Voluntary Extinction

Final Report

ENV 299/399: Simulating Complexity, Chaos, and Emergence

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Abstract

Decreasing fertility rates are a great threat to industrialized nations and it remains to be seen which actions are suitable to address this problem long-term. COBWEB, an agent-based modeling software, was used to simulate how decreasing fertility and aging would affect an arbitrary country if no preventive measures were taken. Additionally, the effect of a range of potential policies that attempted to increase fertility rates was observed. Each of these was repeated ten times, and to assess their efficacy, Mann-Whitney U tests for the short-term effect and calculated Pearson correlation coefficients for long-term significance were used by comparing the potential solution with the baseline scenario. The results suggest that environmental policies should only be implemented as temporary short-term fixes, whereas immigration is a viable long-term solution. Additionally, the success of financial incentives depended on how they are implemented: Direct financial incentives yielded similar results to the environmental policies, but indirect financial policies (improving healthcare and childcare services) were shown to be effective in the long term. Policymakers can consider these results when deciding how to approach this demographic problem.

Introduction

The world has suffered a decrease in fertility rates over recent decades. One-half of the population lives in countries where the total fertility is lower than 2.1 births per woman. Countries and policy-makers face increased pressure, as some countries have reached record-low birth rates. In Europe, some nations are experiencing rates between 1.0 and 1.4, with family sizes of 1.4 to 1.6 per woman born in the mid-1970s (Sobotka *et al*., 2019), and South Korea even reached rates as low as 0.70 in 2023. Past studies show that economic uncertainty, cultural shifts, work-life balance challenges, and educational and career pursuits are factors leading to this lack of fertility (Wilkins, 2019).

This decrease in fertility rate is a pressing issue since it poses many consequences on our society, including straining pension systems and healthcare resources and affecting other sectors like agriculture (Albuquerque & Lopes, 2010). Increasingly many governments are trying to implement family-friendly and more inclusive housing policies and incentivizing certain behaviors, like increased paternal involvement in the household (Fanelli & Profeta, 2021). However, even though some countries have been able to apply successful policies to increase fertility rates, finding the most appropriate approach for each situation and evaluating the response to each measure is complicated, as individual policies are often embedded in a wider institutional and cultural context (ELA, 2022).

There are three objectives to this research: to understand the underlying causes of this recent decrease in fertility,assess the efficacy of these policies to increase fertility rates individually, and assess the compatibility of different policy instruments in combination. This study adapts COBWEB, an agent-based software, to construct different scenarios by adjusting the environment and simulating the effect of different government policies on the population. COBWEB is used to control other factors and measure the effect of these policies in a controlled environment.

Literature Review

Causes of low fertility rates

Gender roles have an impact on childbirth intentions. Research shows that, in general, females tend to have a lower willingness for childbirth than males (Kim & Kim, 2023). Ji and Jung (2021) found that although having multiple children is an incentive for men, this is not the case for women. A reason for this is that women often need to bear additional childcare burdens as primary caregivers in the household, and the only way to prevent fertility from falling to even lower levels could be through improvements in gender equality (Hellstrand *et al*., 2021). The reason for this is that a non-egalitarian patriarchal society allows men to avoid actual caregiving by providing monetary support for the family through taking on paid work in the labor market (Alderotti *et al*., 2021). Meanwhile, women usually take on a more subjugated role and are expected to provide unpaid care work for the family (Lee, 2016). To prevent sacrificing career opportunities in favor of caregiving work in the household, the postponement of fertility in most high-income countries has become more widespread, which has been linked to rising educational enrollment and career building (Hellstrand *et al*., 2021) and in mothers' education levels (Hur, 2021). However, as childbearing age increases additional factors come into play, as health concerns also lower child-bearing intentions (Yi *et al.*, 2020).

In addition to the role of gender equality in the household, occupational factors impact workers' childbearing intentions as well (Yi *et al*., 2020). Family-friendly workplace policies that grant guaranteed maternity leaves and on-site childcare centers are proven to be effective in increasing workers' childbearing intention (Kim & Parish, 2022). In Asian countries, the majority of working women are often deprived of family provisions at their workplaces (Kim & Sun, 2017 hindering employees' childbirth intentions.

Aside from the heavy childcare burden falling on women, the household's socioeconomic resources are also proven to be influential in family-building decisions. There is a negative association between increased economic uncertainty and short-term parenthood intentions (Fahlen & Olah, 2019). However, some research has conflicting views on the importance of job security in shaping fertility intentions: Lim (2021) claims that a husband's employment security has a strong positive association with fertility intention. But Ji and Jung (2021) found that even men who hold a temporary work position receive work-family gains and consequently also have increased fertility intentions, although temporary work may imply that the husband's employment security is unstable. Furthermore, securing stable housing arrangements also plays a significant role as it is shown that an increase in real estate prices leads to a decline in births among people who do not yet own any (Dettling & Kearney, 2014).

Finally, environmental factors can also play a role, as some studies showed an association between higher traffic-related air pollution levels and lower fertility rates (Nieuwenhuijsen, 2014).

Impact/Consequences of low fertility rates

Low and decreasing fertility rates can impact countries in a variety of ways. Aging populations can impact economies and healthcare directly or indirectly (Kim & Sun, 2017; Nakatani, 2019), and a disparity is observed between rural and urban areas in both these sectors. Although an economy may experience growth under an aging population, the consensus is pessimistic. From an economic standpoint, impacts can be estimated with projections. Both Ortega-Gil *et al*. (2022) and Albuquerque and Lopes (2010) predict the potential for economic growth under aging. The latter decomposes the growth into sectors: In the case of Portugal, health, pharmacies, and real estate may gain importance, while education and social security services will lose importance.

These studies suggest the possibility that aging can stimulate economic growth. Ultimately though, it is widely believed that if populations decline, quality of life and economies will stall (Jones, 2020). This is particularly evident in Japan with demographic imbalances, depletions of the labor force, decreases in national incomes, increased income inequality between generations, and strained pension systems (Hong & Schneider, 2020). Overall, this phenomenon can be explained by fewer people entering the workforce and an increased burden to support the elderly (Hong & Schneider, 2020; Parsons & Gilmour, 2018). The consequences of an aging population suggest that low and decreasing fertility impairs the economy.

An aging population reduces fertility and has a negative impact on healthcare systems. To begin, Parsons and Gilmour (2018) and Cheng *et al.* (2020) both model an increase in the dependency ratio and mortality respectively — higher dependency ratios and mortality rates burden healthcare systems as more resources are required to support the older population. These projections are supported by both Nakatani (2019) and Tanaka and Iwasawa (2020), who report the increasingly strained Japanese healthcare systems due to increasing medical costs, and a lack of caregivers, physicians, and medical services. Hence, more seniors needing medical care will further worsen the issue. However, it is projected that healthcare advancements and growth in aging nations are still attainable (Albuquerque & Lopes 2010; Ortega-Gil *et al.* 2022). In conclusion, evidence and modeling suggest there is impending pressure on health systems in low-fertility countries.

Finally, low fertility rates affect the economy and healthcare in urban and rural areas differently. To begin, rural economies are at risk of shrinking. For example, farmers in countries like Japan are not succeeded by their families (Poungchompu *et al*., 2012). This is due to decreasing fertility rates and shifting attitudes. Likewise, the support systems of rural Japanese elders and families are under pressure, due to inadequate rural healthcare (Tanaka & Iwasawa, 2010). On the other hand, the urban situation presents differently. Despite having lower fertility rates than rural areas, urban areas can continue to achieve growth and urbanization (Lerch, 2019; Jones, 2020). This is because of rural-to-urban migration and international migration, which raise fertility in urban areas (Lerch, 2019; Baffour *et al.*, 2023). Thus, urban areas will still maintain the possibility for growth in population and economy that rural areas may not. Furthermore, evidence shows that urban areas typically receive higher-quality medical services with greater ease (Tanaka & Iwasawa, 2010; Hirayama & Miyazaki, 1996, Clark *et al*., 2021). Therefore, it is likely that the already under-serviced rural healthcare systems of countries like Japan will face more stress than their urban counterparts.

Solutions

There are a range of approaches to reduce the impact of decreasing birth rates. Governments have been constantly trying to find solutions and apply policies that will limit the decrease in birth rates such as financial incentives, housing regulations, childcare subsidization, and increased parental leaves (Zhang *et al.,* 2021). Yet, finding the most effective policy for each situation is often a complex task (Zheng *et al.*, 2023).

Some research focuses on studying the different approaches and the clusters of countries with comparable packages of family policies. Sobotka *et al*. (2019) found the following in Europe:

- Nordic countries have focused mainly on providing support for working parents with small children and boosting fathers' involvement in care,
- Continental European countries, like Germany and France, have aimed for more conservative policy models with gradual support of women's employment and work-family reconciliation.
- Some Eastern European countries have favored supporting early childcare provision.

Yet, measuring their long-term impact is challenging as the period fertility reflects changes in both family size and the timing of births (Hellstrand *et al*., 2021). So quantum and tempo effects need to be considered when new policies are implemented.

When deciding which kind of policy to apply, it is important to understand the situation and needs of the region (Zheng *et al.,* 2021). For instance, the 2007 German maternity leave reform, which changed maternal compensation and introduced earnings-related benefits, successfully achieved substantial pro-natal effects, including discontinuous jumps in monthly birth rates and an increase in the probability that higher-educated women would have children. The motivation behind this policy was that "highly educated and high-earning women have fewer children over a lifetime than their less-educated and lower-earning peers" due to their higher opportunity cost of having children (Raute, 2019). Generally speaking, significant reforms in public health care and parental leave have substantial and lasting effects on fertility, illustrating how family-friendly policies contribute to improving fertility rates across countries in Europe (Bergsvik *et al*., 2021).

Another possible solution is boosting immigration, which lowers the dependency ratio and increases birth rates, depending on factors like country of origin (Baffour *et al*., 2023). However, according to projections from Bermingham (2001) and Parsons & Gilmour (2018), immigration is ineffective for most countries given the large numbers required to reverse the decline in their populations. For instance, South Korea would need to accept 93.6 million people per year to offset its aging (Bermingham, 2001).

Conclusion

The consequences of low birth rates do not only impact society broadly but also at an individual level, especially with a disparity between urban and rural areas. Disparity only increases when considering the different methods that researchers use to analyze low birth rates. In particular, quantitative predictions often have to simplify the complexities of a human population. Therefore, due to the limitations of modeling and poor government implementation of policies, many past attempts at increasing immigration and fertility were unsuccessful. Future policy projections are also not encouraging, although it is important to note that quantitative projections have been limited by simplifications and assumptions. Thus, effective solutions remain to be seen, and it is important to find an effective but feasible resolution to limit the future consequences of low birth rates.

Methods

Introduction to COBWEB

COBWEB is an agent-based modelling software that allows simulations to be built in many disciplines including studies on how behavioral changes lead to environmental changes. The main component of COBWEB is the agents, which are allowed to interact with resources and with each other through the different tabs available in the software. Many aspects of the agents may be altered in the Agents tab. Although the number of types of agents is set to 4 by default, COBWEB allows up to 64 different kinds of agents, and each can have its own parameter values and AI. These parameters represent a range of characteristics that agents have, mainly regarding their energy and reproduction. Another one of COBWEB's fundamental components are the resources, the primary energy source for the agents. Each agent has a default corresponding resource, but the consumption of resources by different agents can be modified in the Food Web tab. There are a small number of parameters affecting resource generation, under the Resources tab.

Systems Diagram

The diagram (Figure 1) portrays the interaction of the country's population and immigrants, some of the causes of population declined and some of the proposed solutions:

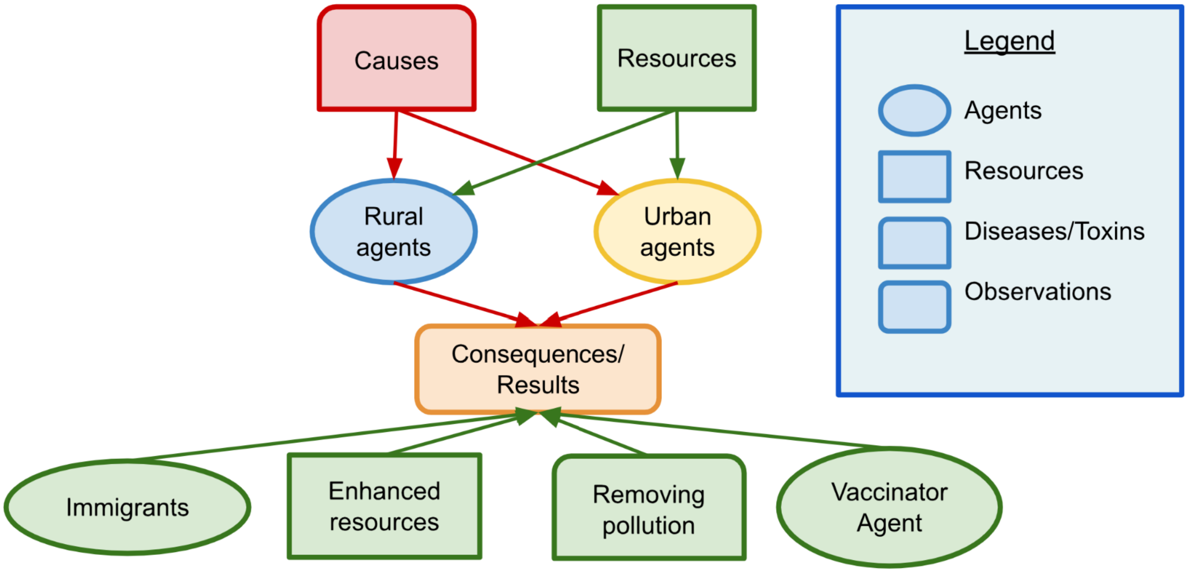


Fig.1: Systems Diagram

This model had four components. First, the model was divided into two zones, one urban and one rural. Each zone contained more resources targeted specifically for their agent type, and zone restrictions were enforced through a step energy punishment on agents that did not correspond to that zone. The second component was the two local agents. These were also urban and local respectively, and they had different characteristics, including different breeding energy thresholds, and energy intake from food. Each tick (COBWEB's time step) represented a month. Hence both types of agents had life expectancies of 1000 ticks, to simulate a life expectancy of around 83 years. The aging parameter was used to hinder fertility so agents gradually had less energy to breed. This reflected the current state of these countries as one of the consequences of low fertility is an aging population.

These agents were susceptible to diseases and toxins which lowered their energy and hinder their breeding abilities. This was the third component of the model. The agents were affected differently by this disease and the transmission rate also depended on their agent type, as urban agents had a higher proportion of the population with the infection to begin with, and it also spread faster between them. In COBWEB, the factors that hindered fertility could only be represented in a limited number of ways. Toxins and diseases in the environment could be understood to represent all current factors, discussed in the literature review, that contribute to low fertility .

The last component was the proposed policies that are attempts at a solution. These were implemented by introducing new kinds of agents, food, and other resources to represent environmental, financial, and demographic policies. All had the intention of increasing birth rates and were only introduced at a single point in time, t=500 ticks, and the outcome was observed for the subsequent 1000 ticks. In particular, financial incentives were represented in two ways: first, through an additional kind of food that reduced competition for resources, and secondly, through a "vaccinator" agent that reduced the diseases affecting the members of the population by healing the ones that had contracted the disease and vaccinating other agents. These solutions represented improvements in the childcare and healthcare sectors, such as costs, which were major causes of low fertility rate.

Immigration was introduced through an additional agent that will have a higher fertility rate (set by a higher probability for breeding) than agents representing the non-immigrants. This addition reflected the fertility rates of the top nationalities of newcomers to the country of interest, e.g. Moroccan immigrants have a higher fertility rate in Italy, than the non-immigrant population (OECD, 2023).

Initially, the model ran for a baseline scenario, i.e. a model without any policies or solution attempts, for 1500 ticks (around three generations of agents). This allowed the causes and consequences to affect the agent population, and a decline in the agent population was expected. When this scenario was complete, it was compared with the policy scenarios. The policy scenarios were created from the baseline by introducing the policy changes at 500 ticks. At first, policies were implemented one at a time to measure their effect independently. At a later stage, cumulative effects could be studied by implementing the individual policy together and measuring the effects in a Randomized-Control Trial (RCT). This latter experiment might have required a model external to COBWEB.

(Please refer to the Appendix for specific model setups)

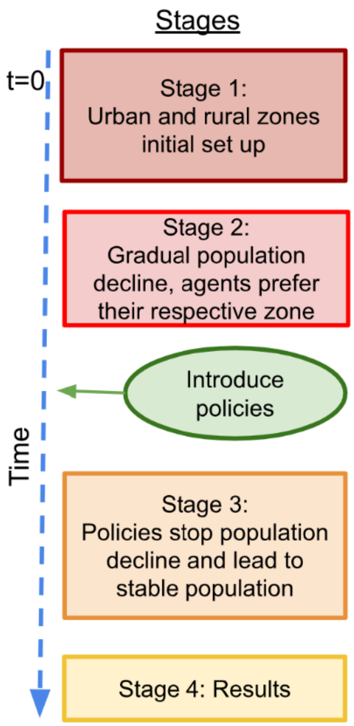


Fig. 2: Stages of the model

Statistical Methods

To assess the efficacy of results, each potential solution will be compared to the base-case scenario that led to the overall “voluntary extinction” or population decline discussed in the previous section, reflecting what would happen if no solution was implemented in the country. Each scenario will be repeated ten times, using different agent AIs to ensure whether the variation of the model results with independent populations is inconsistent with the problem at hand and that the results are replicable. Looking at the observed agent counts for the policy scenarios and the base case, we will observe their respective averages to obtain two time series, one for the base case and another for the policy or solution of interest.

We are interested in both the short- and long-term efficacy of each solution, which are tested using two statistical tests. First, for short-term efficacy, we will carry out a Mann-Whitney U test to assess whether the differences between the two time series are significant. This test uses the first 100 ticks after introducing the solution into the model and normalizing the base case and the solution’s subset of the time series to ensure they intersect and can be compared with this test. A low p-value would suggest that the two series were significantly distinct, indicating that the solution had a significant effect on the agent count in the short term.

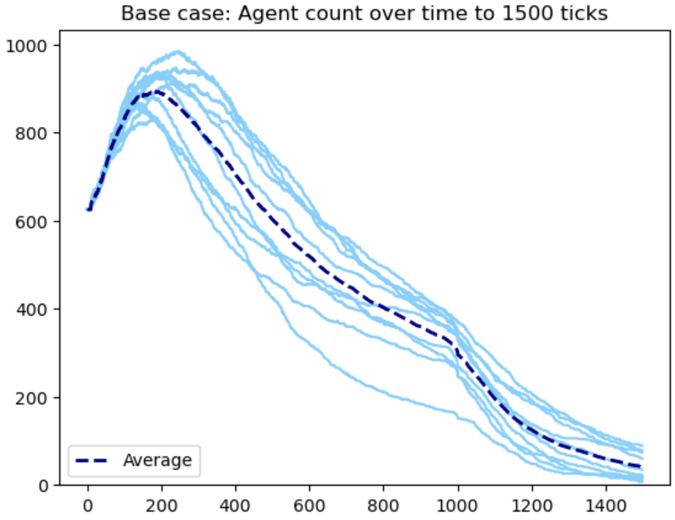
Second, for long-term efficacy, we will compare both time series after the point in which the solution was implemented (t=500 ticks), up to 1500 ticks. Here we will calculate the Pearson R-coefficient to see if the overall patterns of the two time series are similar or not. The base case scenario is expected to yield a decay curve. Hence if this coefficient is small, and looking at the shape of the graph, the solution deviates starkly from the base case’s decay curve and yields a sufficiently different trajectory from the base case scenario. These results would suggest that the solution was effective.

Results

A range of different solution attempts were implemented including environmental, financial, and immigration policies. These results were included because they represent the full scope of base cases and solutions that were assessed.

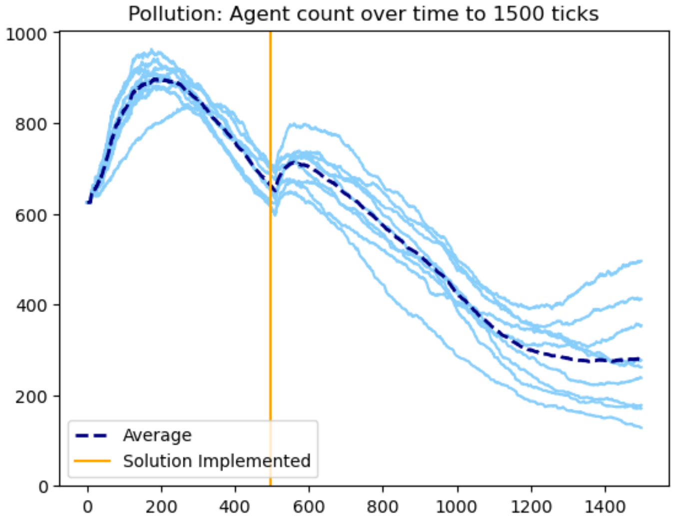
Base case

The base-case scenario showed a gradual decrease over time after 300 ticks for all ten repetitions, which was when the diseases started to affect the breeding ability of the agents. After 1500 ticks we observed near complete extinction of the agents in almost all the test runs.



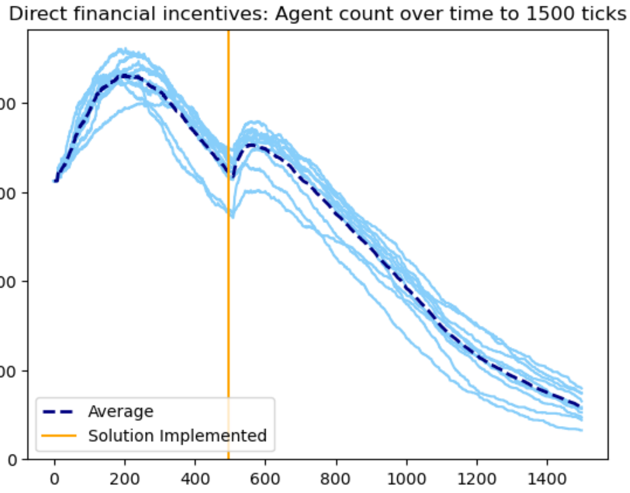
Pollution Factors

Removing pollution factors after 500 ticks resulted in a short-term increase in agent count followed by a resurgence of the previous gradual decline that was taking place before the solution was implemented, which continued up to 1200 ticks, where almost all test runs stabilized leaving about 300 agents (<50% of the initial population) and some showed a small increase in agent count. The Mann-Whitney U test carried out between 500 and 600 ticks yielded a p-value of 0.0005680, which reflected a highly statistical significance. On the other hand, when calculating the Pearson correlation coefficient on the agent count after 500 and comparing it with the base case scenario, a value of 0.98165 was observed, showing a strong linear relationship with the base case.



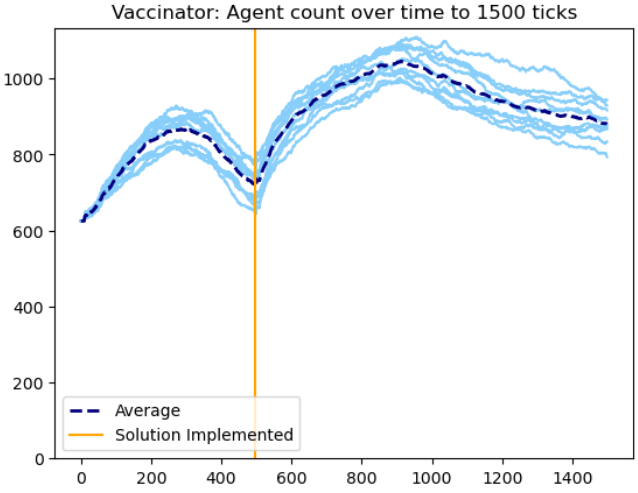
Financial Incentives

Financial incentives were modeled in two ways. First, we introduced an additional food source which increased the agent's energy by less than their preferred food but increased the amount of food available and reduced the competition for resources. Second, we introduced a vaccinator agent that cured diseases and prevented new agents from catching them.

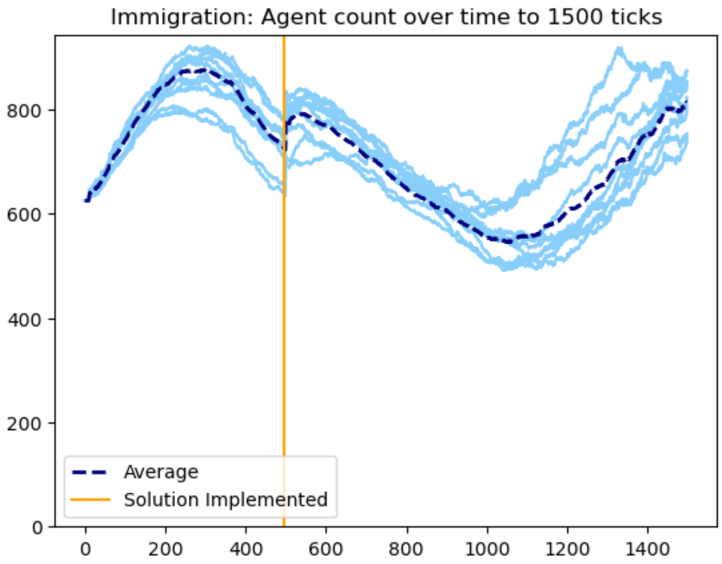


Direct financial incentives yielded a Mann-Whitney U test p-value of 0.0002544. On the other hand, the Pearson correlation coefficient was 0.99023.

On the other hand, the implementation of incentives using vaccinator agents showed a very different graph. The Mann-Whitney U test p-value of 0.314676. The Pearson Correlation coefficient was -0.0124928, reflecting a small negative linear association with the base case.



Introducing Immigration



We introduce 60 immigrant agents (around 10% of the initial population) at time t=500, which is depicted by the sudden jump in agent count in the graph. Despite this, the trend continued its descending pattern for another 500 ticks, at which point it began to increase again and reached its previous peak, before the diseases and toxins had an effect. Here some of the test runs appeared to stabilize at around 800 agents while others were still increasing towards that value.

When comparing it with the base case, the p-value in the Man-Whitney U test for the time between 550 and 650 was 0.6967411620458178. On the other hand, the obtained Pearson R coefficient was 0.172752.

Discussion

The results were evaluated using both Mann-Whitney U test p-values and Pearson's regression coefficients. The reason for the different choices of tests is that the former was only used for the short term analysis, since there were non-linear trends and abrupt changes in agent count directly after the implementation of a solution and the latter is only used to measure the strength of linear relationships.

The results clearly show that the base-case scenario led to extinction in every trial and that the policy scenarios (implementation of solutions) had varying effects. This represents a worst-case scenario that, as discussed in some of the literature, could arise if no appropriate measures are taken in time to stem the trend of decreasing fertility.

The environmental policy was represented by an elimination of pollution, which benefitted urban agents in particular as they had higher initial pollution levels. This policy had a significant effect in the short term as represented by the low Mann-Whitney U test p-value. This suggested that directly after the implementation of the solution, the trend in agent count was significantly different from the base case trend, which aligns with the findings of Nieuwenhuijsen *et al.* (2014). However, removing pollution was not an effective solution in the long term as a correlation coefficient of 0.98 was found, which suggested that the overall patterns of both the base case and this policy scenario were highly correlated, i.e. in the long term, the policy was not effective.

Regarding financial incentives, two scenarios were assessed, leading to two very different results. The first, spawning new resources that gave agents more energy, had a less significant effect. This approach is analogous to the government supplying small amounts of money to incentivize the population to have more children. Here, a similar outcome was shared with the implementation of the environmental policy: it was an effective solution in the short term but not in the long term. Nonetheless, the p-value for the Mann-Whitney U test was slightly lower here, which suggested that direct financial incentives were slightly more effective in the short term. A higher correlation coefficient was also calculated for the overall pattern, which reflected that overall this kind of policy was both more effective in the short-term and less in the long-term than an environmental policy. This result mirrored the findings of Alemán *et al.* (2017), in their study on the "baby bonus" of 2500€ that was given to new parents in Spain between 2007 and 2010.

On the other hand, the second approach consisting of the vaccinator agents showed very promising results. These reflected improving healthcare and child-care services. From the graph, this scenario brought the most distinct changes in the demographic trend pattern in comparison to the other policy scenarios, which was also reflected by the test statistics. The Mann-Whitney U test p-value of 0.3147 showed a significant difference in the short-term effect of both policies and the Pearson correlation coefficient was negative (-0.012), which showed that this solution had no correlation with the base case scenario and is effective in the long term.

Lastly, in terms of immigration policies, there was a different effect. An additional 10% of the initial agent population was introduced as immigrants at 500 ticks, with a higher breeding probability (OECD, 2023). To evaluate the short-term effect of this policy, the first 100 ticks after t=550 were analysed. The short-term analysis did not look at the time right after 500 ticks, like it did for the other policies, since that would have yielded biased results due to the sudden jump in agent count at that point. This test resulted in a high p-value for the Mann-Whitney U test, which implied that immigration did not have a sudden effect on fertility rates. However, the Pearson correlation coefficient for the overall pattern after 500 ticks was 0.173, which meant that the two trends were not similar and the policy scenario trend was significantly different from the base case scenario. This showed that immigration was a potential solution to decreasing fertility rates in the long term, as the population was able to rebound. This aligned with previous research, such as Bermingham (2001), which emphasized that immigration can reverse population decline given large enough numbers of immigrants. Some of the concerns raised in the literature, such as the number of immigrants required to reverse population decline, were addressed; the number of immigrants added to the scenarios was not as substantial as reported in the literature (Bermingham, 2011; Parsons & Gilmour, 2018). Yet, at the end of the simulations, immigrants remained the most numerous agent type, which is another demographic effect that can be considered in the development of policies to increase fertility.

Despite these results, many assumptions were made when modeling this situation. First, it was assumed there were no immigrants at all before an immigration policy. Furthermore, not every single kind of policy scenario was tested. In addition, the causes of declining fertility rates were grouped into one disease in COBWEB, and only air pollution was represented; other types of pollution could be added as an extra toxic resource. Finally, the country was assumed to be arbitrary, which decreases the strength of the result for any particular country and further studies could be made employing real-world data. However, there were facets of the model that strengthened the results. For instance, research has shown that immigration and financial incentives can improve fertility rates, a result that is corroborated by our results (Bermingham, 2001; Raute, 2019).

Conclusion

Population decline due to falling fertility rates and increased aging is one of the major demographic trends in industrialized nations, threatening sustained economic growth and development, the tax base and funding for the needs of seniors, and the ability of a country to defend itself in the long term. Previous literature suggests that three important factors in this situation are the causes and consequences of low fertility rates, and solutions that can be implemented to slow down or reverse this trend. This conclusion is still highly uncertain as previous research suggests that past government policies have largely been inconclusive or unsuccessful in tackling the problem. As a result, simulation models were used to perform a study on the efficacy of some of the potential policies using COBWEB, as the software can yield sufficient, independent results to test different policy scenarios.

The implemented policies focused on different areas, including environmental, financial, and demographic policy scenarios. Overall, environmental policies were found to be only effective in the short term, but they were not viable long-term solutions as their effects were short-lived in the model. In the scenarios reflecting financial incentives, it was observed that direct financial incentives had a similar effect to environmental policies and were only effective in the short term. On the other hand, indirect financial incentives, representing improvements in the childcare and healthcare sectors, provided short term and long term solutions. Finally, immigration policies were not as effective in the short term, but they were eventually able to restore the population of agents to a level that was similar to the initial maximum. It is worth noting that the makeup of the population was reversed from the implementation of the scenario. As a result of this policy, a significant proportion of the population was composed of immigrant agents at the end of the experiment.

Overall, different solutions were observed to have different outcomes and it is important to evaluate what is required in each situation to achieve the desired policy outcome.

In light of these results, policymakers in industrialized nations have promising strategies to consider in order to reduce the decline in fertility. To begin, environmental policies should not be used as the only solution to halt the decline in fertility. Even in the most extreme case of removing all pollution, there was not a significant long-term effect on the population. Instead, governments should prioritize indirect financial incentives, as this solution brought a significant recovery in the population. In addition, a policy to maintain or increase immigration should be entertained by governments, but the success of these policies might cause other demographic changes and require other policies to integrate a large number of immigrants into their societies. Overall, these new results are important to consider because many previous policies in countries like Japan and Korea have not seen success in increasing fertility rates (Kim & Sun, 2017).

Despite this new information, there are still additional steps that may be taken to further the use of this model. It would be useful to consider environmental, financial, and immigration policies together, or implement them multiple times in a single trial. Secondly, many assumptions and caveats were involved when setting up the model, which should be addressed when improving future simulations. Finally, it would be useful to use census data to model the situations of many more countries, as half of the world's population lives in countries with a birth rate lower than the replacement level (Sobotka *et al*., *2019)*. In conclusion, the results provide and strengthen confidence in the existence of solutions to decreasing fertility rates.

Glossary

Fertility rate: the average number of children that are born to a woman over her lifetime

Mann-Whitney U test: Statistical test to check if two sample means from the same population are equal

Pearson’s correlation coefficient: Statistical test to check if two patterns are similar, goes from -1 (perfect negative correlation) to 1 (perfect positive correlation)

p-value: In hypothesis testing, the p-value is the probability of obtaining test results at least as extreme as the result actually observed

Quantum and tempo effects: In this context, quantum effects are reflected by women having more children and tempo effects by having them earlier.

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Appendix

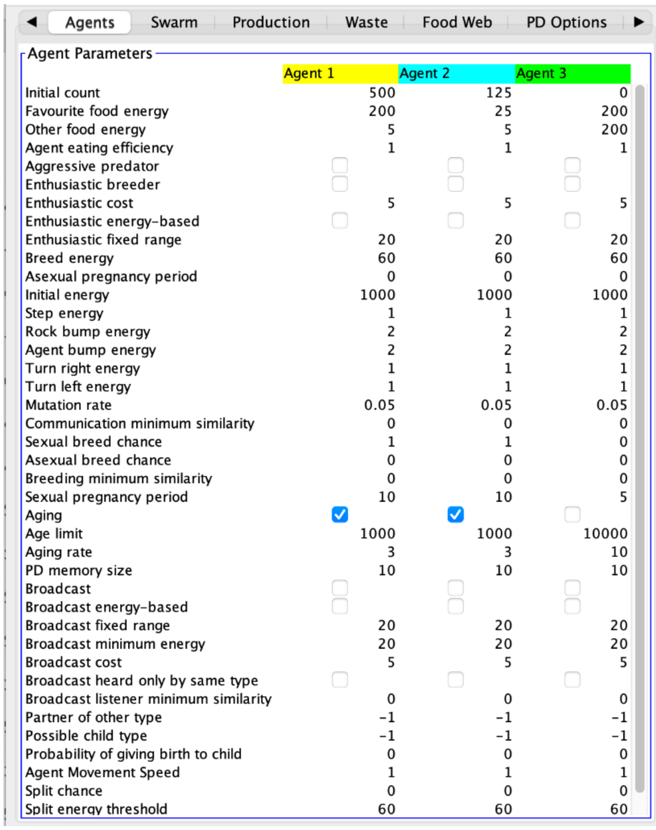
1. Model Setup

Base Model

The base case is the current demographic situation in a country. Starting with the environment tab in COBWEB, set the width and height of the environment to 60. Use 3 agent types instead of 4, and set random stones to 0, so no stones (energy robbing barriers) will affect the model results. Keep all other environment values at their default settings. The environment settings will be changed later when implementing policy scenarios.

Agents

There are three agents in this model. Notice however that the third agent has an initial count of 0, as it is not present in the base case. Instead, only the first and second agents — urban and rural locals — will be present at the start. The only settings that need to be changed from the default in the model are initial count, favorite food energy, other food energy, initial energy, sexual pregnancy period, aging, age limit, and aging rate. It is important to select aging to be on for the first two agents so that the Age limit and Aging rate can work. Use the image on the right to change the settings.

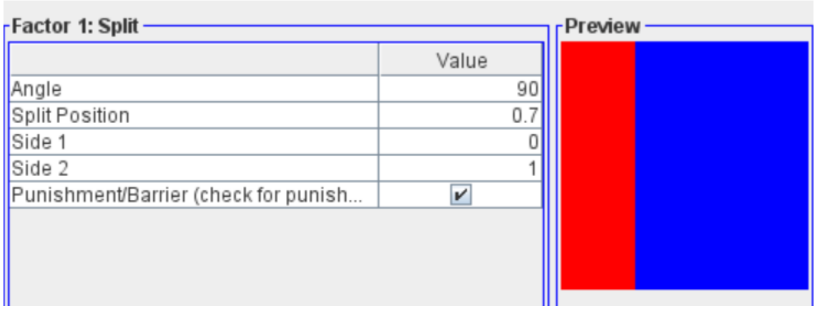


Agent Parameters

	Agent 1	Agent 2	Agent 3
Initial count	500	125	0
Favourite food energy	200	25	200
Other food energy	5	5	200
Agent eating efficiency	1	1	1
Aggressive predator	☐	☐	☐
Enthusiastic breeder	☐	☐	☐
Enthusiastic cost	5	5	5
Enthusiastic energy-based	☐	☐	☐
Enthusiastic fixed range	20	20	20
Breed energy	60	60	60
Asexual pregnancy period	0	0	0
Initial energy	1000	1000	1000
Step energy	1	1	1
Rock bump energy	2	2	2
Agent bump energy	2	2	2
Turn right energy	1	1	1
Turn left energy	1	1	1
Mutation rate	0.05	0.05	0.05
Communication minimum similarity	0	0	0
Sexual breed chance	1	1	0
Asexual breed chance	0	0	0
Breeding minimum similarity	0	0	0
Sexual pregnancy period	10	10	5
Aging	☑	☑	☐
Age limit	1000	1000	10000
Aging rate	3	3	10
PD memory size	10	10	10
Broadcast	☐	☐	☐
Broadcast energy-based	☐	☐	☐
Broadcast fixed range	20	20	20
Broadcast minimum energy	20	20	20
Broadcast cost	5	5	5
Broadcast heard only by same type	☐	☐	☐
Broadcast listener minimum similarity	0	0	0
Partner of other type	-1	-1	-1
Possible child type	-1	-1	-1
Probability of giving birth to child	0	0	0
Agent Movement Speed	1	1	1
Split chance	0	0	0
Split energy threshold	60	60	60

Zones

There are two zones in this model representing urban and rural areas. To add a zone, go to the abiotic factors tab, select split, and press add. The only setting that was changed from the default is the split position. In this image, the left side of the environment was set to have a value of 1, and the right side, of 0.

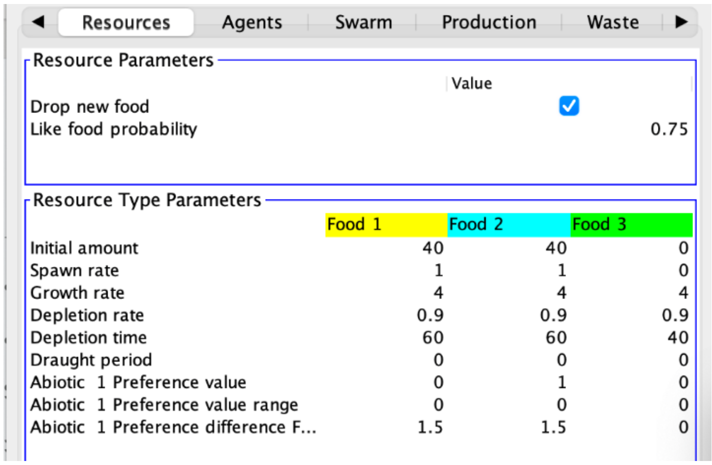


Factor 1: Split

	Value
Angle	90
Split Position	0.7
Side 1	0
Side 2	1
Punishment/Barrier (check for punish...	☑

Resources

First notice that food 3 has an initial amount and spawn rate of 0, which means no food will appear when you run your simulation. The settings to change from the default are initial amount, spawn rate, depletion time, abiotic 1 preference value, and abiotic 1 preference difference factor.



Resource Parameters

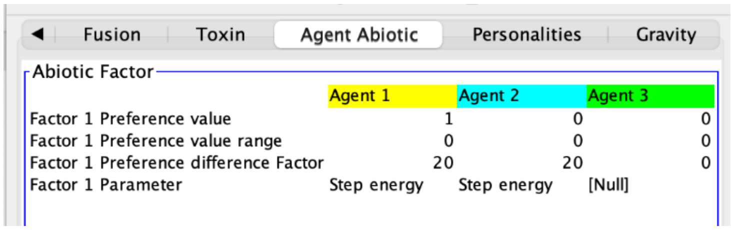
	Value
Drop new food	☑
Like food probability	0.75

Resource Type Parameters

	Food 1	Food 2	Food 3
Initial amount	40	40	0
Spawn rate	1	1	0
Growth rate	4	4	4
Depletion rate	0.9	0.9	0.9
Depletion time	60	60	40
Draught period	0	0	0
Abiotic 1 Preference value	0	1	0
Abiotic 1 Preference value range	0	0	0
Abiotic 1 Preference difference F...	1.5	1.5	0

Agent abiotic

The settings in this tab allow you to reinforce the zone boundaries and restrict agents to certain zones. In the agent abiotic tab, change factor 1 preference value, factor 1 preference difference factor, and factor 1 parameter from the default settings.

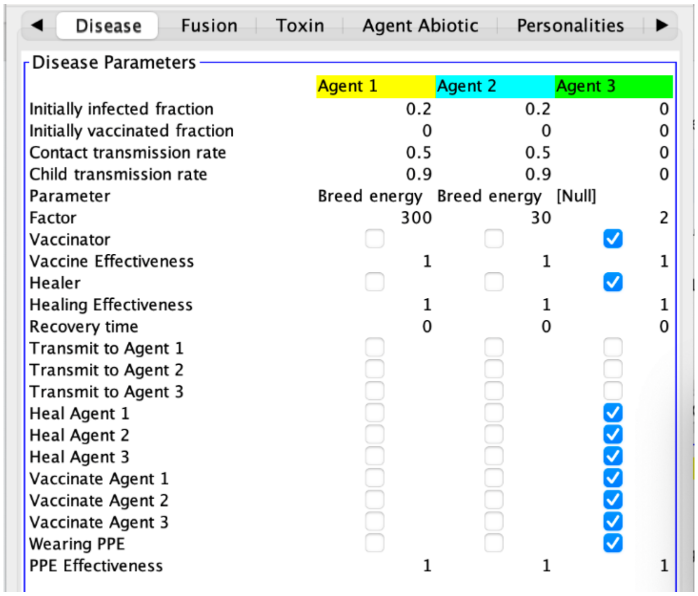


Abiotic Factor

	Agent 1	Agent 2	Agent 3
Factor 1 Preference value	1	0	0
Factor 1 Preference value range	0	0	0
Factor 1 Preference difference Factor	20	20	0
Factor 1 Parameter	Step energy	Step energy	[Null]

Disease

The disease tab is used to add the causes of low fertility rates. Change the initially infected fraction, parameter, and factor from the default. Do not change Agent 3 for now, these settings will be changed depending on the policy that you want to implement as Agent 3 can represent immigrants or vaccinators.

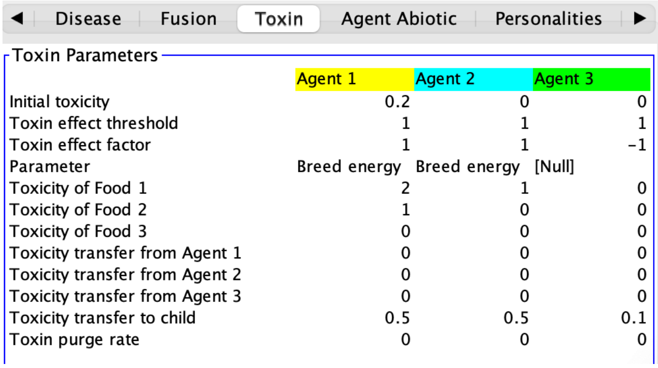


Disease Parameters

	Agent 1	Agent 2	Agent 3
Initially infected fraction	0.2	0.2	0
Initially vaccinated fraction	0	0	0
Contact transmission rate	0.5	0.5	0
Child transmission rate	0.9	0.9	0
Parameter	Breed energy	Breed energy	[Null]
Factor	300	30	2
Vaccinator	☐	☐	☑
Vaccine Effectiveness	1	1	1
Healer	☐	☐	☑
Healing Effectiveness	1	1	1
Recovery time	0	0	0
Transmit to Agent 1	☐	☐	☐
Transmit to Agent 2	☐	☐	☐
Transmit to Agent 3	☐	☐	☐
Heal Agent 1	☐	☐	☑
Heal Agent 2	☐	☐	☑
Heal Agent 3	☐	☐	☑
Vaccinate Agent 1	☐	☐	☑
Vaccinate Agent 2	☐	☐	☑
Vaccinate Agent 3	☐	☐	☑
Wearing PPE	☐	☐	☑
PPE Effectiveness	1	1	1

Toxins

In the toxin tab, the toxins represent pollution in the environment. The settings that need to be changed include initial toxicity, toxin effect factor, parameter, the toxicity of food 1 and food 2, and toxicity transfer to the child. Do not change Agent 3 right now, as these may be changed depending on the policy.



Toxin Parameters

	Agent 1	Agent 2	Agent 3
Initial toxicity	0.2	0	0
Toxin effect threshold	1	1	1
Toxin effect factor	1	1	-1
Parameter	Breed energy	Breed energy	[Null]
Toxicity of Food 1	2	1	0
Toxicity of Food 2	1	0	0
Toxicity of Food 3	0	0	0
Toxicity transfer from Agent 1	0	0	0
Toxicity transfer from Agent 2	0	0	0
Toxicity transfer from Agent 3	0	0	0
Toxicity transfer to child	0.5	0.5	0.1
Toxin purge rate	0	0	0

Creating an Experiment

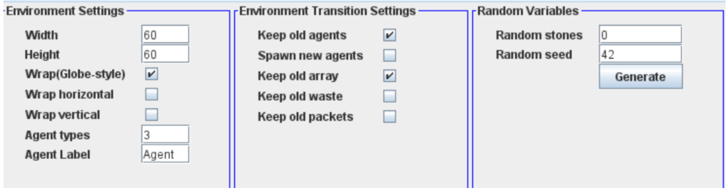
The base case represents the current situation of a country. In the model, the base case was run for 1500 ticks in the baseline scenario and 500 ticks in the policy scenarios. After 500 ticks, a parabola appears when looking at the population graph, and many resources will be present in the grid. Furthermore, agents will be infected with disease and toxicity. At this time, the population is entering a decline, and a policy must be implemented if the objective is to reverse the decline. Once at 500 ticks, the environment tab will need to be changed to resume your simulation at 500 ticks. This will be explained individually in the policies.

Multiple, independent populations are required to explore variation and conduct experiments. New, independent populations were generated by changing the seed in the AI tab. Changing the AI seed lets you change agent behavior. After every run is finished, at 2000 ticks, reset the settings to the base case. Then click the new seed button in the AI tab for all agents. This introduces variation between our results providing a check on model resilience as well as sufficient datasets for statistical testing. By changing the AI seed, you will notice differences in the agent outcomes. Perhaps they cluster together more or move differently; this is expected.

Financial Policy Model (resources)

500 ticks

At 500 ticks, select keep old agents, keep old array, and deselect spawn new agents. This is because, for this policy, it is necessary to keep the old agents and resources.



Environment Settings

Width 60

Height 60

Wrap(Globe-style) ☑

Wrap horizontal ☐

Wrap vertical ☐

Agent types 3

Agent Label Agent

Environment Transition Settings

Keep old agents ☑

Spawn new agents ☐

Keep old array ☑

Keep old waste ☐

Keep old packets ☐

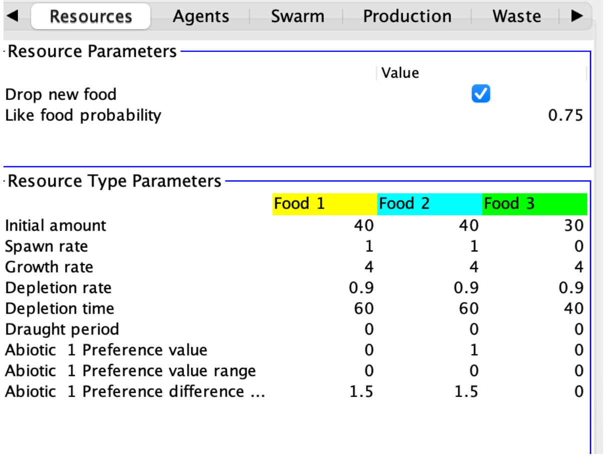
Random Variables

Random stones 0

Random seed 42

Resources

For this first financial policy, change the spawn rate of resource three from 0 to 30. This allows the resources that represent money to spawn. These will be green, and will appear when the simulation is resumed. Make sure you read the “Creating an Experiment” section for instructions on how to resume your simulation at 500 ticks properly.



Resource Parameters

	Value
Drop new food	☑
Like food probability	0.75

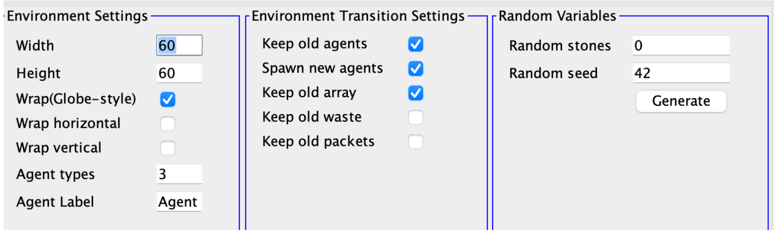
Resource Type Parameters

	Food 1	Food 2	Food 3
Initial amount	40	40	30
Spawn rate	1	1	0
Growth rate	4	4	4
Depletion rate	0.9	0.9	0.9
Depletion time	60	60	40
Draught period	0	0	0
Abiotic 1 Preference value	0	1	0
Abiotic 1 Preference value range	0	0	0
Abiotic 1 Preference difference ...	1.5	1.5	0

Financial Policy Model (vaccinators)

At 500 ticks modify the simulation:

As for direct financial incentives, old agents and the old array must both be maintained, to keep both the existing agents and resources. Since new agents are needed for this policy, check “spawn new agents”.



Environment Settings

Width	60
Height	60
Wrap(Globe-style)	☑
Wrap horizontal	☐
Wrap vertical	☐
Agent types	3
Agent Label	Agent

Environment Transition Settings

Keep old agents	☑
Spawn new agents	☑
Keep old array	☑
Keep old waste	☐
Keep old packets	☐

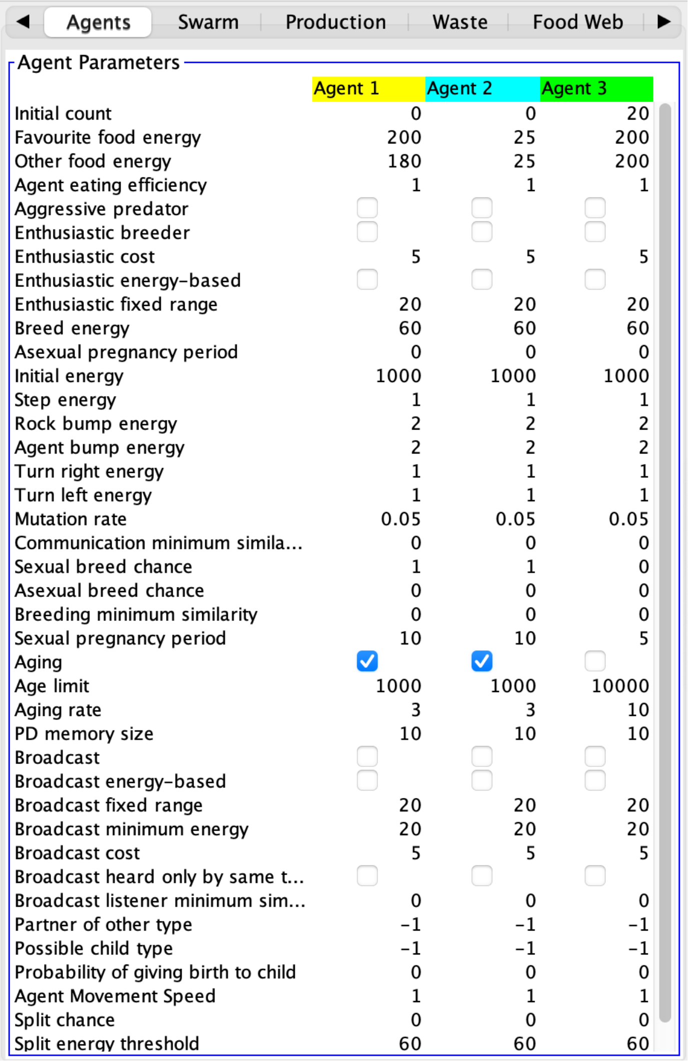
Random Variables

Random stones	0
Random seed	42

Next, change the Agents, Disease, and Toxin tabs:

Agent

There will be 20 vaccinator agents, which will obtain the same energy from all food sources and this will be the same energy urban agents get from their favorite food, 200. Every other setting will be kept the same for the other two agents, except for the parameters regarding breeding and aging. The vaccinator agents will not reproduce, and they will have a life expectancy longer than the duration of the experiment, so by setting their breeding chance to 0, they will not age, and set their life expectancy to 10000. Additionally, increase the other food energy parameter for the other two agents: set it to 180 for Agent 1, and 25 for Agent 2.

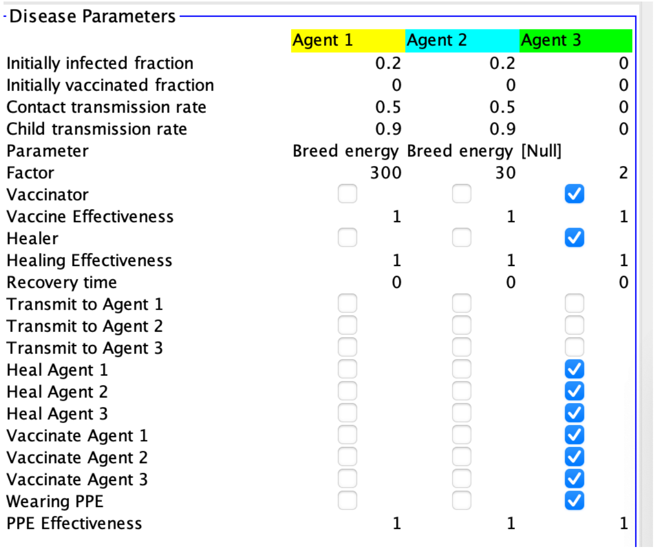


Agent Parameters

	Agent 1	Agent 2	Agent 3
Initial count	0	0	20
Favourite food energy	200	25	200
Other food energy	180	25	200
Agent eating efficiency	1	1	1
Aggressive predator	☐	☐	☐
Enthusiastic breeder	☐	☐	☐
Enthusiastic cost	5	5	5
Enthusiastic energy-based	☐	☐	☐
Enthusiastic fixed range	20	20	20
Breed energy	60	60	60
Asexual pregnancy period	0	0	0
Initial energy	1000	1000	1000
Step energy	1	1	1
Rock bump energy	2	2	2
Agent bump energy	2	2	2
Turn right energy	1	1	1
Turn left energy	1	1	1
Mutation rate	0.05	0.05	0.05
Communication minimum simila...	0	0	0
Sexual breed chance	1	1	0
Asexual breed chance	0	0	0
Breeding minimum similarity	0	0	0
Sexual pregnancy period	10	10	5
Aging	☑	☑	☐
Age limit	1000	1000	10000
Aging rate	3	3	10
PD memory size	10	10	10
Broadcast	☐	☐	☐
Broadcast energy-based	☐	☐	☐
Broadcast fixed range	20	20	20
Broadcast minimum energy	20	20	20
Broadcast cost	5	5	5
Broadcast heard only by same t...	☐	☐	☐
Broadcast listener minimum sim...	0	0	0
Partner of other type	-1	-1	-1
Possible child type	-1	-1	-1
Probability of giving birth to child	0	0	0
Agent Movement Speed	1	1	1
Split chance	0	0	0
Split energy threshold	60	60	60

Disease

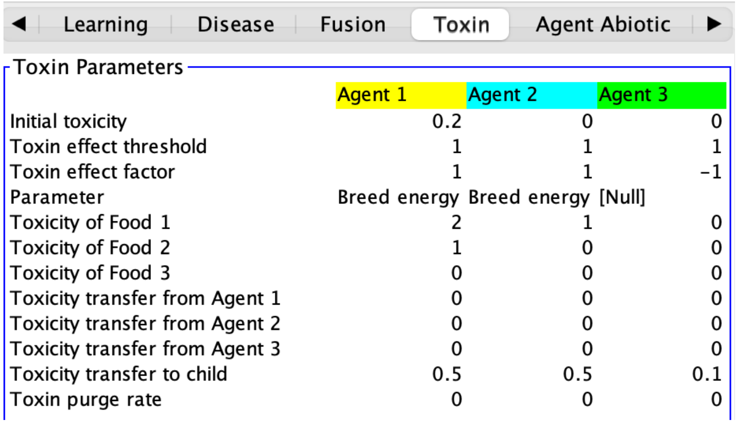
In the disease tab, set Agent 3 to be both a vaccinator and a healer for the other two agents. Ensure that the vaccinator and healer boxes are checked, and allow them to heal and vaccinate Agents 1 and 2 by checking the corresponding boxes. Make sure that Agent 3 cannot contract the disease: set their initially infected fraction and their transmission rates to 0. This ensures that their population remains constant.


Disease Parameters

	Agent 1	Agent 2	Agent 3
Initially infected fraction	0.2	0.2	0
Initially vaccinated fraction	0	0	0
Contact transmission rate	0.5	0.5	0
Child transmission rate	0.9	0.9	0
Parameter	Breed energy	Breed energy	[Null]
Factor	300	30	2
Vaccinator	☐	☐	☑
Vaccine Effectiveness	1	1	1
Healer	☐	☐	☑
Healing Effectiveness	1	1	1
Recovery time	0	0	0
Transmit to Agent 1	☐	☐	☐
Transmit to Agent 2	☐	☐	☐
Transmit to Agent 3	☐	☐	☐
Heal Agent 1	☐	☐	☑
Heal Agent 2	☐	☐	☑
Heal Agent 3	☐	☐	☑
Vaccinate Agent 1	☐	☐	☑
Vaccinate Agent 2	☐	☐	☑
Vaccinate Agent 3	☐	☐	☑
Wearing PPE	☐	☐	☑
PPE Effectiveness	1	1	1

Toxin

Similarly, for agent 3, make sure they do not suffer from the toxins, so set their initial toxicity to 0 and do not select a punishment parameter for them.



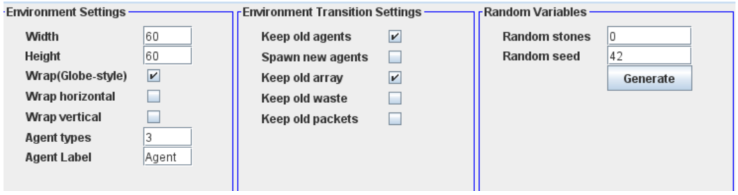
Toxin Parameters

	Agent 1	Agent 2	Agent 3
Initial toxicity	0.2	0	0
Toxin effect threshold	1	1	1
Toxin effect factor	1	1	-1
Parameter	Breed energy	Breed energy	[Null]
Toxicity of Food 1	2	1	0
Toxicity of Food 2	1	0	0
Toxicity of Food 3	0	0	0
Toxicity transfer from Agent 1	0	0	0
Toxicity transfer from Agent 2	0	0	0
Toxicity transfer from Agent 3	0	0	0
Toxicity transfer to child	0.5	0.5	0.1
Toxin purge rate	0	0	0

Remove Pollution Model

500 ticks

At 500 ticks, select keep old agents, keep old array, and deselect spawn new agents. This is because, for this policy, it is necessary to keep the old agents and resources.



Environment Settings

Width	60
Height	60
Wrap(Globe-style)	☑
Wrap horizontal	☐
Wrap vertical	☐
Agent types	3
Agent Label	Agent

Environment Transition Settings

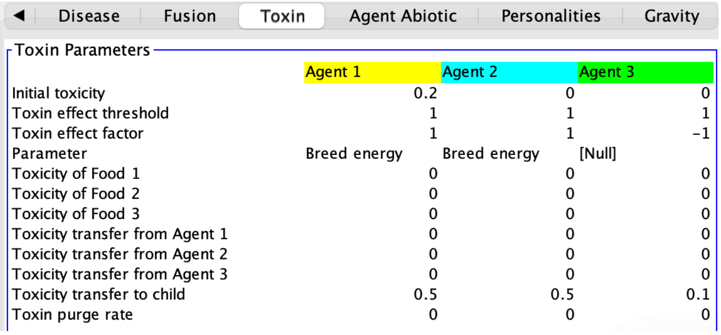
Keep old agents	☑
Spawn new agents	☐
Keep old array	☑
Keep old waste	☐
Keep old packets	☐

Random Variables

Random stones	0
Random seed	42

Toxin

This model represents the environmental policy of eliminating pollution in the environment. At tick 500, stop the simulation and go to the toxin tab. Set all toxicity of food 1, and food 2, to 0. However, old agents will still have toxicity in them from previously eating toxic food, which is expected. Make sure to read the Creating an Experiment section.



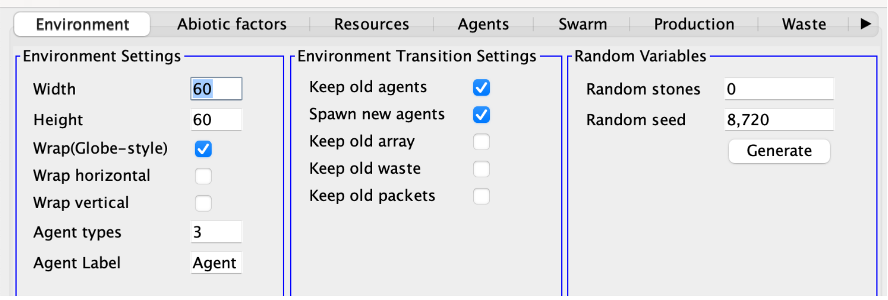
Toxin Parameters

	Agent 1	Agent 2	Agent 3
Initial toxicity	0.2	0	0
Toxin effect threshold	1	1	1
Toxin effect factor	1	1	-1
Parameter	Breed energy	Breed energy	[Null]
Toxicity of Food 1	0	0	0
Toxicity of Food 2	0	0	0
Toxicity of Food 3	0	0	0
Toxicity transfer from Agent 1	0	0	0
Toxicity transfer from Agent 2	0	0	0
Toxicity transfer from Agent 3	0	0	0
Toxicity transfer to child	0.5	0.5	0.1
Toxin purge rate	0	0	0

Immigrant Policy Model

At 500 ticks modify the simulation:

As in the previous solution attempts, keep the current agents and also check the spawn new agents box to add the immigrant agents.



Environment Settings

Width 60
Height 60
Wrap(Globe-style) ☑
Wrap horizontal ☐
Wrap vertical ☐
Agent types 3
Agent Label Agent

Environment Transition Settings

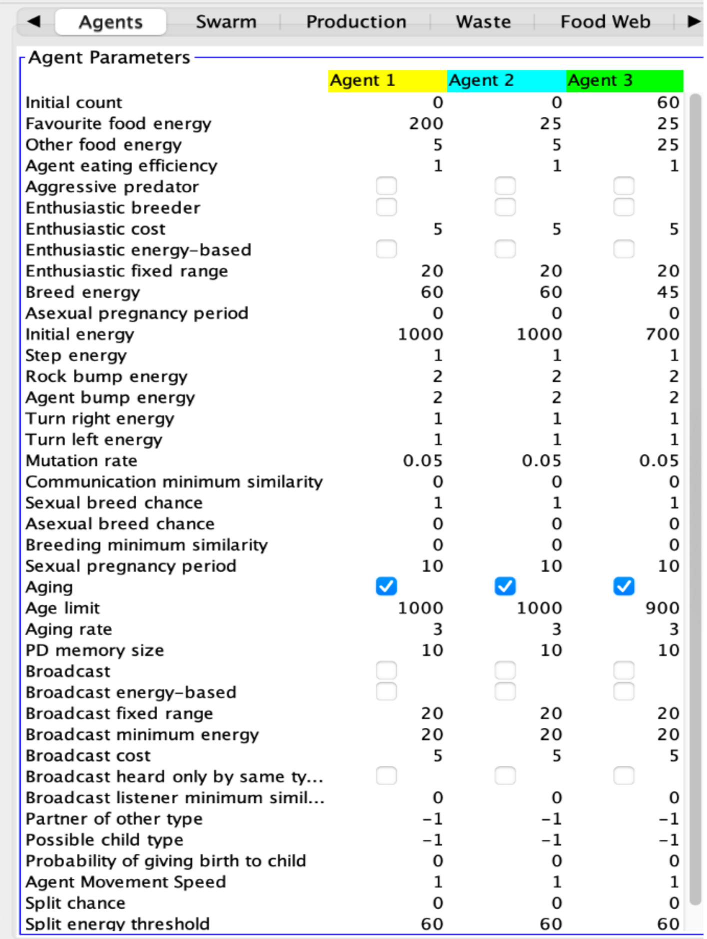
Keep old agents ☑
Spawn new agents ☑
Keep old array ☐
Keep old waste ☐
Keep old packets ☐

Random Variables

Random stones 0
Random seed 8,720

Agent

Add 60 immigrant agents (Agent 3) who will have slightly different settings from the local agents. They will obtain the same energy from all kinds of food since the food is aimed at urban and rural agents in particular, so set both to be 25. They will have a higher chance of breeding, so set their breed energy to 45 instead of 60 and also set their initial energy to 700, which is less than the initial energy of the other two agents. Finally, set their age limit to 900, which is also lower than the limit for the other agents.

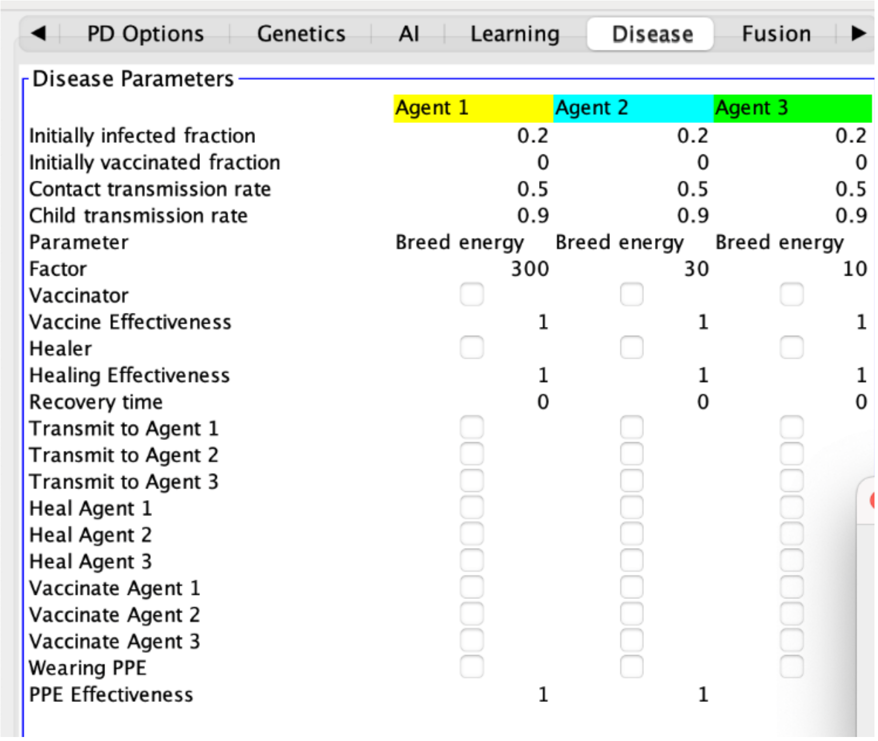


Agent Parameters

	Agent 1	Agent 2	Agent 3
Initial count	0	0	60
Favourite food energy	200	25	25
Other food energy	5	5	25
Agent eating efficiency	1	1	1
Aggressive predator	☐	☐	☐
Enthusiastic breeder	☐	☐	☐
Enthusiastic cost	5	5	5
Enthusiastic energy-based	☐	☐	☐
Enthusiastic fixed range	20	20	20
Breed energy	60	60	45
Asexual pregnancy period	0	0	0
Initial energy	1000	1000	700
Step energy	1	1	1
Rock bump energy	2	2	2
Agent bump energy	2	2	2
Turn right energy	1	1	1
Turn left energy	1	1	1
Mutation rate	0.05	0.05	0.05
Communication minimum similarity	0	0	0
Sexual breed chance	1	1	1
Asexual breed chance	0	0	0
Breeding minimum similarity	0	0	0
Sexual pregnancy period	10	10	10
Aging	☑	☑	☑
Age limit	1000	1000	900
Aging rate	3	3	3
PD memory size	10	10	10
Broadcast	☐	☐	☐
Broadcast energy-based	☐	☐	☐
Broadcast fixed range	20	20	20
Broadcast minimum energy	20	20	20
Broadcast cost	5	5	5
Broadcast heard only by same ty...	☐	☐	☐
Broadcast listener minimum simil...	0	0	0
Partner of other type	-1	-1	-1
Possible child type	-1	-1	-1
Probability of giving birth to child	0	0	0
Agent Movement Speed	1	1	1
Split chance	0	0	0
Split energy threshold	60	60	60

Disease

Change some of the parameters in the Disease tab and set all of the parameters to be the same as for the other two agents, except for the Factor parameter, which will be the lowest of the three at 10.

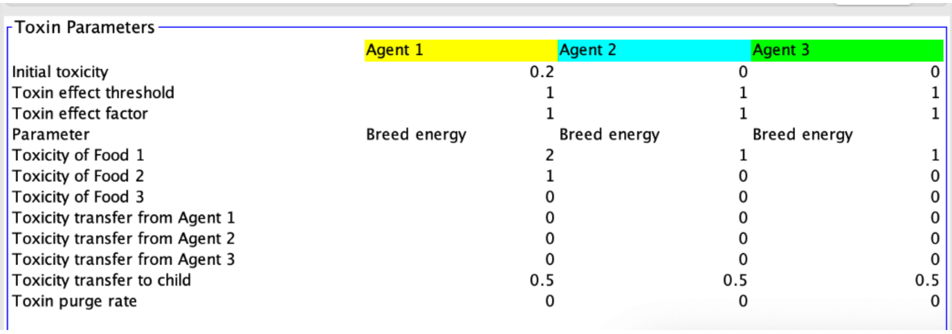


Disease Parameters

	Agent 1	Agent 2	Agent 3
Initially infected fraction	0.2	0.2	0.2
Initially vaccinated fraction	0	0	0
Contact transmission rate	0.5	0.5	0.5
Child transmission rate	0.9	0.9	0.9
Parameter	Breed energy	Breed energy	Breed energy
Factor	300	30	10
Vaccinator	☐	☐	☐
Vaccine Effectiveness	1	1	1
Healer	☐	☐	☐
Healing Effectiveness	1	1	1
Recovery time	0	0	0
Transmit to Agent 1	☐	☐	☐
Transmit to Agent 2	☐	☐	☐
Transmit to Agent 3	☐	☐	☐
Heal Agent 1	☐	☐	☐
Heal Agent 2	☐	☐	☐
Heal Agent 3	☐	☐	☐
Vaccinate Agent 1	☐	☐	☐
Vaccinate Agent 2	☐	☐	☐
Vaccinate Agent 3	☐	☐	☐
Wearing PPE	☐	☐	☐
PPE Effectiveness	1	1	

Toxin

Make sure that in the Toxin tab, the parameter values of Agent 3 are the same as for Agent 2.



Toxin Parameters

	Agent 1	Agent 2	Agent 3
Initial toxicity	0.2	0	0
Toxin effect threshold	1	1	1
Toxin effect factor	1	1	1
Parameter	Breed energy	Breed energy	Breed energy
Toxicity of Food 1	2	1	1
Toxicity of Food 2	1	0	0
Toxicity of Food 3	0	0	0
Toxicity transfer from Agent 1	0	0	0
Toxicity transfer from Agent 2	0	0	0
Toxicity transfer from Agent 3	0	0	0
Toxicity transfer to child	0.5	0.5	0.5
Toxin purge rate	0	0	0

2. Start-up Guide

Introduction

COBWEB is an agent-based software that allows simulations to be built and studies how behavioral changes lead to environmental changes. As this suggests, the main component of this software is the agents, which are allowed to interact with resources and each other through the different tabs COBWEB offers. It has a wide range of applications in fields like economics and biology, however, our focus will be on how it can be applied to demographic modeling and how zones, waste and aging can be tailored for this.

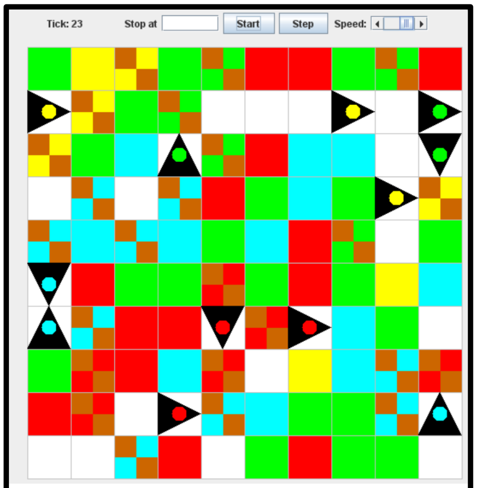
Agents

Agents are the main component of COBWEB and many aspects surrounding them may be altered in the Agents tab: Firstly, the total number of agents can be set to any non-negative number and the number of types of agents is set to 4 by default but it allows up to 64 different kinds, where each can have its parameter values. Furthermore, there is a range of characteristics that agents have, mainly regarding their energy and reproduction. In terms of energy, one can manipulate their 'Initial energy', how much of it they gain by consuming food ('Favorite/Other food energy'), the energy they need to move ('Step energy' and 'Turn energy') and also the energy they lose by bumping into other components of the model ('Agent/Rock bump energy'). COBWEB allows both sexual and asexual reproduction, but for demographic modeling, we will focus on the first case. In this case, the pregnancy period and chance of breeding can be modified.

Resources

Another of COBWEB's fundamental tools is to generate resources. Resources are the primary energy source for the agents. Each agent has a default corresponding resource, but the consumption of resources by different agents can be modified in the Food Web tab.

There are many parameters that can manipulate resources, under the Resources tab. The number of resources and their generation and depletion can be changed. Also, there are multiple ways to use resources. In our project, resources represent government policies that raise fertility.



Agents (triangles, Resources (squares), and Waste (checkers).

Waste

In the waste tab, ‘Waste consumption energy’ represents the change in energy when an agent consumes waste. By setting it to a positive value, the agent will gain energy after consuming the waste. This indicates that the waste provides energy to the agent consuming it and hence it can be regarded as good waste. On the contrary, negative values lead to an overall reduction in the agents’ energy. ‘Step waste energy loss’ is a punishment parameter that represents the energy loss when an agent steps into waste. Additionally, there are waste gain and loss limits that represent the threshold values for the amount of energy needed to produce waste and the energy lost by producing waste respectively. ‘Waste decay’ reflects the rate at which unconsumed waste decays. In our model, waste represents the consequences of low birth rates. So, a negative ‘Waste consumption energy’ can be used to replicate this.

Specialty Features

Zones

The COBWEB simulation space can be divided into regions representing different environments. The Abiotic Factor Tab includes a wide range of dynamic and static patterns to choose from. Once a factor pattern is chosen, bands can be introduced into the environment by clicking on the patterns to add the active factors block and the number of bands can be amended. Each band has a designated value and bands with the same designated value have the same regional properties. Punishments can be implemented to restrict agents from venturing outside their designated band.

The Agent Abiotic tab can be used to tailor the behavior of agents in different bands. The preferred band for each type of agent can be assigned by inputting the band-designated value into the preference value section for each agent. To assign multiple preferred bands, we can insert a preference value range that represents the range of corresponding bands. Lastly, we can set a value for preference difference factor which represents the extent of punishment on the agent and choose a parameter of which punishment takes place. “Step energy” is the best punishment parameter if we want to observe a rapid effect based on the locations of the agents. In the Resources tab, we can do a similar tailoring procedure for food.

To simulate the urban-rural environment in our model, two agent types (urban/ rural residents) and two bands (urban/ rural area) will be introduced. Preference values for the agents should be set to align with the region they should be in. To prevent urban residents from venturing into a rural zone (or vice versa), we will check the punishment box for each band, set a non-zero preference difference factor, and select a punishment parameter for the agents.

Aging

Aging	☑
Age limit	300
Aging rate	100

Aging is one of COBWEB's specialty features that can be applied to agents. Aging is found under the Agents tab. As in the real world, it allows the hypothetically immortal agents to age.

1. Aging: First, select the aging checkbox to toggle on the feature. If it is not checked, then none of the aging settings will apply.
2. Age limit: agents will die after the time stamp reaches the indicated value. If aging is not used, agents could hypothetically live forever. Furthermore, each tick in time can be used to represent any unit of time such as hours, or years.
3. Aging rate: this controls the amount of energy extracted from food. Therefore, a higher aging rate will cause agents to die more quickly, as they will not intake nutrients efficiently. In general, this means that agents will have less energy to expend, whether for movement or reproduction.

Aging can be used in a range of situations. In our population decline project, elevated aging rates are one of the most typical consequences present. Even more, COBWEB allows a high aging rate to affect the ability of an agent to spend energy, and hence reproduce. As such, aging can be used to induce the decreasing birth rates of a population and to accurately represent the current situation in a country.