more tired and hungry the ant is, the more greater e will be.

We also have to consider other agents like the *Nest* (or *Home*) that act as food storage for the colony, the *Death Ants* (that include the dead foragers, dead nurses and dead queen) and the *Death Larvae*.

We can summarise all the agents and the interaction previously listed with the following abstract diagram:



The diagram, that is like a graph, contains nodes labelled with the name of the agents (the square brackets inside a node is used to define a parameter) and 2 types of edges:

- The edge with the arrow, that indicate a change of state/agent using a rule; for instance $a - rule \rightarrow b$, meaning "the agent *a* performs the rule and becomes the agent *b*", like $larva - dies \rightarrow death\ larva$, meaning "the agent $larva$ performs the rule $dies$ and becomes the agent $death\ larva$".

- The edge with the dot, that indicate the interaction with another agents; for instance $a - rule -\bullet\ b$, meaning "the agent *a* performs the rule and interacts with the agent *b*", like $forager - collect\,food \rightarrow home$, meaning "the agent $forager$ performs the rule $collect\,food$ and interacts with the agent $home$ ".

Temperature and food influence

As mentioned, 2 factors affect an ant colony, and they are the *temperature* and the *food availability*.

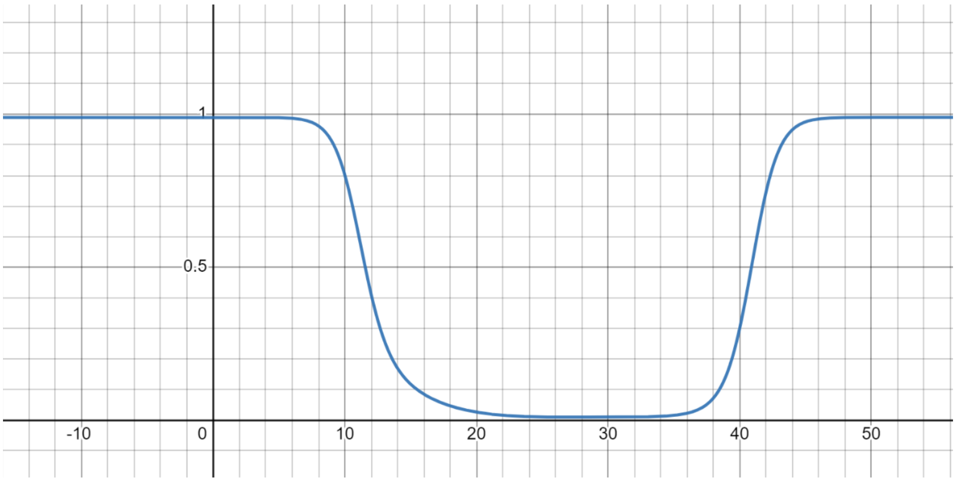
Temperature. The ideal temperature for an ant is between 23 and 35 °C (for simplicity we consider the ideal temperature equal to 29 °C and a maximum variation of ± 10 °C from the average, beyond which the temperature has greater influence); at these temperatures ants are more likely to forage for food and keep a colony active (the ant's metabolism is optimal, so it will use less food). The temperature influences the queen reproduction, the nurses and foragers work, the metabolism of all the ants and the death probability of larvae.

The influence of temperature is described by the following mathematical function (that is a Generalised Normal Function):

$$y = 0.99 - 0.98 \cdot \left(\frac{b}{2(s+D)g\left(\frac{1}{b}\right)} \right) \left(e^{-\left(\left(\frac{(x-T)}{s+D}\right)^{b}\right)} \right) \left(\frac{1}{1+e^{a(x+b_1)}} \right) \left(\frac{1}{1+e^{-a(x+b_2)}} \right)$$

with parameters $b = 4$, $s = 15$, $D = 10$, $g = 0.32$, $T = 29$, $a = 1$, $b_1 =- 41$ and $b_2 =- 11$.

The result is the following curve:



This function ranges between 0 and 1 (0, 1) and it is used in the model to affect the probability of a rule. We can see, also from the picture, that from 23 to 35 the function value is near to 0, but as soon as we move away from it, the function increases exponentially, until the value reaches ~1 at about 5 and 45.

Food. The amount of food present in the environment determines the survival or not of the colony. The consumption of food depends on the role of the ant, the metabolism of the ant and the work of the ant.

Of course, the more food there is in the environment, the less time will be required for harvesting and the more food there will be in the nest. At the end the colony will survive and grow only if there is enough food. As soon as the food in the nest runs out, the ants begin to starve.

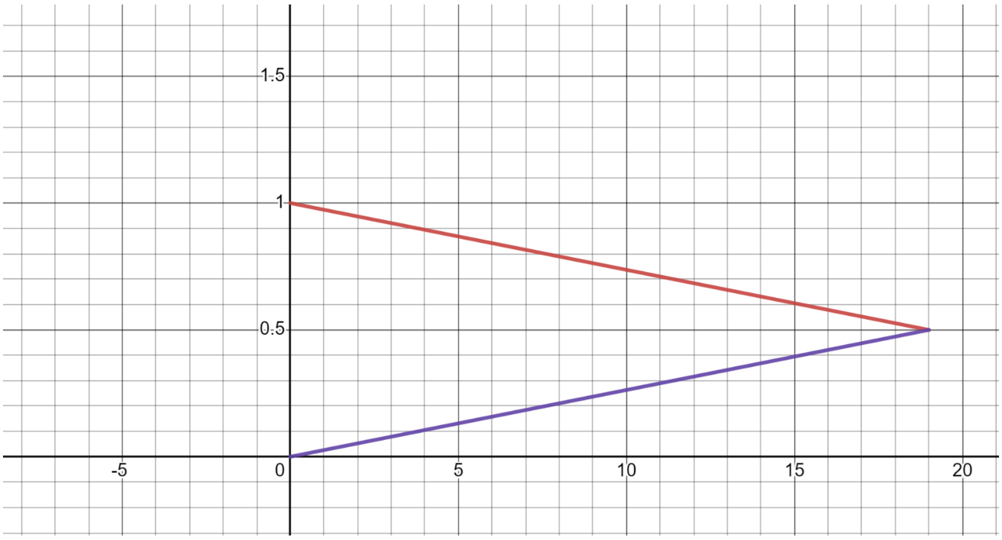
The food influences mainly the queen reproduction, the foraging of food and the change of work (nurse ↔ forager); in particular the last one has a trend that can be represented by the following mathematical functions:

$$y = 1 - \frac{\frac{x}{F-1}}{2} \left\{0 \le x \le F-1\right\}$$

$$y = \frac{\frac{x}{F-1}}{2} \left\{0 \le x \le F-1\right\}$$

Where $F = 20$ and it is the storage capacity of the nest.

This is the relative chart:



This functions are used to manage the change of work between foragers and nurses depending on the food available in the nest:

- In red, the probability that a nurse becomes a forager; it increases as soon as the food storage becomes empty.
- In violet, the probability that a forager becomes a nurse; it increases as soon as the food storage is full.

Population Continuous Time Markov Chain

In this section it is defined the PCTMC of the Ant Colony; the model is defined as the tuple $M = (X, D, T, d_0)$, where X is the vector variables, D is the counting domain, T is the transition rules and d_0 is the initial configuration.

Vector Variables

$H[0,\ Food], Q[0,\ Energy], L[0,\ Energy], N[0,\ Energy], F[0,\ Energy], DL, DA$

Counting Domain

$(0,\ N_h)\ x\ (0,\ N_q)\ x\ (0,\ N_l)\ x\ (0,\ N_n)\ x\ (0,\ N_f)\ x\ (0,\ N_{dl})\ x\ (0,\ N_{da})$

Initial State

$(1,\ 1, N_l, N_n,\ N_f,\ 0,\ 0)$

Transition rules

1. $queen\ lays\ eggs,\ 1Q\ 1H,\ 1Q[+\ 1]\ 1H\ 15L,\ \left(\lambda_{queenFertility} - \frac{tI}{5}\right) \cdot fS \cdot e \cdot cS \cdot \%L$
2. $queen\ consume\ energy,\ 1Q,\ 1Q[+\ 1],\ \lambda_{queenConsumeEnergy} + \frac{tI}{2}$
3. $larva\ consume\ energy,\ 1L,\ 1L[+\ 1],\ \lambda_{larvaConsumeEnergy} + \frac{tI}{2}$
4. $nurse\ consume\ energy,\ 1N,\ 1N[+\ 1],\ \lambda_{nurseConsumeEnergy} + \frac{tI}{2}$
5. $forager\ consume\ energy,\ 1F,\ 1F[+\ 1],\ \lambda_{foragerConsumeEnergy} + \frac{tI}{2}$
6. $nurse\ eats,\ 1H\ 1N,\ 1H[-\ 1]\ 1N[-\ 1],\ \lambda_{eat} \cdot e$
7. $forager\ eats,\ 1H\ 1F,\ 1H[-\ 1]\ 1F[-\ 1],\ \lambda_{eat} \cdot e$

8. $nurse\ feeds\ queen,\ 1N\ 1Q\ 1H,\ 1N[+\ 1]\ 1Q[-\ 1]\ 1H[-\ 2],\ \lambda_{nurseFeedsQueen} \cdot \%N$

9. $nurse\ feeds\ larva,\ 1N\ 1L\ 1H,\ 1N[+\ 1]\ 1L[-\ 1]\ 1H[-\ 1],$
$\left(\lambda_{nurseFeedsLarva} - \frac{tI}{2}\right) \cdot fS \cdot \%N$

10. $nurse\ cleans\ nest,\ 1N\ 1H\ 1DL,\ 1N\ 1H[+\ 1],\ \left(\lambda_{nurseCleans} - \frac{tI}{2}\right) \cdot \%DL$

11. $forager\ collects\ food,\ 1F\ 1H,\ 1F[+\ 1]\ 1H[+\ 2],\ \left(\lambda_{foragerWorks} - \frac{tI}{2}\right) \cdot fA \cdot \%F$

12. $queen\ dies,\ 1Q,\ 1DA,\ \lambda_{queenDeath} \cdot cS$

13. $larva\ dies,\ 1L,\ 1DL,\ \frac{\left(\lambda_{larvaDeath} \cdot e\right)}{3} + \frac{2 \cdot tI}{3}$

14. $nurse\ dies,\ 1N,\ 1DA,\ \lambda_{workerDeath} \cdot e$

15. $forager\ dies,\ 1F,\ 1DA,\ \lambda_{workerDeath} \cdot e$

16. $larva\ becomes\ forager,\ 1L,\ 1F,\ \lambda_{larvaGrows} \cdot \%L$

17. $larva\ becomes\ nurse,\ 1L,\ 1N,\ \lambda_{larvaGrows} \cdot \%L$

18. $nurse\ becomes\ forager,\ 1N,\ 1F,\ \lambda_{changeOfWork} \cdot (1 - \%fS + sA) \cdot \%N$

19. $forager\ becomes\ nurse,\ 1F,\ 1N,\ \lambda_{changeOfWork} \cdot (\%fS + sA) \cdot \%F$

Where:

- $Food$ is a constant and represents the capacity of the food storage of the colony.
- $Energy$ is a constant and represents the hungry levels of an ant.
- H is the Home (or nest) of the colony; the parameter $H[] = fS$ represent the food inside the nest.
- Q is the Queen of the colony; the parameter $Q[] = e$ represent the hungry level of the queen.
- L are the larvae (eggs, pupa, and larva); the parameter $L[] = e$ represent the hungry level of the larva.
- N are the nurses; the parameter $N[] = e$ represent the hungry level of the nurse.
- F are the foragers; the parameter $F[] = e$ represent the hungry level of the forager.
- DL are the death larvae
- DA are the death ants (queen, foragers, and nurses)
- $fS \in \{ x \in N \mid 0 \leq x < 10 \}$ is the *food storage level* and represents how much food is stored in the nest; this is a global parameter that depends on H. The higher is fS, the more food will be in the nest.

- $e \in \{ x \in N \mid 0 \leq x < 10 \}$ is the *energy level* of the ant and represents how much an ant is hungry; this is a local parameter (depends on the ant). The higher is e, the hunger will be the ant.

- $tI \in \{ x \in R \mid 0 \leq x \leq 1 \}$ is the *temperature influence*; this is a global parameter. The higher is tI, the more the ants are negatively affected.

- $fA \in \{ x \in R \mid 0 \leq x \leq 1 \}$ is the *food availability* and represents how much food there is in the environment; this is a global parameter. The higher is fA, the more food there is in the environment.

- $cS \in \{ x \in R \mid 0 \leq x \leq 1 \}$ is the *colony size* and represents how bigger the colony is with respect to the standard; this is a global parameter.

- $sA \in \{ x \in R \mid 0 \leq x \leq 1 \}$ is the *starve ants* and represents the percentage of the population that is starving; this is a global parameter. The higher is sA, the more ants are starving.

Implementation

The implementation of the model is made by using the tool *Sibilla*.

Code

The following code is the actual implementation of the model previously defined. In particular the script specifies the *.pm (population model)* file, used by *Sibilla*. The code is also available at the github link.

```
/*
 * Matteo Romagnoli - PAS Exam
 *
 * Ant Colony
 * The ant colony is composed by different type of ants, each having a particular role:
 * - Queen (Q): is the queen of the colony, it is going to depositate new Eggs (Larve), depending on the food storage & queen hungry / mass;
 * - Nurses (N): this ants are going to operate always inside the nest, and provide food to the queen & larves;
 * - Foragers (F): they collect food from the outside and provide nutrients for the nest. They never operate inside the nest;
 * - Larvae (L): with the term Larvae we refer to Eggs, Larvae and Pupa, and so, they are not still ants, but they require food in order to grow; when old enough (adult ant), they become Foragers or Nurses.
 *
 * Nurses and Foragers can change their role depending on the amount of food stored in the nest.
 *
```

```
 * In particular 2 factors influence the colony survival & grow:

 * 1. Temperature: the ideal temperature is between 23 and 35 °C (we assume 29 °C as the ideal temperature); at these temperatures, ants are more likely to forage for food and maintain an active colony (optimal metabolism).

 * 2. Quantity of food in the environment.

 *

 * The consumption of food depends on the role of the ant, if it works inside or outside (temperature), the level of energy and the global food storage.

 *

 * The temperature has effects on workers' size, immature ants' development, and queen's reproduction:

 * 1- There is no effects of temperature and food on an ant colony’s energy and population dynamics.

 * 2- Temperature elevations (or diminution) will increase the risk of ant colonies dying out because they need to consume more energy to sustain themselves.

 * 3- Changes of food availability will affect energy and population dynamics of ant colonies.

 *

 */



/* ======================================= */

/*              CONST & AGENTS             */

/* ======================================= */

/* -------- Maths constants -------- */

const e = 2.718281;

const beta = 4;

const sigma = 15;
```

```
const gamma = 0.32;

const alpha = 1;

const boundaryR = -41;

const boundaryL = -11;


/* -------- Environment Parameters -------- */

param initial_larvae = 20;

param initial_nurses = 100;

param initial_forager = 100;


param temperature = 5;

param foodAvailabilityRate = 0.5; /* Ranges between 0 and 1 */


/* -------- Generic Constants -------- */

const ENERGY = 4;                /* Energy (or hungry) level of an ant: 0 =
no hunger (full of energy), 4 = really hungry (no energy) */

const FOOD_STORAGE = 20;         /* Food storage: 0 = no food, 10 = storage
full of food */

const IDEAL_TEMPERATURE = 29;    /* The ideal temperature for the ant is
between 23 and 35 °C; we can consider 29°C and the tolerance +-10°C */

const DELTA_TEMPERATURE = 10;    /* The delta of the temperature (tolerance
of the ant +- 10°C) */


/* -------- Helper constants --------- */

const initial_ants = initial_nurses + initial_forager + initial_larvae;

const delta_ants = initial_ants * 0.25; /* 25% tolerance */
```

```
/* -------- Agents -------- */

species H of [0, FOOD_STORAGE];                  /* Home (nest)   : H[i]
specify the amount of food in the nest */

species Q of [0, ENERGY];                        /* Queen         : Q[i] queen
with hungry level i */

species L of [0, ENERGY];                        /* Larvae        : L[i]
hunger of the larva */

species N of [0, ENERGY];                        /* Nurse         : N[i]
hunger of the nurse ant */

species F of [0, ENERGY];                        /* Forager       : F[i]
hunger of the forager ant */

species DL;                                      /* Death larva */

species DA;                                      /* Death ant */


/* -------- Probability Rates & Multipliers -------- */

const eggsLaysDelayRate     = 0.1;

const queenFertilityRate    = 1.0;  /* Ranges between 0.2 and 1 -> (0.2, 1]
*/


const baseConsumeEnergyRate = 0.25;

const eatRate               = 1.0;

const transformationRate    = 0.5;

const larvaGrowRate         = 0.2;


const nurseFeedQueenRate    = 2.0;

const nurseFeedLarvaRate    = 0.6;  /* Ranges between 0.5 and 1 -> (0.5, 1]
*/

const nurseCleanRate        = 0.25; /* Ranges between 0.2 and 1 -> (0.2, 1]
*/
```

```
const foragerWorkRate       = 0.75; /* Ranges between 0.5 and 1 -> (0.5, 1]
*/


const changeOfWorkRate      = 0.5;


/*

 * The probability that the queen dies is pretty low, because, it can dies
only in 2 ways:

 * - by human's work;

 * - other ants kill it;

 * Since, in this model, the human influence is not take into account, the
queen will die only if the workers ant kill it;

 * but again, also the second condition is not probable since, the workers
kill a queen only if there is a surplus of queen in a colony.

 * In the model we consider only one queen.

 *

 * The queen will die only when the colony is dying and it remains alone.

 */

const queenDeathRate        = 0.001;

const larvaDeathRate        = 1.0;      /* If larva is not well feeded, it
will die */

const workerDeathRate       = 0.25;


/* Must range between 0 and 2 */

const larvaConsumeEnergyMultiplier    = 1.75;

const queenConsumeEnergyMultiplier    = 1;

const nurseConsumeEnergyMultiplier    = 0.5;

const foragerConsumeEnergyMultiplier  = 1;
```

```
/*
 * The function (generalised normal function) ranges between ~0 and ~1: as
we move away from 29 °C, the influence function increases until reaches the
maximum.
 *
 *              ^
 * Probability |
 *              |
 *              |
 *              |
 *              |
 *              |
 *   ~1   -----------\                         /-------------
 *              |     -\                      /
 *              |       -\                   |
 *              |         \                  |
 *              |          -\              /
 *              |            \            |
 *              |             \           |
-
 *              |              \         /
 *   ~0         |               \--------/
 *       -------+-------------------------------------------->
 *            0 |              23   29   35      Temperature
 *              |
 *              |
```

```
 *
 */
const temperatureInfluence = 0.99 - 0.98 * ( beta / (2 * (sigma + DELTA_TEMPERATURE) * gamma * (1 / beta))) * (e ^ -(((temperature - IDEAL_TEMPERATURE) / (sigma + DELTA_TEMPERATURE))^beta)) * (1 / (1 + e ^ (alpha*(temperature + boundaryR)))) * (1 / (1 + e ^ (-alpha*(temperature + boundaryL))));

const eggs = 30; /* number of eggs the queen will lay */

const antBound = eggs * 7;


/* ======================================= */
/*                 LABELS                  */
/* ======================================= */
label nurses = { N[i for i in [0,ENERGY]] }

label foragers = { F[i for i in [0,ENERGY]] }

label workers = { N[i for i in [0,ENERGY]], F[i for i in [0,ENERGY]] }

label larvae = { L[i for i in [0,ENERGY]] }

label ants = { N[i for i in [0,ENERGY]], F[i for i in [0,ENERGY]], Q[i for i in [0,ENERGY]] }

label starve_l_q = { Q[i for i in [ENERGY/2,ENERGY]], L[i for i in [ENERGY/2,ENERGY]] }



/* ======================================= */
/*                  RULES                  */
/* ======================================= */
/* --------- Reproduction rules ---------- */
/* The queen will lay eggs depending on 7 factor:
```

```
 * - the fertility (queenFertilityRate);

 * - the more satiated the queen, the more likely she is to lay eggs (1.0 -
i / ENERGY);

 * - the temperature;

 * - the number of current larvae (1 / (#larvae + 1));

 * - it is highly influenced by the food stored in the nest, indeed the more
food there is in the nest (food storage), the more likely the queen is to
lay eggs ((f / FOOD_STORAGE)^2);

 * - the size of the colony;

 * - food availability;

 *

 * The queen will lay a number of eggs that are constant (eggs) and consume
a lot of energy.

 */

rule queen_lays_eggs for i in [0, ENERGY/2] and f in [FOOD_STORAGE/2,
FOOD_STORAGE] {

  Q[i]|H[f] -[ (1.0 - i / ENERGY) * ((f / FOOD_STORAGE) ^ 2) *
(queenFertilityRate - temperatureInfluence / 5) * (1 / (#larvae + 1)) *
((#ants * (foodAvailabilityRate ^ 0.5)) / antBound) ]->
Q[i+2]|H[f]|L[0]<eggs>

}



/* ------- Consume energy rules --------- */

/* The energy consumed (Metabolism of the ant) depends on the Mass of the
ant (that is abstracted with the Multipliers) and the Temperature:

 * - Farter is the temperature from the ideal temperature, faster will be
the metabolism (temperature influence);

 * - The heavier the ant, the faster the metabolism (multiplier).

 */

rule larva_consume_energy for i in [0, ENERGY-1] {
```

```
  L[i] -[ baseConsumeEnergyRate * larvaConsumeEnergyMultiplier +
temperatureInfluence / 2 ]-> L[i+1]

}

rule queen_consume_energy for i in [0, ENERGY-1] {

  Q[i] -[ baseConsumeEnergyRate * queenConsumeEnergyMultiplier +
temperatureInfluence / 2 ]-> Q[i+1]

}

rule nurse_consume_energy for i in [0, ENERGY-1] {

  N[i] -[ baseConsumeEnergyRate * nurseConsumeEnergyMultiplier +
temperatureInfluence / 2 ]-> N[i+1]

}

rule forager_consume_energy for i in [0, ENERGY-1] {

  F[i] -[ baseConsumeEnergyRate * foragerConsumeEnergyMultiplier +
temperatureInfluence / 2 ]-> F[i+1]

}




/* ----------- Eating rules ------------ */

/*

 * When an ant eats then the food from the global storage is decreased by
one. Only Nurses and Foragers eat food directly.

 */

rule nurse_hungry_eats for i in [ENERGY/2, ENERGY] and f in [1,
FOOD_STORAGE] {

  N[i]|H[f] -[ i / ENERGY * eatRate ]-> N[i-1]|H[f-1]

}

rule forager_hungry_eats for i in [ENERGY/2, ENERGY] and f in [1,
FOOD_STORAGE] {
```

```
  F[i]|H[f] -[ i / ENERGY * eatRate ]-> F[i-1]|H[f-1]

}



/* ------------- Work rules ------------- */

/* The work of the ants are mainly influenced by the Temperature:

 * - The farther the temperature is from the ideal temperature, slower the
Nurse will be and the slower it will be for feed the queen and larvae;

 * - The farther the temperature is from the ideal temperature, the slower
the Forager will be and the slower it will be for food to be harvested.

 *

 * Moreover, the Foragers are also influenced by the availability of the
food: the more food there is, the greater it will be for food to be
harvested.

 */

rule nurse_feed_queen for i in [0, ENERGY-1] and j in [2, ENERGY] and f in
[2, FOOD_STORAGE] {

  N[i]|Q[j]|H[f] -[ nurseFeedQueenRate * (((#nurses) * 2 + 1) / (#ants + 1))
]-> N[i+1]|Q[j-2]|H[f-2]

}

rule nurse_feed_larva for i in [0, ENERGY-1] and b in [ENERGY/2, ENERGY] and
f in [FOOD_STORAGE/2, FOOD_STORAGE] {

  N[i]|L[b]|H[f] -[ (nurseFeedLarvaRate - temperatureInfluence / 2) * (f /
FOOD_STORAGE) * (#nurses / #ants) ]-> N[i+1]|L[b-1]|H[f-1]

}

rule nurse_clean_nest for i in [0, ENERGY-1] and f in [0, FOOD_STORAGE-1] {

  N[i]|H[f]|DL -[ (nurseCleanRate - temperatureInfluence / 5) * (#DL / eggs)
]-> N[i]|H[f+1]

}

rule forager_collects_food for i in [0, ENERGY-1] and f in [0,
FOOD_STORAGE-3] {
```

```
  F[i]|H[f] -[ (foragerWorkRate - temperatureInfluence / 2) *
foodAvailabilityRate * (#foragers / #ants) ]-> F[i+1]|H[f+3]

}



/* ------------- Die rules ------------- */

/* The probability of death mainly depends on the energy level: the hungrier
the ant, the more likely it is to die.

 * However, the probability of death also depends on the kind of ant:

 * - it is more likely the larva dies if not well feeded or if the
temperature is not adequate;

 * - the worker death rate is pretty low.

 */

rule queen_dies {

  /* The power (^10) is used to delay the queen's death when executing the
model more time (when replica > 1), in order to obtain consistent results.
*/

  Q[ENERGY-1] -[ queenDeathRate * (1 // #ants) ^ 10 ]-> DL

}

rule larva_dies for i in [ENERGY / 4 * 2, ENERGY] {

  L[i] -[ (i / ENERGY * larvaDeathRate) / 3 + temperatureInfluence / 3 * 2
]-> DL

}

rule nurse_dies for i in [ENERGY / 4 * 3, ENERGY] {

  N[i] -[ i / ENERGY * workerDeathRate ]-> DA

}

rule forager_dies for i in [ENERGY / 4 * 3, ENERGY] {

  F[i] -[ i / ENERGY * workerDeathRate ]-> DA

}
```

```
/* ------- Larvae transformation rules -------- */

/* When a larva has grown enough, it will turn into: Nurse or Forager; the probability is the same for both, and it is 50%.

 * The growth is accelerated by the number of the larvae: the more larvae there are in the nest, the faster they will become adults.

 */

rule larva_becomes_nurse for i in [0, ENERGY] {

  L[i] -[ transformationRate * larvaGrowRate * #larvae * %larvae ]-> N[i]

}

rule larva_becomes_forager for i in [0, ENERGY] {

  L[i] -[ transformationRate * larvaGrowRate * #larvae * %larvae ]-> F[i]

}



/* ------------- Change of work rules -------------- */

/* During the life, an ant (Forager or Nurse) that is not dying ([0, ENERGY / 4 * 3]) can change the job:

 * - A Nurse can become a Forager if the amount of food stored in the nest is scarce, the starve ants is low and the percentage of Nurses increase;

 * - Viceversa, a Forager can become a Nurse if the amount of food stored in the nest is plentiful, the starve ants are high and the percentage of Foragers increase.

 */

rule nurse_becomes_forager for i in [0, ENERGY / 4 * 3] and f in [0, FOOD_STORAGE] {

  N[i]|H[f] -[ changeOfWorkRate * #nurses * (1 - (f / (FOOD_STORAGE - 1) + #starve_l_q / (#larvae + 1)) / 2) * (#nurses // #workers) ]-> F[i]|H[f]

}
```

```
rule forager_becomes_nurse for i in [0, ENERGY / 4 * 3] and f in [0,
FOOD_STORAGE] {

  F[i]|H[f] -[ changeOfWorkRate * #foragers * (f / (FOOD_STORAGE - 1) +
#starve_l_q / (#larvae + 1)) / 2 * (#foragers // #workers) ]-> N[i]|H[f]

}




/* ======================================= */

/*          MEASURES & PREDICATES          */

/* ======================================= */

measure n_queen = #Q[i for i in [0,ENERGY]];

measure n_nurse = #nurses;

measure p_nurse = %nurses;

measure n_forager = #foragers;

measure p_forager = %foragers;

measure n_larvae = #larvae;

measure p_larvae = %larvae;

measure n_ants = #ants;

measure n_death = #DA;

measure n_larvae_death = #DL;

measure n_starve_l_q = #starve_l_q;


predicate colony_stationary = ((#nurses + #foragers + #larvae + delta_ants
>= initial_ants) || (#nurses + #foragers + #larvae - delta_ants <=
initial_ants));

predicate colony_growing = (#nurses + #foragers + #larvae > initial_ants);

predicate colony_survived = (#Q[i for i in [0,ENERGY]] > 0);
```

```
predicate colony_dying = ( #Q[i for i in [0,ENERGY]] == 0 );




/* ======================================= */

/*                SYSTEM DEF               */

/* ======================================= */

system initial =
H[FOOD_STORAGE-1]<1>|Q[0]<1>|N[0]<initial_nurses>|F[0]<initial_forager>|L[0]
<initial_larvae>|DA<0>|DL<0>;
```

Expectations

From the studies and observations we know that an Ant Colony:

- Grows quickly in perfect conditions, in both case of a new colony or an old one;
- Dies if in an hostile environment (like miss of food or pretty low/high temperature), in both case of a new colony or an old one;
- In a environment with middle condition the colony try to survive; in particular at around 12 °C
    - a big colony can survive if food is not a problem
    - a medium colony only survive for a period of time
    - a small colony will die after a while

  We have similar scenarios when food is lacking but the temperature is favourable.

Results

The simulations take place in 1000 time units that correspond to about 6 months (180 days, when the colony is active) with a delta time of 1 unit. In order to make the simulation more general, it is reproduced 10 times (10 replicas for each simulation).

For each simulation we collect the *summary statistic* of different measures regarding:

- the number and percentage (with respect the population) of foragers;
- the number and percentage (with respect the population) of nurses;
- the number and percentage (with respect the population) of larvae;
- the number of alive ants (only queen, foragers and nurses);
- the number of dead ants (only queen, foragers and nurses);
- the number of dead larvae (only larvae);
- the number of agents (only queen and larvae) that are starving.
- the home's number in a particular state ($H[0]$, $H[1]$ ... $H[19]$)

Each file contains 4 fields, that are the *time step* (from 0 to 999), the *mean* of the collected value, the *variance and* the *standard deviation.*

During the simulation the temperature and the food availability parameters do not change.

We take in consideration 12 simulations, 6 simulations with a *new colony* (consisting of the queen, 20 larvae, 10 foragers and 10 nurses) and 6 simulation with a *old colony* (consisting of the queen, 20 larvae, 100 foragers and 100 nurses), all of which they start with a nest full of food, and each of which designing a scenario (different temperature and food availability).

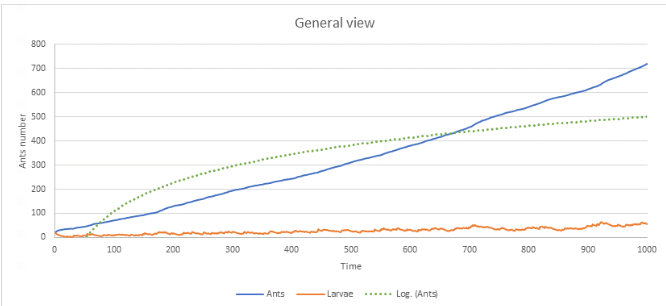
Five charts have been defined for each simulation:

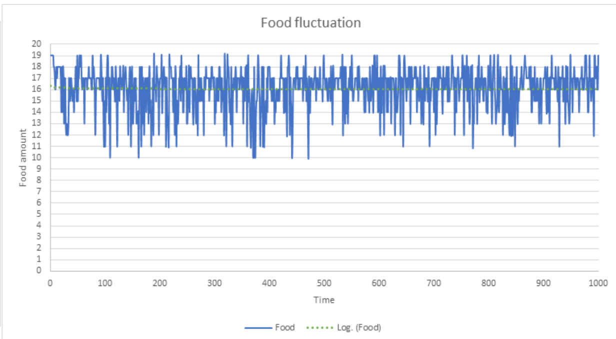
1. ***General View*** representing the trend of the colony during the time (is the colony dying or not?);
2. ***Ants Distribution*** representing the distribution of the roles in the colony during the time (how much foragers, nurses and larvae are there?);
3. ***Deaths*** representing the number of death ants and death larvae during the time;
4. ***Food Fluctuation*** representing the amount of food stored in the nest, and the relative trend, during the time;
5. ***Hunger Colony Distribution*** representing the amount of ants, foragers and starve agents, and the relative amount of food in the nest (plus the trend), during the time.

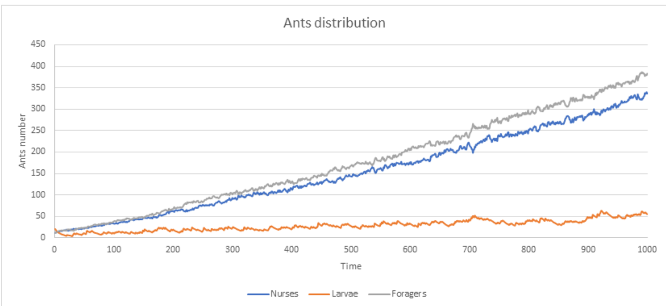
Simulation 1

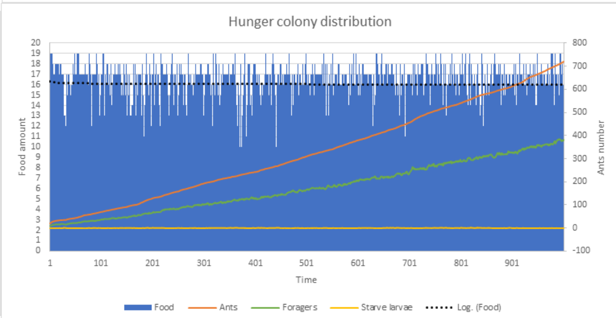
A new colony in an ideal environment where $Temperature = 29\,°C$ and $Food\ availability = 1$.

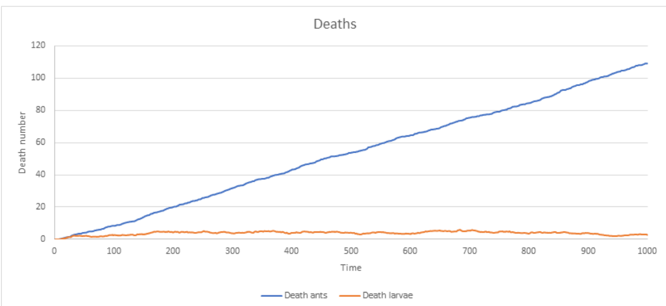
As we can imagine, in ideal conditions, the ant colony will grow quickly. Since there is a lot of food, the food storage never becomes empty, moreover remains always half full (as we can see in the food fluctuation chart), and the number of nurses and foragers are more or less equally distributed (number of nurses is almost the same as the number of foragers). In the last graph we can see that the population is not starving.







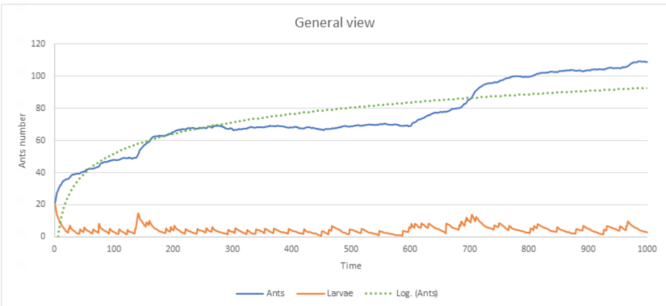


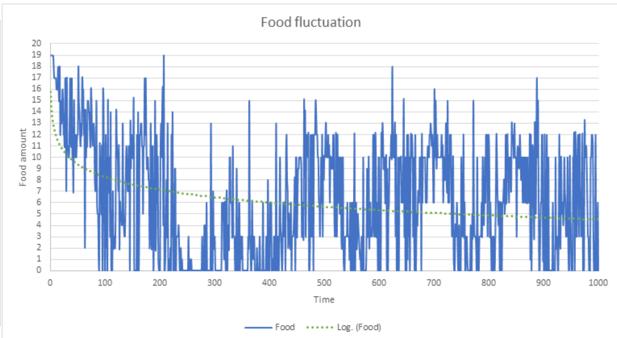


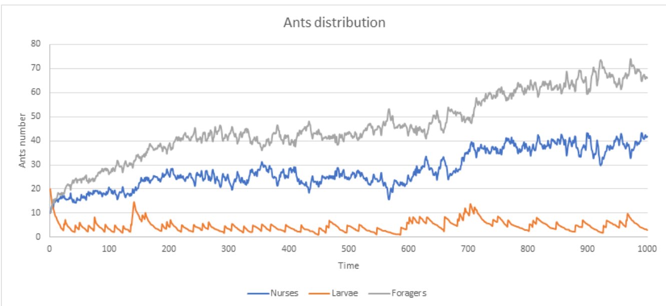
Simulation 2

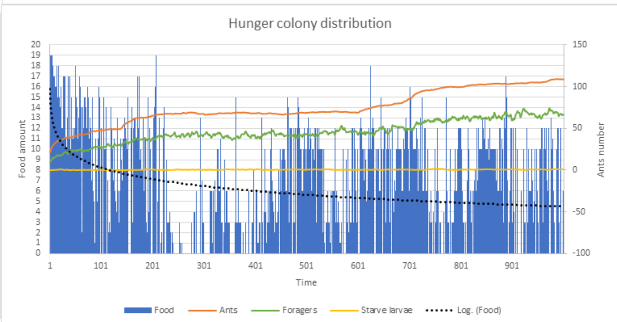
A new colony in an environment where $Temperature \ = \ 29\,°C$ and $Food\ availability \ = \ 0.5$.

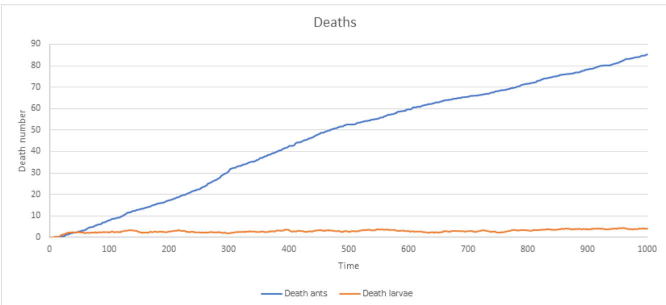
Also in this case, the ant colony will grow, however it is slower than the first. Since here the problem is the food, the food storage tends to become empty (as we can see in the food fluctuation chart), but at the same time, the number of foragers increases with respect to the nurses. In the last graph we can see that the population is not starving, but sometimes, we can notice some peaks (~5 agents).









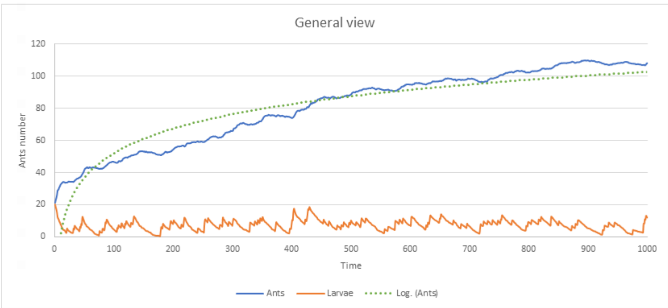


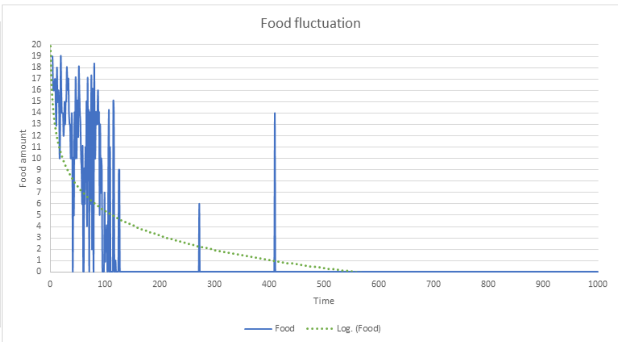
Simulation 3

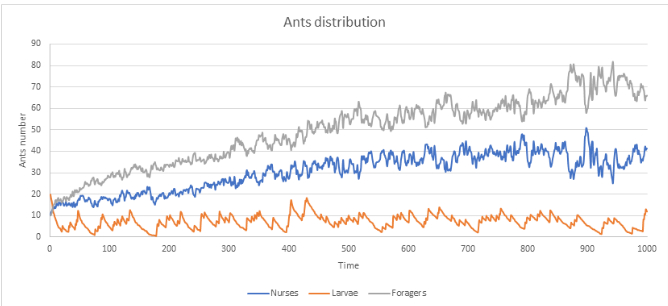
A new colony in an environment where $Temperature = 12.5\,°C$ and

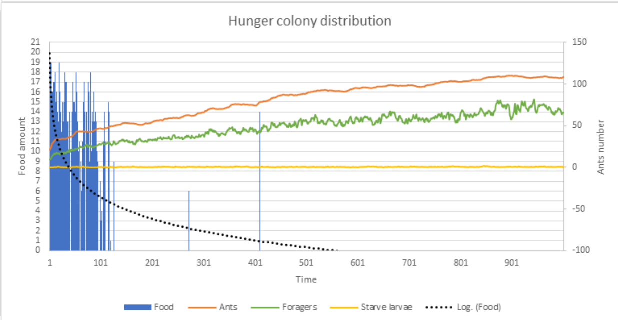
$$Food\ availability = 1.$$

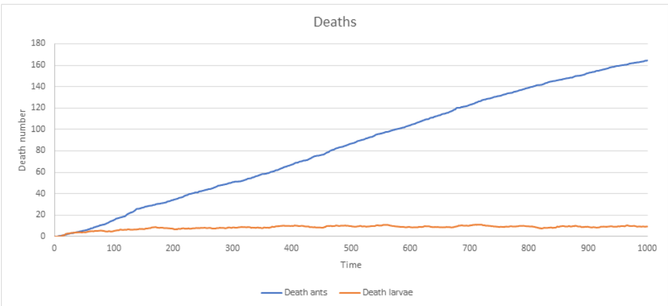
In this scenario, the ant colony will grow really slow. We can observe that the number of death ants overcome the number of alive ants (at the end). Also if the food is not a problem, the temperature requires a constant and large amount of food to eat, and this is visible in the Food Fluctuation graph: the food storage is always empty, because the ants eat all the available food in order to survive.







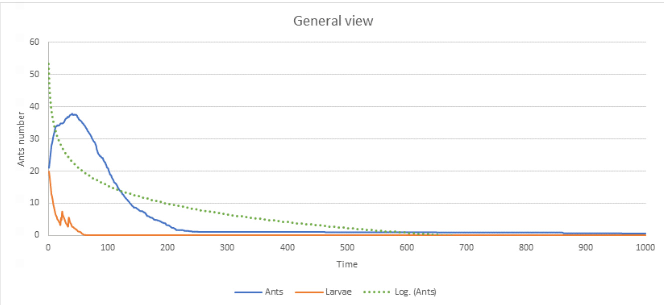


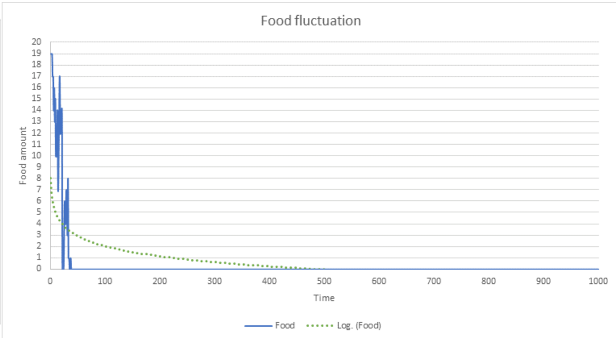


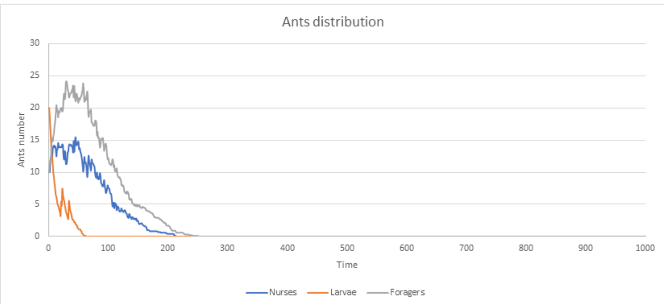
Simulation 4

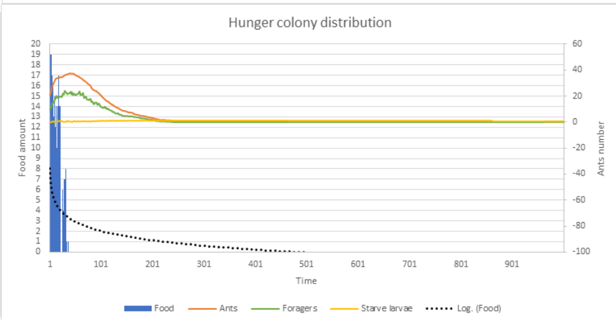
A new colony in an environment where $Temperature\ =\ 12.5\ °C$ and
$$Food\ availability\ =\ 0.5.$$

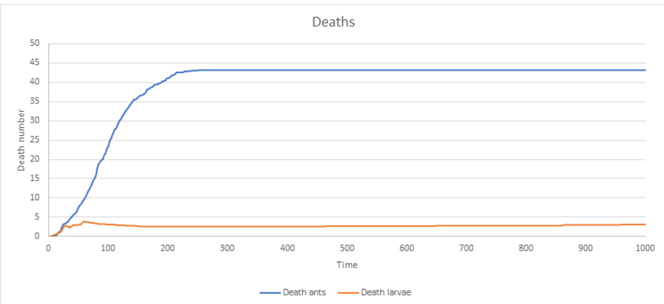
In this case the whole ant colony dies after about 200 time units (~36 days). Also if there are more foragers to harvest for food, the request for food is so high that the colony dies. We have to keep in mind that initially the colony has only 20 workers.







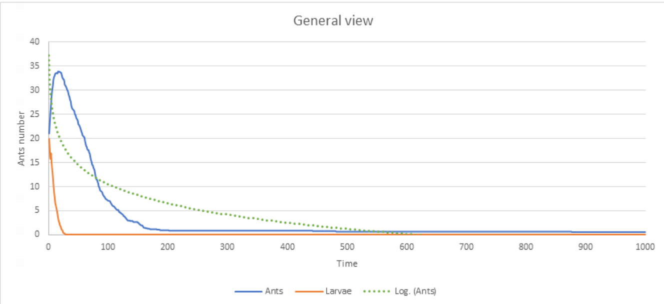


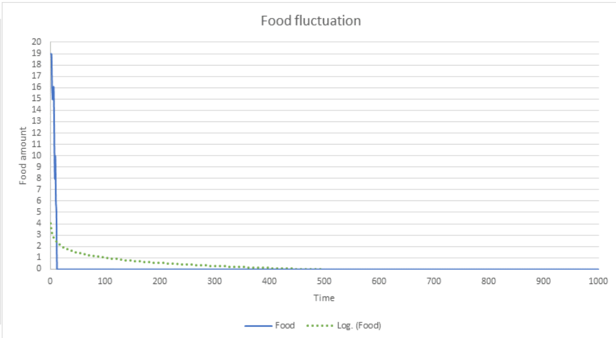


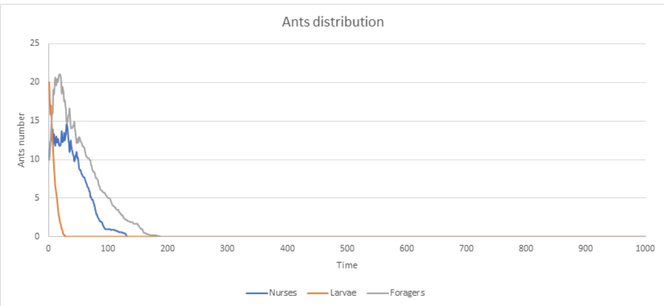
Simulation 5

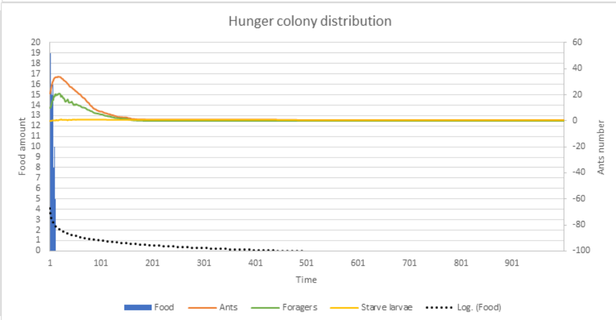
A new colony in an environment where $Temperature\ =\ 5\,°C$ and $Food\ availability\ =\ 1.$

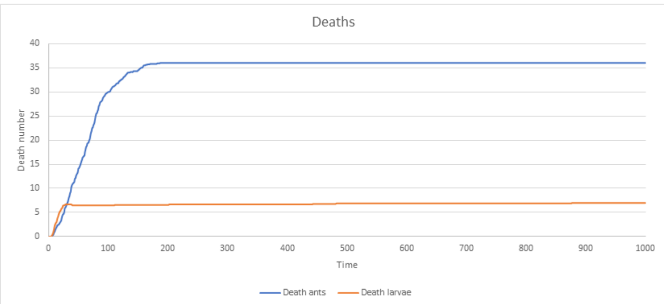
As we can imagine, in these conditions the colony dies after a while (~30 days).







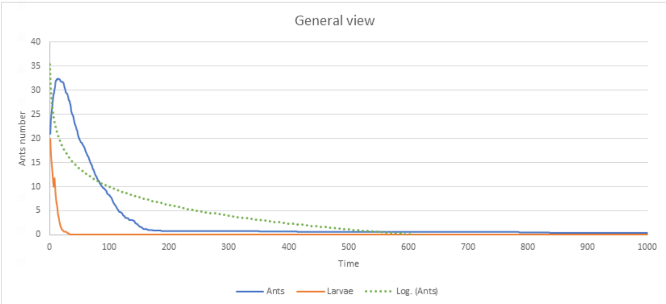


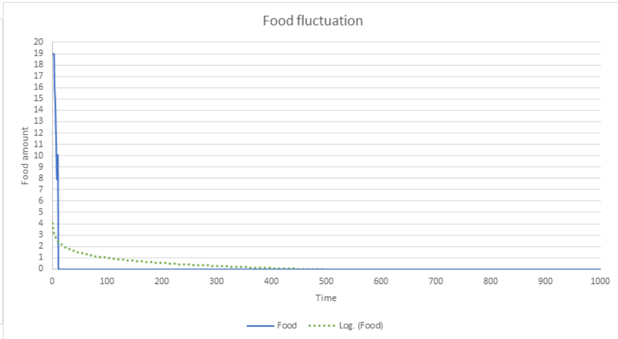


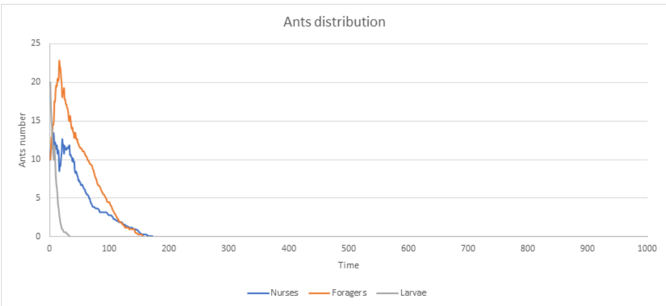
Simulation 6

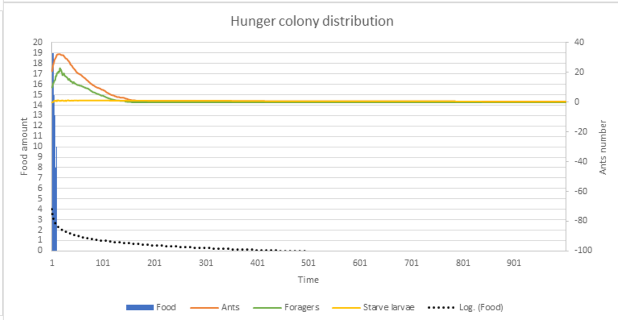
A new colony in an hostile environment where $Temperature\ =\ 5\,°C$ and $Food\ availability\ =\ 0.5$.

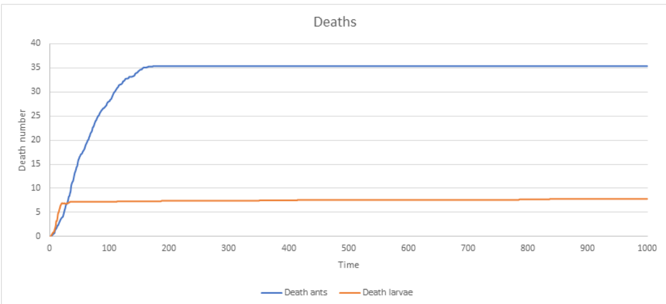
As we can imagine, in these conditions the colony dies after a while (~30 days).







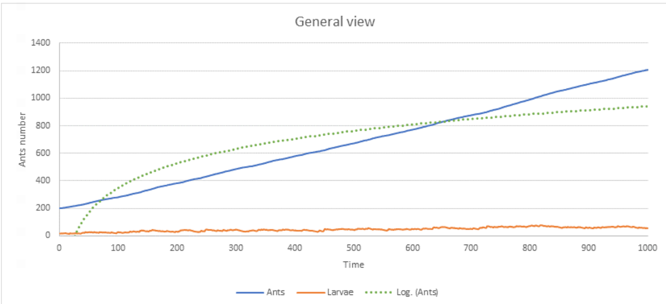


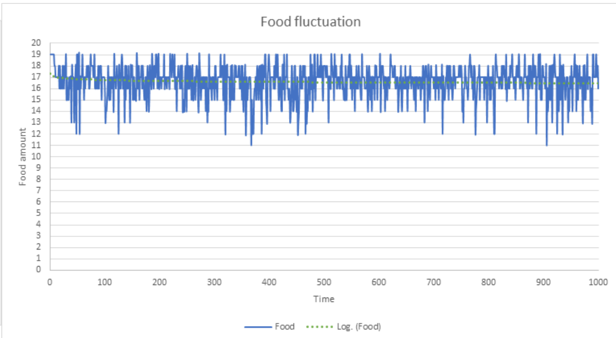


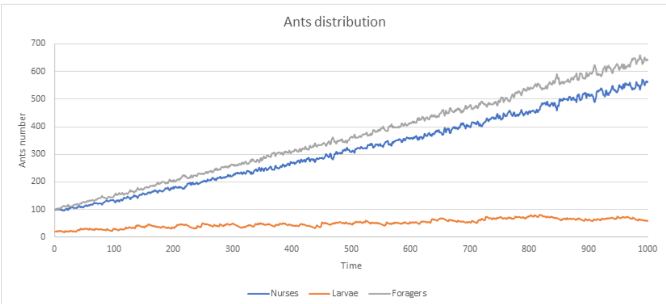
Simulation 7

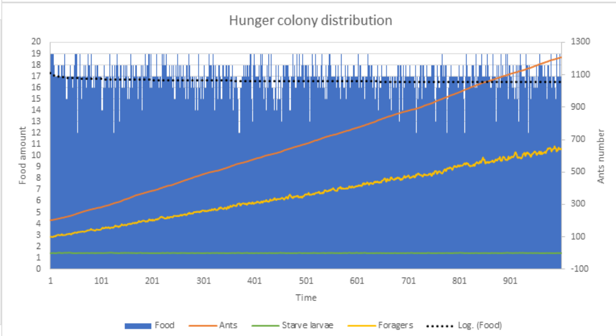
A old colony in an ideal environment $Temperature \; = \; 29\,°C$ and $Food\ availability \; = \; 1.$

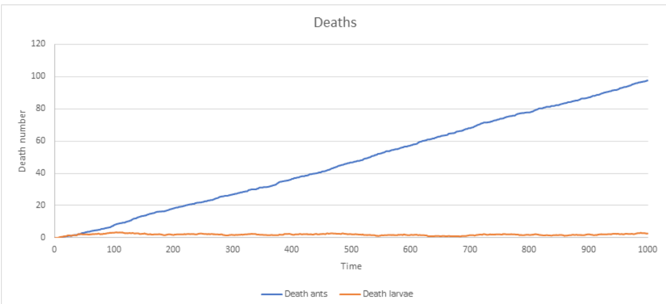
In this simulation, with the ideal conditions, the ant colony will grow, of course. Since there is a lot of food, the food storage never becomes empty, moreover remains always full (as we can see in the food fluctuation chart), and the number of nurses and foragers are more or less equally distributed (number of nurses is almost the same as the number of foragers). In the last graph we can see that the population is not starving. This scenario is similar to the small colony in the same condition (*Simulation 1*).







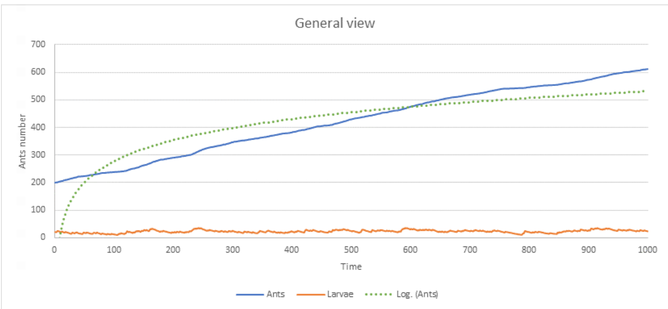


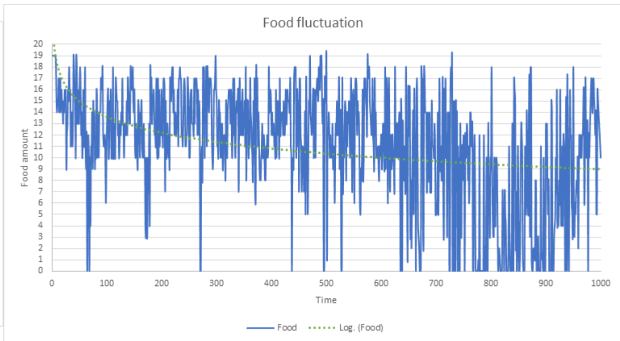


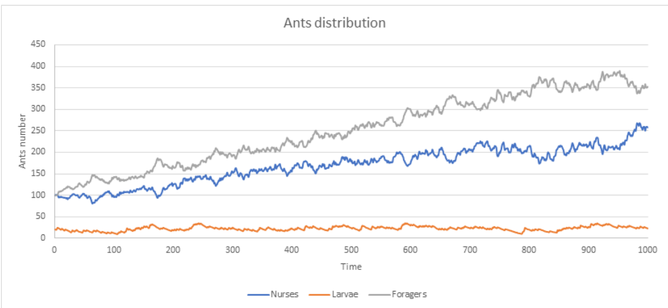
Simulation 8

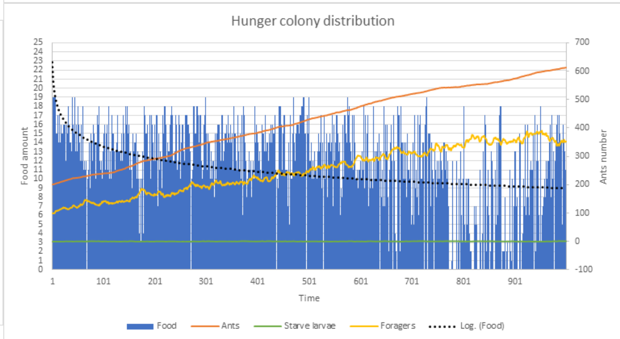
A old colony in an environment where $Temperature = 29\,°C$ and $Food\ availability = 0.5$.

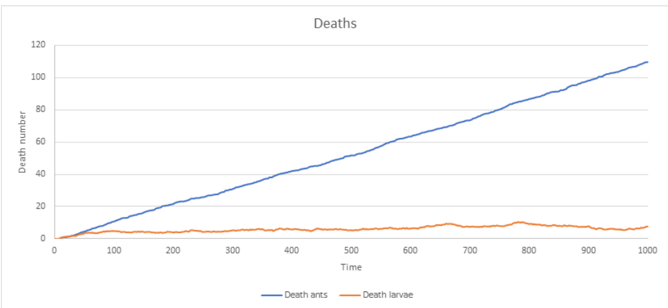
Respect to *Simulation 2*, the colony grows faster because of the number of initial workers. As soon as we move till the end (1000 time units), the food storage tends to become empty; for this reason, there is a big gap between foragers and nurses.







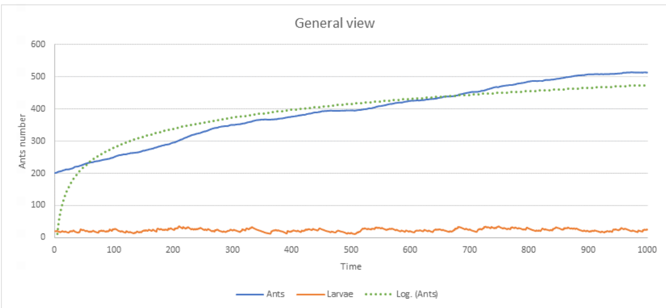


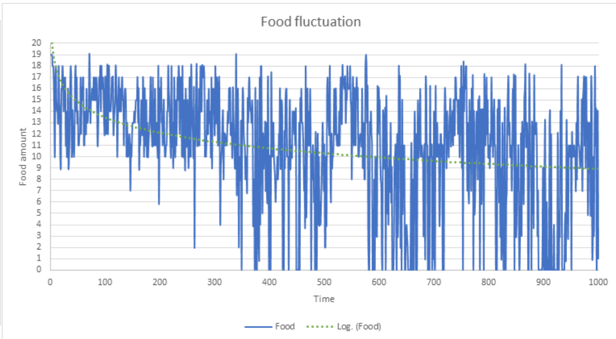


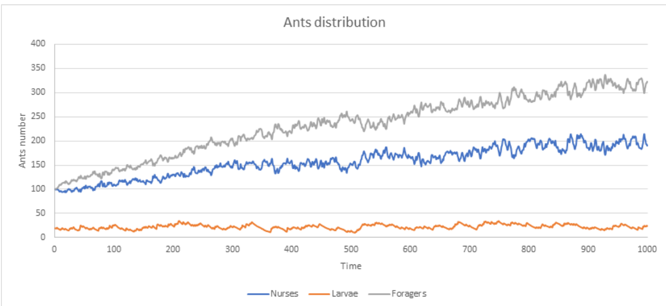
Simulation 9

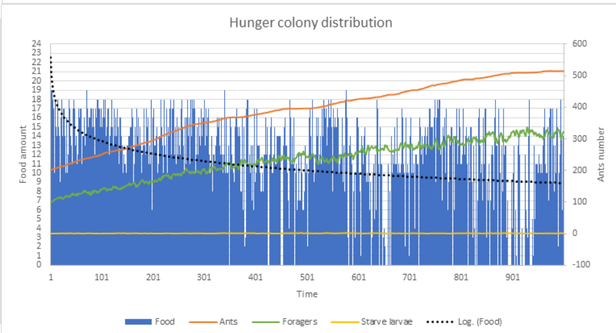
A old colony in an environment where $Temperature = 12.5\,°C$ and $Food\ availability = 1$.

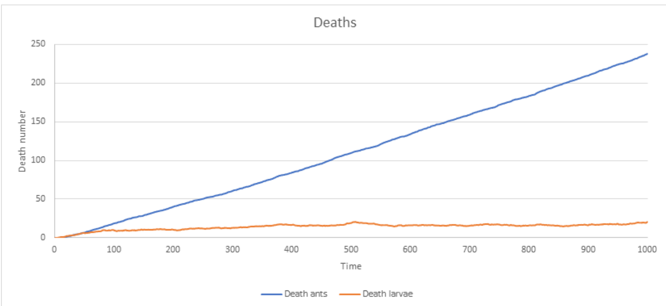
In this scenario, the ant colony will grow slowly. Respect to *Simulation 3*, in this case, the food storage rarely becomes empty. This means that an old (or bigger) colony is better able to survive than a new (or small) colony.







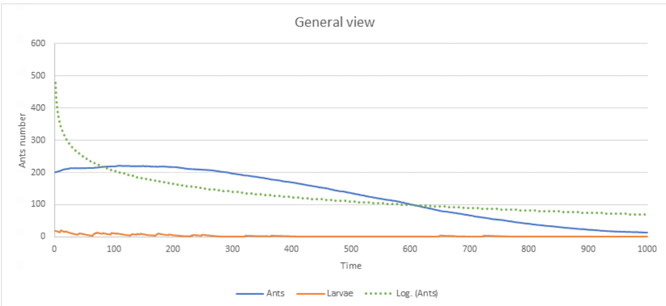


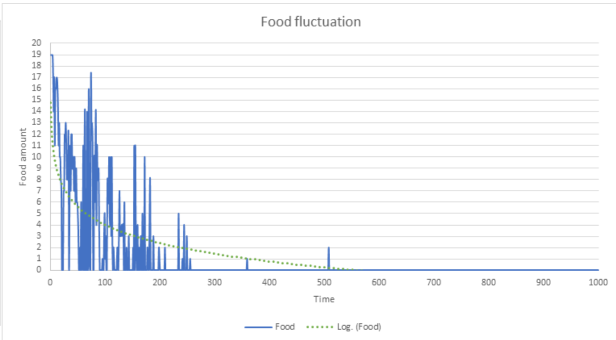


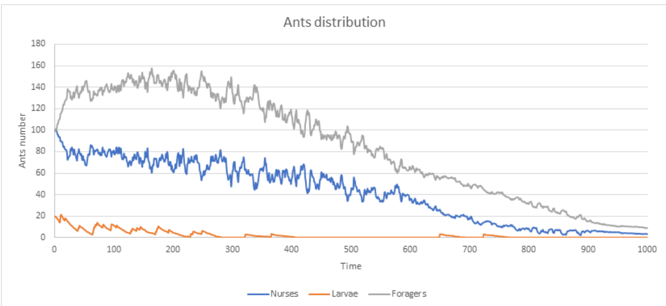
Simulation 10

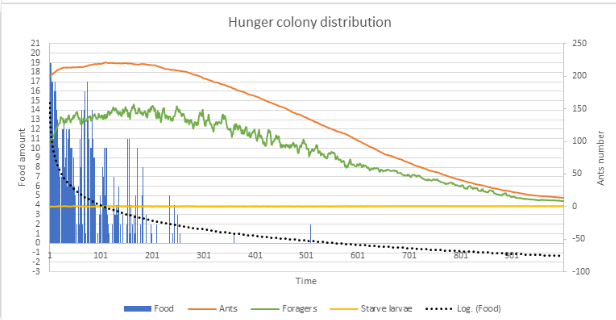
A old colony in an environment where $Temperature\ =\ 12.5\,°C$ and $Food\ availability\ =\ 0.5$.

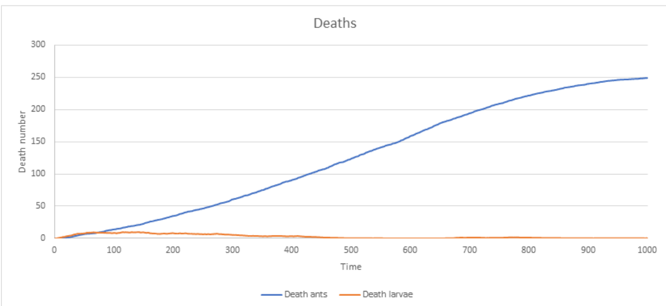
In this simulation the ant colony is slowly dying. This is because at the end the queen dies (the larvae are no more generated as we can see in the Ants Distribution graph). However, if the colony is bigger or the time under this condition is shorter, then the colony may survive.







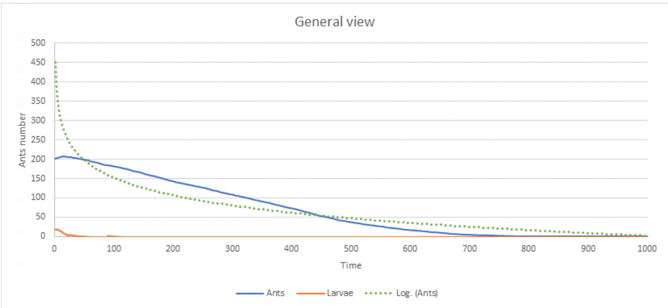


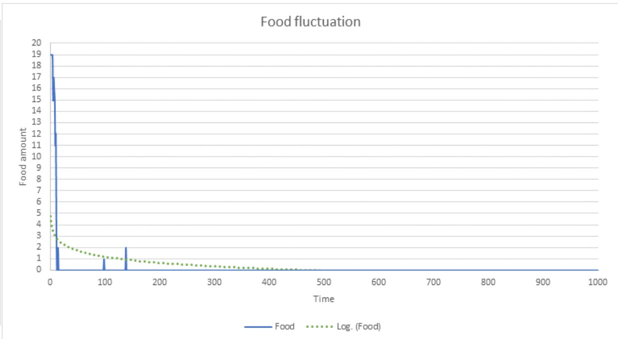


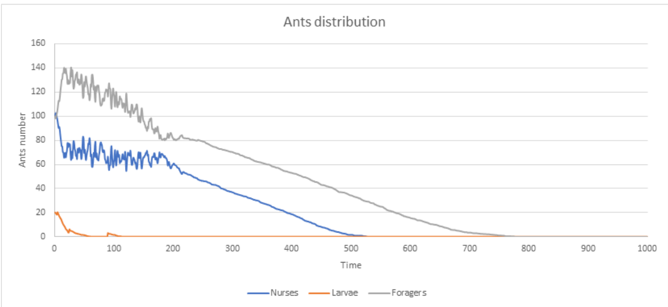
Simulation 11

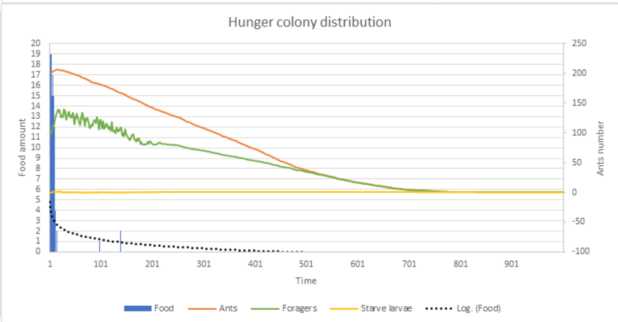
A old colony in an environment where $Temperature\ =\ 5\,°C$ and $Food\ availability\ =\ 1.$

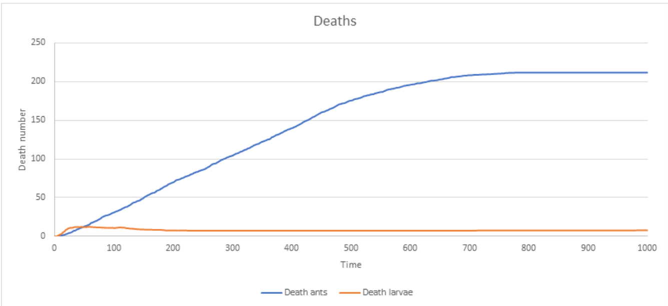
As we can imagine, in these hostile conditions, the ant colony will die not so fast. The queen dies after 200 time units (~36 days), and then the whole colony dies after 700 time units (~126 days).







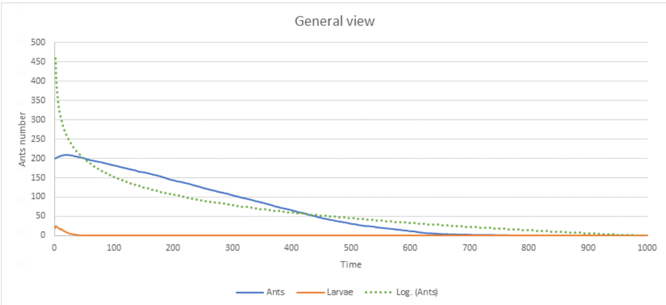


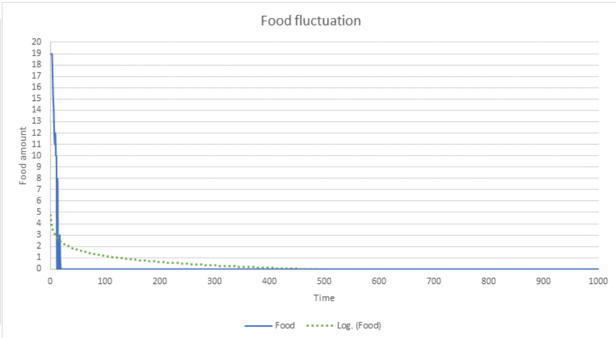


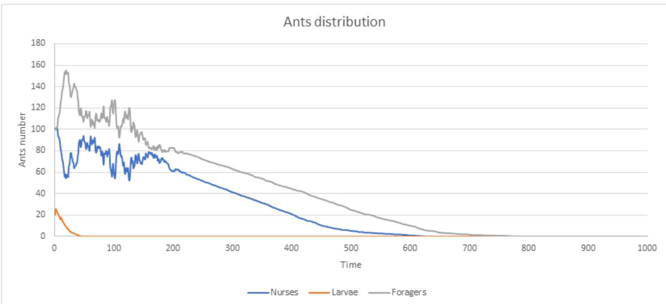
Simulation 12

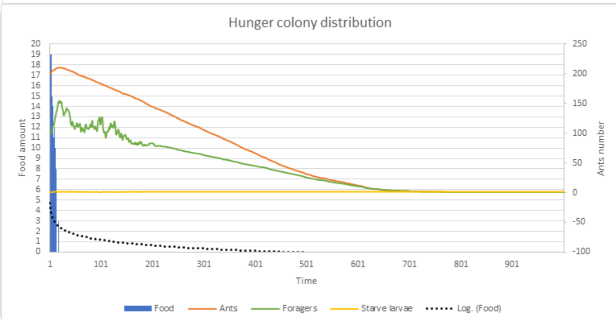
A old colony in an hostile environment where $Temperature\ =\ 5\,°C$ and $Food\ availability\ =\ 0.5$.

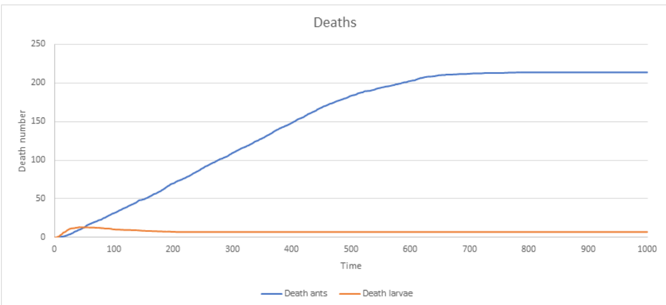
As we can imagine, in these hostile conditions, the ant colony dies quickly: after 100 time units the queen dies (~18 days), and after that all the ants in the colony (in around 500 time units, or ~90 days).





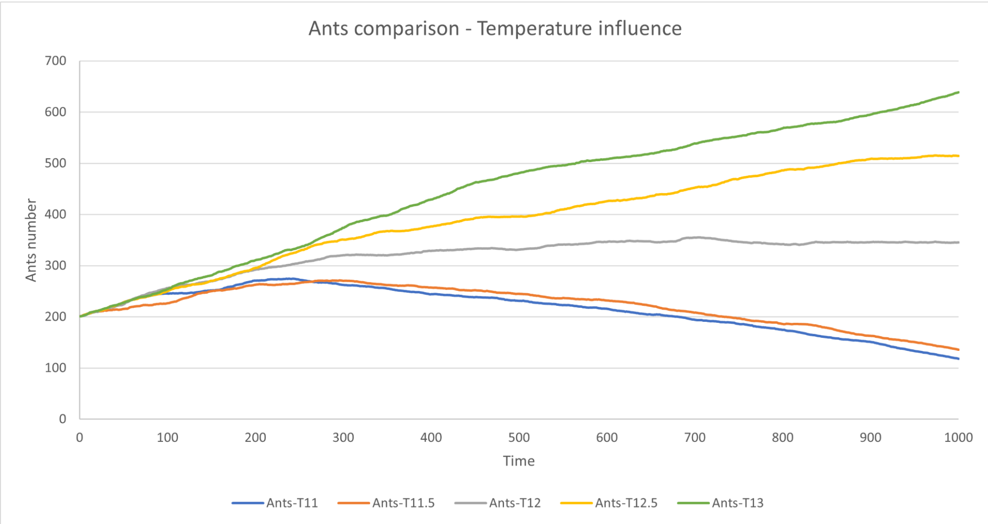






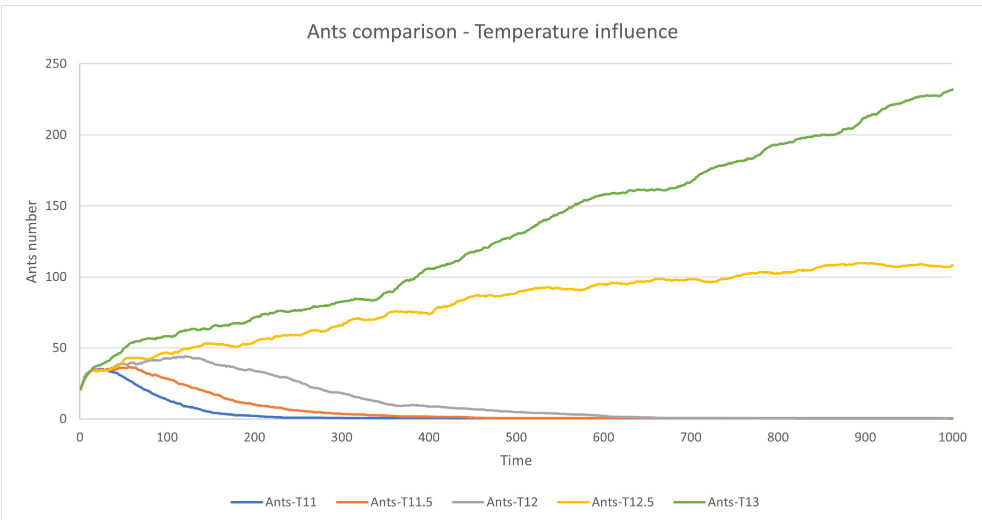
Other simulations

We can investigate more on what happens in an old colony when the temperature varies from 11 °C to 13 °C and food availability is 1.



We can observe that as soon as the temperature overcomes 12 °C the ant colony starts growing; at 12 °C the colony remains stationary and below this temperature, the colony dies.

While in the new colony, we have this graph:



Essentially, the small colony, in order to survive, requires a temperature 0.5 °C greater than the older one.

Conclusion

By changing the temperature and food availability, the model revealed the impact on the ant colony.

Increasing the temperature can boost the colony speed, because it will speed up the workers, the queen reproduction, the development speed of larvae… However, moving far away from the ideal temperature (increasing or decreasing the temperature) will cause the degradation of the colony, because the metabolism will increase as well as the activities' speed of the ants decrease. Moreover the ant colony in an hostile environment will use more food than another in a moderate environment.

In an environment with the same conditions, a small colony will be disadvantaged over a bigger one. The scarce resources will increase colonies' risk for dying out. Nevertheless, the rich food sources could protect ant colonies from food shortage and starvation.

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