Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Lecture with Computer Exercises:
Modelling and Simulating Social Systems with MATLAB

Project Report

Optimize Network Productivity by Simulating Ant Behaviour

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Contents

1 Abstract

The amount of people transported by train in Switzerland has been constantly rising in the last years. This growth brings many questions to the SBB, the largest train company in Switzerland. [8] In this paper we discuss the approach of maximizing the amount of people transported in the Swiss rail network. In an optimised scenario trains would be able to fill their capacity and more people could be transported with the same resources. This increase of efficiency would help with counteracting the pressure on the rail network. We will approach this problem with a model, which is inspired by the path finding of ant colonies. Ants have been found to be very efficient at finding paths, which lead to food sources. Those paths are optimised in terms of travel time to the source and the quality of the food.

2 Individual contributions

The paper is an team effort of Joël Mathys and Marc Rauch. There was no strict division of the work, but both of us had a focus on a certain part of the paper.

- Joël Mathys: Simulation, visualisation, graph generation, writing of report
- Marc Rauch: Behaviour of single ants, writing of report

3 Introduction and Motivations

The amount of people who use the Swiss rail network has risen by over 900% in the last 100 years. However the number of train stations and the total distance covered by rails have only seen a growth of less then 20% [8]. Therefore the efficiency, of transporting those customers has become more important.

In this paper we describe the efficiency as passengers transported per time. The goal is to maximize this efficiency and transport as many passengers as possible in a given time period. For this optimization the resources should only be redistributed, but no additional trains or stations have to be added to the system. We assume, that the most efficient way to transport these people is a compromise between distance to the destination and the size of the target city. If a train connection covers a long distance, then the destination city has to be large, so that enough passengers have the desire to use this connection. If the distance is short, and the demand for the connection is lower, it is still worthwhile to allocate some resources to that connection. Ants have a similar goal when searching for a new food source. They have to find a compromise between distance to a source and the quality of the provided food. Many studies show, that the method used by ants to find this optimum is very efficient. In fact they are so competent, that over the last 20 years lots of research was done in solving problems with the inspiration from ants. These so called ant colony optimization (ACO) algorithms are mainly used in solving hard problems, which can not be efficiently solved. Through the research many promising algorithms have been found [2]. For the rest of this paper we are going to explore the following questions:

- How can the productivity in a network with multiple colonies be maximised?
- What are the results when applied on the Swiss rail network?

We investigate those questions with the help of an ACO similar approach. The difference to an conventional ACO being, that we do not try to find an efficient algorithm to the problem, but are more interested in the social behaviour of the ants. The analogy between the ant model and the rail system will be described In chapter 4.3. The productivity in the ant network is defined as the amount of food, that is brought back to the colonies per time. We are looking to investigating the following parameters:

1. The population sizes do not change.
2. The ants are free to change colonies globally.
3. The ants can only change colonies locally.

In the end we compare the resulting efficiency of each of those strategies.

We expect to see an increase in productivity with both the local and global reallocation of ants. We suspect, that the effectiveness of the the two strategies strongly depend on the used graph.

4 Description of the Model

4.1 Single ant behaviour

The model is based on research on the ant Lasius niger, in the book ”Self-organization in biological systems” [1]. This paper describes the process of trail formation in ants. This phenomenon can easily be observed in the wild, by placing some sugar solution. After a short while the food will be discovered and shortly after, the number of ants at the food source will increase rapidly, until eventually it stabilizes and a well established trail of ants can be observed from the nest to the sugar. To study this behaviour, several experiments have been conducted on a colony of Lasius niger. The research was done under Laboratory conditions, so that the terrain could be controlled and therefore the experiments are repeatable. The terrain was constructed in such a way, that there was one path leading away from the colony, which then split into two paths with a food source at the end of both paths. The length, as well as the quality of the food sources could be controlled. Then the behaviour of the ants was observed and formulated as a mathematical model.

4.1.1 Trail laying

It was found, that the ants would place chemicals, so called pheromones, which motivates other ants to follow the laid path. When an ant finds a food source it will lay pheromones on the way back to the nest and on the following trips to the source. This acts as a positive feedback for the other ants, which are likely to follow that trail. Trail laying is only observed by ants, who found food. The intensity of the laid trails is dependant on the quality of the found food. The better the food source, the more pheromones will be deposited. The frequency of laying pheromones is also reduced based on the current direction of the ant. If the ant is walking in a trajectory with a bad angle to the direct route to the nest less pheromones will be placed. The placed chemicals also evaporate over time. They undergo an exponential decay given by formula 1.

$$\frac{dC}{dt} = -\frac{1}{l}C \tag{1}$$

where l is the lifetime of the pheromones and C the concentration.

4.1.2 Binary choices

In the experiment there was a choice the ants had to make, when the path split into two and they have to decide, whether to go left or right. This decision is made based on the concentration of pheromones on each branch. So that the branch with a higher concentration of pheromones on it has a better chance of being chosen. For that decision a formula for the probability of choosing one of the two branches was found.

$$P_L = \frac{(k + C_L)^n}{(k + C_L)^n + (k + C_R)^n} \; and \; P_R = 1 - P_L \tag{2}$$

n is the non-linearity factor. with a high value of n a branch with little more pheromones then the other will be strongly favoured. With experiments it is approximately found that $n = 2$. k stands for the likelihood of the ant taking a path with no pheromones on it. P is the probability of choosing the left or right path and C the concentration of pheromones on each path.

4.1.3 U-Turns

It is often observed, that ants on a trail make an U-turn, return to the last branch point and follow the other path. After an U-turn the ant does not lay a trail, until it has gone back to the branch and follows the new path. There are two causes of this behaviour. If the amount of pheromones on the trail is low the ant may turn around. The second reason is direction based. If the orientation to the target is not good the probability of an U-turn is high. This probability can be modelled by equation 3. [1]

$$P = \frac{P_0}{1 + \alpha C} \tag{3}$$

P_0 stands for the probability of an direction based U-turn. α describes the importance of the pheromone based U-turn.

4.2 Extensions

For our project we could not use the model as given in the paper, So the model was changed in some aspects to ease the implementation and add additional functionality. Because the goal of this paper is to model more complicated networks then the one with only one binary decision, formula 2 has to be adapted to support a choice between more than just two paths.

$$P_i = \frac{(k + C_i)^n}{\sum_{j=1}^{nr} (k + C_j)^n} \tag{4}$$

nr describes the number of adjacent edges on the node.

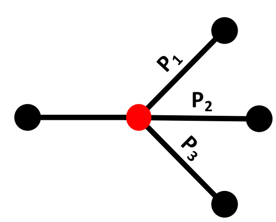

Figure 1: Decision of an ant approaching a traffic node of degree 4 (represented in red) from the left hand side, with the probabilities P_1 to P_3 of the next edge.

Notice, that although the graph is not directed the decision of taking the same edge back to where the ant came from is not allowed. This edge is not part of the decision set. Because we represent the terrain on which the ants move by a graph, the implementation of direction based turns is very difficult. Therefore we set $P_0 = 1$ in equation 3 and are left with the pheromone based U-turn equation.

Also we need the possibility of multiple colonies in the graph. Doing so the colonies and the food source are merged to one type of node. Every colony sees all nodes, except for their home node as food source. This has to be done, to simulate a not centralized network like the Swiss train system, where there are more then one train station.

Since the topic of this paper is the investigation of global and local reallocation in a graph we have to add that functionality to our model. Local redistribution happens, when an ant reaches a food source. With a probability depending on the difference in the productivity per ant of both colonies the ant will be reallocated to the new colony. In contrary to the local approach, the ants do not have to walk to their new home in the global solution. Instead the reallocation happens, when the ant arrives at its own nest. If the productivity of that ant is lower, then the global average productivity, The ant can be transferred to a new colony.

4.3 Relation to the Swiss rail network

The Swiss rail network should be described with the help of this model. The network is given as a graph, which connects all train station to each other. The following analogies between the ant and the train model have been made:

- The train stations are represented by sources, as well as colonies.
- The trains are represented by ants.
- The travelling passengers are represented by food.

In the new model the train stations are the starting point and the destination of all trains. Therefore there is no more distinction between colonies and sources, since colonies are sources for ants of a different colony. When a train reaches its destination, it gets filled up with people. With every arrival of trains at a station the amount of food at this station decreases, as there are less passengers waiting to be transported. This devaluation of the stations is counteracted by a regeneration rate, which is proportional to the popularity of the station. A popular station has a high regeneration rate, as there are lots of new potential passengers arriving in a given time step. With those analogies the productivity, which was defined as food carried to each colony per time is defined as people transported to each station per time. This is exactly the quantity, which we want to optimize.

5 Implementation

For the implementation of the model we used MATLAB. In order to keep the code readable as the project grows, we split the main functionalities into different files.

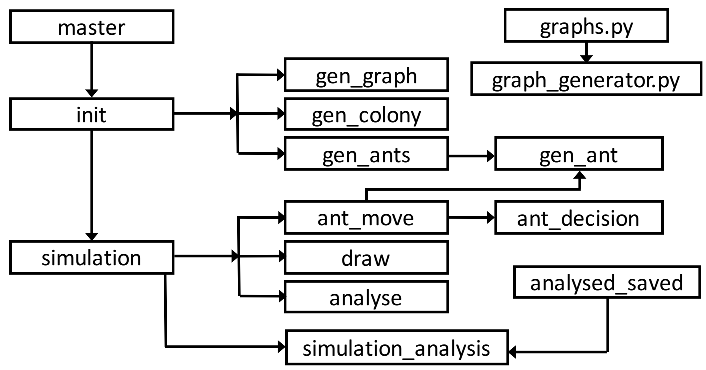

Figure 2: Dependencies of the different MATLAB scripts. The arrows indicate calls of functions

The only executable file is *init.m*. It defines all global variables like the mean lifetime of pheromones, the number of ants and the parameters of the simulation. All the objects, which are important to the simulation are also created in this file. This is done by a call of *gen_sources*, *gen_colonies*, *gen_graph* and *gen_ants*. The generated structures are then fed into the *simulation* script, where a simulation loop is implemented and the position of the ants is updated by *ant_move* for the specified number of iterations. The relevant data is then stored and processed by the *analyze* function. In the end the result of the analysis is visualized by the *draw* function.

5.1 Environment

The environment of the model is mainly defined by the graph on which the simulation runs. The graph itself is generated by the python script *graph_generator*. It constructs the nodes and weighted edges of the graph. Furthermore it determines the different types of nodes for the network. The edges are chosen in a way, such that the probability of the edge being in the graph decreases exponentially with the distance of the edge. This implies, that nodes, which are located closer together have a higher probability to form a connection. This results in a graph which is closer to a real network (such as the rail network).

In the *init* script, the graph gets initialized. There are two different types of nodes in the network. The source nodes and traffic nodes. Each source node is the start of a colony. However the members of a colony do not see their own starting node as a food source (they can not get their food from their starting node). But the starting nodes of other colonies are seen as food sources. Afterwards the ants are generated and distributed equally among the colonies.

Finally the global parameters are set for the simulation. The parameters were chosen by us empirically. Each colony gets 200 ants, which is enough to build sophisticated paths and is computationally feasible. The mean live time of pheromones is set to 30, this ensures that ants can explore most of the graph and the pheromones are still there to enforce the probability when they encounter the path a second time. The food limit per source was set to 200 as well to match the number of ants in the system. However the sources differ in their food regeneration rate. The simulation itself runs 1000 time steps, where each ant moves a distance of 1 per time step. This has proven to be enough time to stabilize the system.

5.1.1 Rail network

For the second part of our goal, to maximize the productivity in the Swiss rail network we have to be able to utilize the graph of this network. We got the data to construct this graph from a graphic outlining all the far distance connection of the SBB [6]. We chose to select the colonies to be the train stations with the most visitors per day [4]. The weight of the edges is not given by the physical distance, but by the time it takes to travel from one node to the other by a direct connection (based on the SBB time table)[5]. To draw the graph we used the Swiss coordinate system and normalized it, so that Geneva is the origin. In the drawn version the edges represent geographical distance.

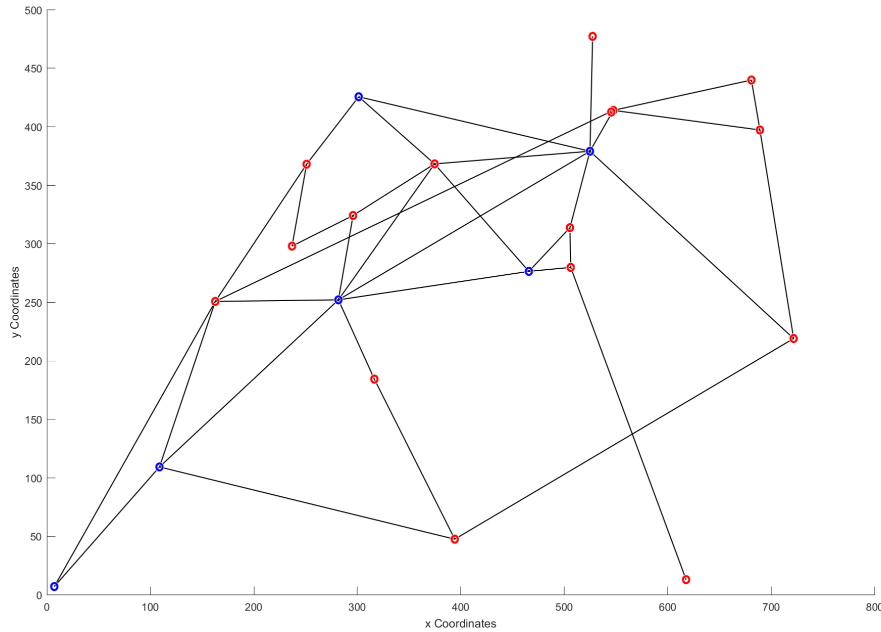

Figure 3: Graphic of the Swiss Rail Graph. The blue circles indicate sources (and colonies), the red circles represent traffic nodes. The units of the x- and y-axis are from the Swiss coordinate system

5.2 Ant behaviour

The movement and decision of the ants is based on the model described in chapter 4. The script responsible for the update of the position at every time step is called *ant_move*. There the next position of the ant on the graph is determined. The ant has a variable to store the progress on the edge. As soon, as this progress reaches the weight of the edge a node has been reached. If the node is a food source, different from the starting point the ant will bring some of the food back to the colony. By doing so the food source will experience a devaluation. The ant follows exactly the same path back to its nest, that it took on the way to the source. On the way back it will deposit pheromones, with an intensity depending on the quality of the found food source. The pheromones are saved in a variable on the edges. Each colony has their own pheromones, the decision of the ant is not affected by the trail laying of the ants from other colonies. If the found node is a traffic node, then the ant has to make a decision between the adjacent paths. This decision happens in the *ant_decision* function. As seen in formula 4 the decision depends on the concentration of pheromones on the path. This concentration is calculated by

$$c = \frac{pheromones}{weight} \tag{5}$$

Where weight is the length of an edge. The ant is free to choose from all the edges on the node, except for the one it used to get there. However this freedom presents another problematic. Because the ant is free to choose between all the edges it is allowed to walk in circles. Those cycles would then be reinforced by the trail laying on the way back. To solve this we still allow the ants to walk in circles, but when they do the circle will be removed from the path vector, which is used to find the way back to the nest. The U-turns are implemented exactly as described in equation 3. At every time step this probability is calculated. With this probability a U-turn happens and the ant walks back to the last visited node.

5.3 Ant reallocation

As described in the introduction chapter, the goal is to maximise the productivity of the network by reallocating ants to other colonies. In the following the implementation of the two strategies is explained.

5.3.1 Local reallocation

Remember from chapter 3, that the productivity of an colony is calculated by the total food, brought back to the colony per time per ant. Hence the local reallocation tries to improve the overall productivity by redistributing ants from less productive towards more productive colonies. Now when the ant finds a colony it has a probability of staying there and work for them (Formula 6)

$$P = max(0, \frac{Prod_{ant} - Prod_{new}}{Prod_{ant} + Prod_{new}}) \tag{6}$$

P describes the probability of staying at the new colony, $Prod_{ant}$ stands for the productivity of the arriving ant and $Prod_{new}$ for the productivity of the ants at the new colony. The probability is low, when there is no significant difference between the productivities of the colonies and high if a colony outperforms the other.

5.3.2 Global reallocation

In contrary to the local approach, the ants do not have to walk to their new home in the global solution. Instead the reallocation happens, when the ant arrives at its own nest. If the productivity of that ant is lower, then the global average productivity, the ant can be transferred to a new colony. To determine whether the ant is moved a modification to equation 6 is made, where $prod_{new}$ is replaced by the global average productivity. If moved the target colony is then determined by chance out of all the colonies accordingly to their productivity, which perform better then average. If an ant is transferred, it happens instantly. At the next time step the ant will be part of the new colony.

6 Simulation Results and Discussion

6.1 Generated graphs

To answer the first part of the research question, which is to compare the effects of no, global and local reallocation. For the simulation we chose to simulate 1000 time steps and use 30 simulations for each strategy. The regeneration rate of the sources is chosen randomly with the best rate being 10 times higher then the lowest. This is about in the range, that we found by analysing the amount of passengers at a train station per day. The number of colonies is chosen randomly between two and ten. Each of those colonies has 200 ants. We generated 40 different graphs and run our model on all of them. The simulation on many different graphs, with different regeneration rates and different amount of colonies should give us the ability to make a statistical statement about our results.

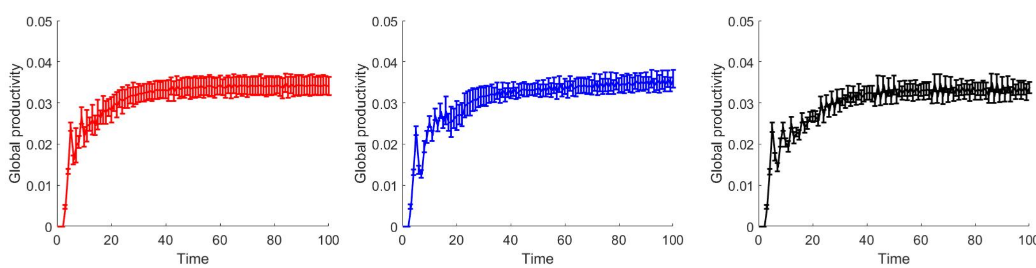

Figure 4: Plot of the global productivity of one graph using the above described parameters. The red line uses global reallocation, blue local and black does not use any reallocation.

The results of the simulations for each of the graphs looks very similar. The total productivity, which we wanted to optimize is very similar for all of the three strategies, and with the error margin being quite high it is not possible to draw the conclusion, that one of the strategies is better then the other ones.

6.1.1 Interpretation

By looking at the amount of pheromones on the edges we assume the scenario, that every colony exploits a source, which is not used by the other colonies. This sign of cooperation shows, that the sources run low quickly and therefore the competition for a source is not worth. All colonies use this strategy and the sources are emptied quickly. Hence the reallocation of ants to a new colony does not have a great impact on the productivity, since the sources can not be exploited any more.

We suspect, that the results could be changed, with a modification of the parameters, like the mean life time of the pheromones, the number of ants per colony and most importantly the regeneration rate of the sources. The explanation, which is shown above would indicate, that the regeneration rate of the sources is low in comparison to the devaluation caused by the ants.

6.2 SBB Network

To answer the second question we ran our model on the SBB graph, We chose 2000 time steps, 5 train stations (the largest one in the SBB network) and 30 simulations for each strategy. The regeneration rate of the stations is chosen to match the total number of visitors per day of the stations. The results of the productivity have a strong similarity to the ones found in 6.1. Again the error margin is very high and no conclusive results, supporting any of the strategies can be found. However when plotting the edges of the graph weighted by the amount of pheromones on them we can recreate the path taken by the ants.

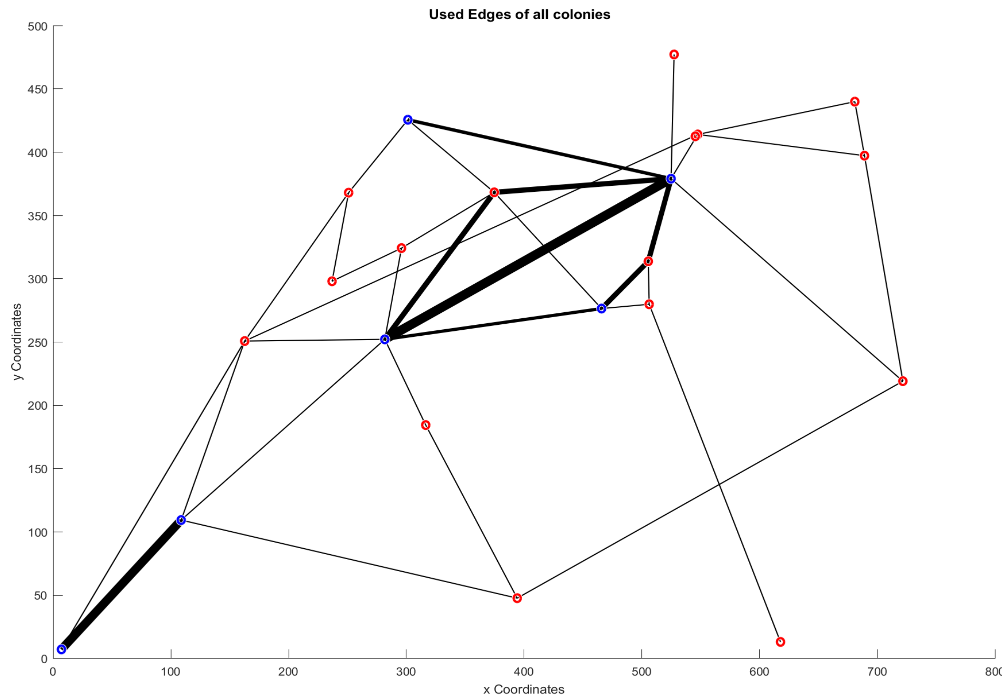

Figure 5: Graphic of the Swiss rail graph. The thickness of the edges represent the pheromone concentration. The units of the x- and y-axis are from the Swiss coordinate system

6.2.1 Interpretation

We conclude, that for the parameters chosen the way, in which the trains are reallocated does not cause a statistically significant change in the productivity. However it is possible to identify the important connections to maximize the productivity. Since all of the strategies chose the same edges we assume, that those connections are essential for a high productivity in the network

7 Summary and Outlook

The main goal of this project was to simulate the behaviour of multiple ant colonies interacting in a network and then measure the productivity. Furthermore once we wanted to apply two strategies to optimize the productivity in the network by reallocating ants. The model was applied to generated graphs to produce a more network-independent conclusion and to the real world graph of the Swiss Railroad network.

Simulating the behaviour of multiple colonies leads to a stable equilibrium for the global production. Applying the two different strategies to increase the result also leads to a stable global production, but it only differs slightly from the base result. When analysing the results over multiple simulations the difference is quite small and no significant improvement can be found when applying the redistribution strategies.

When the model is applied to the Swiss Rail Graph it yields similar results for all three ant population strategies regarding the global productivity of the network. The ants seem to prefer to exploit sources that are not shared with other colonies. This requires implicit collaboration between the ants and seems to be the desired state among all three strategies and therefore they only differ slightly. When we focus on the preferred edges of the ant colonies, they resemble the routes with high traffic volume in the real rail network.

There are some points to continue with this project. As seen in the simulation results, the ants are unable to make use of the redistribution and exploit sources with higher quality (higher regeneration rate). It would be interesting to see if one could make use of the redistribution by using another quality measure to further differentiate the sources from each other. This could be done by setting an individual food limit or adding a separate quality measurement. Another aspect than one could further investigate is to add sources that are no colonies them self. This could resemble destinations that are desirable to reach, but should not get additional resources (as trains).

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