The environmental and behavioural impact upon the population growth

Group X-ray
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Abstract

This paper discusses agent-based computer simulations of an environment including prey and predators, foxes and rabbits, to examine the result of additional behavioural effects on the two populations. The simulations observed consist of three different environments; each differing by the behaviour of the agents. In the most basic model, the agents wander stochastically while only the predators are dependent on energy. Two expansions of the basic model were implemented; one in which an energy component was added to the prey, while the other introduces flocking behaviour to the prey and hunting behaviour to the predators. These models were used to examine their effect on the population sizes and distributions. It was found that implementing an energy-based approach has a positive effect on the stability of the population distribution over time, whilst the addition of flocking and hunting behaviour increases competitivity within the model, leading to early extinction and high variation in the spread of the data.

1 Introduction

Collective dynamics is the study of behavioural patterns and interactions within and between larger groups of individuals. Individuals share knowledge and make decisions on a local level, which may affect the global behaviour and characteristics of the population. Meanwhile, there are also systems that apply collective intelligence to perform competitive behaviour, like a predator-prey system. A model that describes a predator-prey system, is the renowned Lotka–Volterra model. (Forrest, 2011) This is, however, a mathematical model that is unable to present detailed information regarding the influence of environmental and behavioural effects on the interaction between the populations (i.e. predator vs. prey). The research described in this paper aims to solve this problem through the use of visual simulations that show the interactions between two populations of agents. Several studies have already been carried out on the addition of extra behavioural and environmental factors. Abrams and Matsuda (2004) Venturino (1994) The following questions were answered:

- Research Question 1: How are the population size and distribution affected if both predator and prey become energy-dependent?
- Research Question 2: How do flocking and active hunting behavior of the preys and predators respectively affect the population size and distribution compared to a naive model that implements random wandering?

Analysis was carried out by observing the behaviour of the agents over three different simulated models. The agents used were rabbits (prey), foxes (predator) and grass (energy resource). A base scenario was implemented in which prey and predator only interacted if they arrived at the same position through random movement, with foxes eating the rabbits to replenish their energy, otherwise they would die. The other two scenarios served as simulations for each separate research question, having the energy concept and hunting/flocking behaviour added respectively. A comparative study

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was carried out on the distribution and population size over time, using statistical tests and graphical plots. This paper goes deeper into how the interaction between the rabbits and foxes was implemented, and how different energy-dependency in both populations as well as flocking and active hunting affect the collective behaviour.

2 Methodology

The agents implemented during this research belong to three classes; Rabbit, Fox, and Grass. All agents use only local information, with local sensing and communication. The design of the agents discussed in this paper is behaviour-based as suggested by (Oyekan and Hu, 2014). Two main scenarios were implemented and one basic scenario to which the main scenarios were later compared. The basic scenario includes the Rabbit and Fox agent classes. The basic model is initialised with 20 agents from each class. For each scenario, different parameters were selected and tuned after a trial and error method through multiple runs for each simulation, as can be seen in Table 1. The selected parameters were the ones that provided the best results, longest simulation run time with both populations avoiding extinction. In this basic model, the rabbit class is wandering around. Every five seconds, rabbits reproduce using a probability-based method that compares the set reproduction probability of 0.5 to a value that is sampled from a uniform distribution between 0 and 1. If the sampled value is lower than a rabbit's reproduction probability, it will not reproduce and vice versa. Rabbits die only when they are eaten by an agent of the Fox class. The Fox class also implements wandering. Random wandering was selected as a movement mechanism because the basic model implements a naive approach where no active hunting or survival behaviour is applied. Foxes start with a starting energy of 10. Their decay rate is one energy unit per second. When the energy of a fox is lower than 10 it is considered hungry. While being hungry, the fox is able to eat agents of class Rabbit. If the fox is hungry and it is at the same location as a rabbit, it eats the rabbit. After eating a rabbit, the energy of the eating fox is replenished by 0.5 energy units. In addition to the energy replenishment, for every eaten rabbit, the fox has a probability-based reproduction function that is dependent on its level of energy. The reproduction probability for agents of class Fox is probability-based and is dependent on the agent's energy level, using a uniform probability. This means that the foxes have higher chances of reproduction when their energy level is low, so the purpose is that of a survival mechanism to keep the population dynamic alive. This probability function was chosen for the reason that it provides more balance in the models and prevents an exponential growth in the predators due to high reproduction chances for every newly spawned fox. Once the energy level of the fox reaches zero, the fox dies. Figure 1 contains the finite state machine of this process.

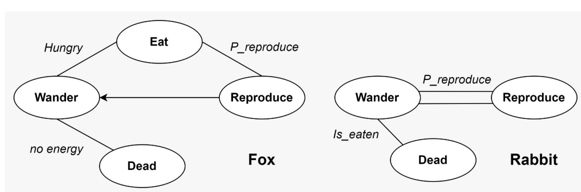

Figure 1: Finite state machine of the basic model

The first extension of the basic model is an implementation of an energy element for the prey, the Rabbit class. In order to implement the energy element for the rabbits a new class was introduced, a Grass class. The grass is initialised in 10 locations in the simulation. Each grass agent can be eaten by a rabbit, after being eaten it is not edible for five seconds because it has to regrow. After that, the grass grows back, becomes green again, and is edible again for the rabbit. In a similar method to the foxes and inspired by nature, the rabbits eat when and only if they are hungry, which means they have low levels of energy. After eating grass the rabbit receives one energy unit, while they lose 0.5 energy unit per time step. This implementation is motivated by nature, as rabbits need to consume grass in order to maintain a certain level of energy. See Figure 2. The second extension of the basic model is an implementation of two nature-inspired behaviours. The first is flocking behaviour for the prey, the Rabbit class. In nature, flocking behaviour has been connected to its predator evasion (Beaver and Malikopoulos, 2021). The implementation of the flocking behaviour is based on three main elements; alignment, cohesion, and separation (Figure 3).

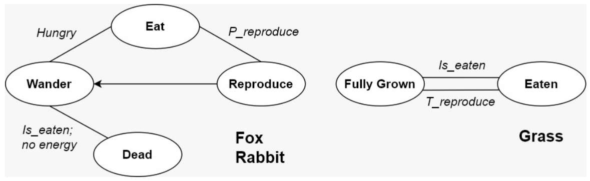

Figure 2: Finite State machine of the Energy model

Each of these elements is an individual behaviour consisting of vector contributions to the adjustments of the agent's velocity vector. Each action creates a steering force that updates a given agent's velocity. The three actions all depend on neighbouring agents. See Figure 2. Alignment is responsible for the steering in the average direction of neighbouring agents with the average velocity of its neighbours. The cohesion is responsible for steering towards the average position and being a part of the flock, and this is done using the average position of neighbours and cohesion force. The separation prevents collision of the agents and helps an agent avoid being too close to neighbouring agents. This is done by using the average distance to neighbours. Another component of the flocking is random steering, this adds a stochastic element to the movement of the agents. Different functions are used in these implementations to calculate forces using velocity vector, radius to determine neighbours, and weights for each action to calculate the total force.

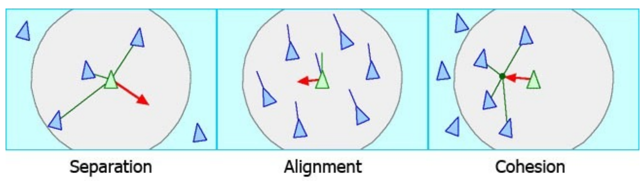

Figure 3: The main three steering forces in flocking (Price, 2020)

The alignment (1), separation(2), and cohesion (3) formulas.

$$v_N = \frac{1}{|N|} \sum_{i \epsilon N} v_i \qquad (1)$$

$$a = v_N - v_{boid}$$

$$s = \frac{1}{|N|} \sum_{i \epsilon N} (x_{boid} - x_i) \quad (2)$$

$$f_{total} = \frac{\alpha s + \beta c + \gamma a + \varepsilon w}{M_{boid}} \qquad (3)$$

$$V_{boid} = V_{boid} + f_{total}$$

$$X_{boid} = X_{boid} + V_{boid} \cdot \Delta t$$

The second behaviour implemented in this simulation is a chasing ability to the Fox class agents. This behaviour improves the rabbit eating efficiency for the agents of class Fox, and by that, they can gain energy more efficiently. In this simulation, the rabbits are flocking which helps them evade more easily from the predators. Therefore, the foxes needed to be more efficient at hunting. The chaser ability allows the foxes to chase after agents of the Rabbit class when their energy level drops below the very hungry level, which is set on 3 energy units. Once the fox is starving and it observes a rabbit within a radius of 50, it increases its speed in the direction the prey is heading towards. As a result, the predator chases after its prey when it senses that it is hungry, as can be observed in nature. See Figure 4.

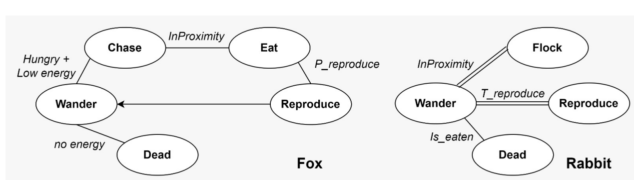

Figure 4: Finite State machine of the Flocking model

Table 1 contains an overview of all the model parameters.

Table 1: Model parameters

	basic		energy			flock	
	fox	rabbit	fox	rabbit	grass	fox	rabbit
radius	15	15	15	15	-	15	15
chasing_radius	-	-	-	-	-	50	-
min;maxVelocity	-	-	-	-	-	1;1.5 (+0.05*rabbit when chasing)	1;1.5
Initial population size	20	20	20	20	10	-	-
movement_speed	1.5	1.5	1.5	1.5	-	-	-
start_energy	10	-	5	5	-	-	-
energy_gain	0.5	-	0.5	1	-	-	-
energy_decay/s	1	-	1	0.5	-	-	-
max_energy	-	-	10	10	-	10	10
reprod_prob	1/energy	0.5	1/energy	0.5	-	1/energy	0.5
reprod_time	-	5s	-	5s	(growth) 5s	-	5s
Alignment;Separation;Cohesion	-	-	-	-	-	-	2; 4.5; 4
RandomWeight	-	-	-	-	-	-	0.5

3 Experiments

3.1 Experimental Setup

A series of experiments were conducted based on the population sizes over time. These included visual and statistical analyses for each of the models mentioned in the Methodology. Visualisation was done through the use of line and box plots, while the statistical analysis considered the means and standard deviations of the populations in each model, as well as their results of the Wilcoxon signed-rank test.

Line plots make it possible to view patterns that occur by perturbing the agents' behaviour with the implemented factors (i.e. the energy concept in both species and flocking behaviour by the prey). However, they give no clear indication of how the data is distributed. For this reason, the second part of the visual analysis was carried out using box plots. The Wilcoxon test was conducted under the assumption that the populations do not follow a normal distribution. In addition to the box plots, this test helped gain more insight into whether the two populations are significantly different, meaning that they come from distributions with differently located data.

For all parts equal, each model was run for five minutes, adding up to a total of eighteen thousand frames. The parameters in each model can be found in Table 1. The simulations were stopped if both populations had gone extinct or when one of them would grow exponentially. In the case of the latter, the simulation was terminated if the total number of agents within one of the populations passed a hundred. Results of the energy-based and flocking model were compared to that of the basic model to view changes in the population dynamics with the addition of the aforementioned behaviours.

3.2 Results

3.2.1 Visual analysis

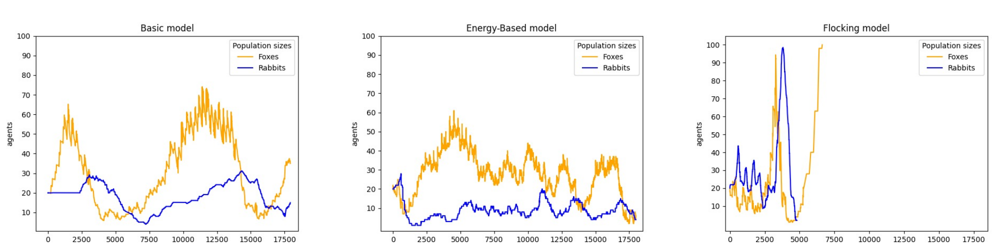

Figure 5: (a) Basic model line plot (b) Energy based model line plot (c) Flocking model line plot

Figure 5 shows the population plots of the three models, while Figure 6 contains the box plots that were used to analyze the distribution of the population for each species. The population sizes in the basic model form an oscillating pattern that has the same characteristics as the Lotka-Volterra model that was previously discussed. The populations alternate between low and high numbers of agents, meaning the number of rabbits decreases when the number of foxes increases and vice versa. The same can be said for the energy-based model, though there are some differences between the two to take note of. The first is the number of fluctuations, and the second is the range of these variations. As opposed to the basic model, which is characterised by the two overlapping graphs that seem to oscillate rather than fluctuate (i.e. at a steady pace), the energy-based model shows a pattern of shorter and smaller fluctuating variations within each population. The number of rabbits seems to be slowly decreasing, which can have the increase of foxes in combination with low energy levels as a potential cause. Compared to the first two models, the flocking model shows a significant difference, as it was terminated, due to the extinction of the foxes and exponential growth in the number of rabbits. This could be the result of a trade-off between a higher predation rate and increased mortality of both species. (Singh, 2021)

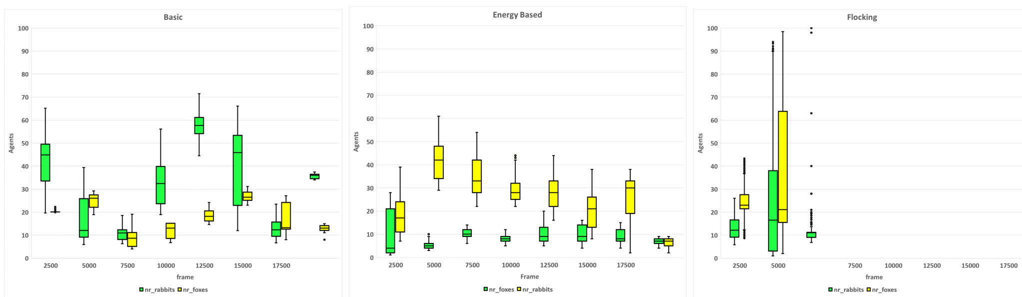

Figure 6: (a) Basic model box plot (b) Energy based model box plot (c) Flocking model box plot

The box plots in Figure 6 show the division of the populations in quantiles over intervals of 2500 frames, which give an idea of the changes in distribution over time. The line in each box represents the median of the distribution, while the whiskers show the range. The dots indicate outliers. The plot of the basic model consists of a combination of bigger and smaller spreads illustrated by the varying lengths of the boxes. For both the basic and energy-based models, the range of the foxes is considerably smaller than that of the rabbits, which is in line with the minimums and maximums that can be estimated from their previously discussed line plots. Moreover, the variation in the energy-based model is subject to little variation with a relatively consistent size of the box plots over time. On the other hand, the variation within the populations of the flocking model seem similar if one observes an individual interval, but they show a large increase in variety and range when comparing intervals. The lengths of the boxes differ greatly per interval, and as the foxes have gone extinct, the last box plot represents the distributions which contain high outliers as a consequence of the exponential growth in rabbits that were observed in the foregoing section. In terms of outliers, the flocking contains most, which could be caused by the irregular cycles in the system. Finally, the distributions over time of all three models show skewness with their medians not being centred.

3.2.2 Statistical Analysis

The purpose of conducting statistical analysis is to evaluate the performance of the different simulations. This was partially achieved by calculating the mean and standard deviation (std) from the collected raw data. The mean is calculated by using all the raw output values, which is then divided by the number of output values collected. To further understand the value of the mean, it is crucial to investigate the spread of the data by calculating the standard deviation. The mean and standard deviation are the two main parameters of a normal distribution curve. When looking at the mean values (in Table 2) for the basic simulation, the nr_rabbits has a mean of approximately 155% higher than the mean for the nr_foxes. In combination with the mean value, when looking at the std the nr_rabbits value is 298% larger than the std of the nr_foxes. In other words, this illustrates that the nr_rabbits had its data points further spread out, whereas the nr_foxes had its data points more clustered around its mean value. Unlike the basic and energy-based simulations where the nr_rabbits had a higher mean and std, the flocking simulation had the opposite output. The nr_foxes had a mean of 173% higher than the mean for the nr_rabbits, as well as an std of 132%. This simulation had a more widely spread agent count for the nr_foxes. This data portrays the impact of the agent population control. The basic and energy-based model data's wide spread of data points for the nr_rabbits indicates that the environments provided a higher chance of survival and reproduction. In comparison to the rabbits, it is clear that the foxes were in a disadvantageous environment to survive and reproduce. This can be seen by its low mean value and clustered data points. Although the energy-based model had the same theoretical output (where the nr_rabbits mean and std exceeded the nr_foxes), it does not mean that there was no difference made. By comparing both means and stds, it is clear that the basic model has higher mean and std values than the energy-based model. That is to say that the energy-based models change in environment had negatively impacted the two agent species in survival rate and reproduction. Nonetheless, the flocking simulation provided a case where the foxes had the upper hand in reproduction, in comparison to the rabbits. Signifying that the hunting and flocking behaviour had positively affected the foxes to reproduce. As a result, the rabbits were incapable of reproducing, due to the number of foxes. To put it another way, despite the foxes having the upper hand in hunting, it did not allow its species to live longer, due to the fact that they had hunted all the rabbits in a short period of time, thus having no food to survive on. These outputs imply that the change in environment, parameters and behaviours have had an effect on the two dependent samples.

Table 2: Processed data for all models

	basic		**energy**		**flock**	
	mean	std	mean	std	mean	std
nr_rabbits	62.74728	77.65151	27.64651	11.16687	17.87613	16.84535
nr_foxes	40.28269	25.9954	8.818537	4.52855	31.07191	22.26978

Nevertheless, to check whether this statement holds, the Wilcoxon signed-rank test was conducted to assess the significance of the data to reject the null hypothesis. wil (2018) In other words, it is a statistical comparison of the average of two dependent samples. This statistical test measures whether the difference of the two populations is significant enough by rejecting one of the hypotheses stated below.

- Null hypothesis: The average of agents is equal between the two groups.
- Alternative hypothesis: The average number of agents is not equal between the two groups.

For all simulations, the null hypothesis was rejected because the p-values scored below 0.05. For the basic model the p-value was 6.033989331855553e-183, for the energy-based model the p-value was 8.583505472264416e-40 and for the flocking model p-value of 1.4531471365890308e-99. Conveying that the different parameters and environments have a significant impact on its populations. Thus, also backing up the observations made based on the mean and std. In this manner, through the statistically processed data, it can be concluded that the population size is affected when altering the agents' behaviour, parameters and environment.

4 Conclusion

From comparing the basic and energy-based models, it is possible to conclude that if both predator and prey become energy-dependent the populations are able to survive for the full simulation length, whilst having less variation in their population sizes and distributions. Furthermore, the comparison between the basic and flocking models showed that adding flocking and active hunting behaviours to the preys and predators respectively results in extinction of the foxes, which in turn results in exponential growth of the rabbits. In addition, the distribution varies significantly more over time as opposed to the basic and energy-based model. Challenges faced while tackling these questions were implementing nature-inspired behaviours in a digital environment and tuning all the parameters to yield meaningful results.

An improvement that can be added to this research is to change the spatial environment to stimulate the flocking behaviour. Further research can delve deeper into implementing nature-inspired behaviours to each population; sexual reproduction, age element, increased chasing radius for the foxes when they have critically low energy levels, and a food web approach with energy transfer from prey to predator.

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