# A Three Industry Macroeconomic Model of a Closed Economy

Ian Stuart

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**Abstract**

Modern economies are extremely complex and it is easy to become lost in the complexity of the world around us. Economics is a social science and is only limited by Natural Science and human behavior. By providing the means of simulation, agent based models can give us new ways to analyze and explore both hypothetical and existing economies. In this paper I present a minimalist model of a closed economy with the primary purpose of demonstrating mechanisms in which the share of labor shifts between industries. A key attribute of the model is its imposed exponentially increasing productivity. The model also presents a modified/alternative way of classifying the sections of an economy that is particularly convenient for the purposes of agent based modeling and computer simulation. The results of the repeated simulations demonstrate the emergence of important economic behaviors and suggests that the model, or future iterations of it, could have considerable practical use.

## 1 Introduction

Agent based models can have great potential to improve the understanding of particular processes and mechanisms, to help evaluate and verify and refine theories, and to improve upon existing educational methods (Edmonds & Meyer 2013). In recent years agent based models have become increasingly important in economics (Chen et al., 2014, p. 140). In this paper I mention a few economic models for comparison and then describe my model in detail.

In "Innovation and Employment: An Agent-Based Approach" Neves et al. (2019, January 31) explore the relationship between innovation and employment. The model described in their article implements product innovation, which is not detailed in my model and is thus not directly comparable to any feature of my model. Their model also details process innovation, which allows for the same production with less labor; as process innovation increases overall productivity relative to the number of employees, it could be loosely compared to the increasing productivity that exists in my model. The implementation of process innovation and the simulation results support the idea that increasing productivity has a negative influence on employment, which the authors also felt was logically derivable in general. The model described does not detail inventory or mechanisms of consumption but instead assumes everything produced is consumed within the same time step (Neves et al., 2019, January 31).

Both the Eurace@Unibi model detailed by Dawid et al. (2011, October) and Lagom generiC model detailed by Furst et al. (2009, January) simulate closed economies. They both implement loans, debt, interest, firm/share ownership, dividends, and variation in employee pay; none of which are included in the model I detail in this paper. They both, in common with my model, implement consumption that is affected by the income and monetary holdings of individual agents (Dawid et al., 2011, October; Furst et al., 2009, January).

Models that depict only a section of an economy are more common than those than depict a whole economy (Chen et al., 2014, p. 140); thus it seems apparent that there is ample cause for further macroeconomic agent based modeling. Exploration, research, development, and collaboration in this area could someday, in a responsible manner, lead to greater public accessibility to the potential insights that agent based models can provide.

From the perspective of where my development process started, representing an economy in its entirety (as opposed to just modeling a section of an economy) reduced the degree that the model relied on assumptions and, even though the model is subjunctive, increased its inherent validity.

The next seven sections (up to but excluding the discussion section) denote the seven elements described in the ODD protocol (Edmonds & Meyer, 2013;Grimm et al., 2020).

## 2 Purpose And Patterns

### 2.1 Purpose

The main purpose of this model is to demonstrate a mechanism in which, during the exponential increase in productivity, the relative share of labor in an economy shifts between industries. A key characteristic of the model is that it accounts for all money within the simulation, doesn't include debt, and includes only a single mechanism for the addition of new money into the scenario (and no mechanism for money to disappear within the model).

#### 2.1.1 Patterns

A number of key patterns/characteristics were key in the design of this model. Firstly, in line with the stated purpose, a significant shift in the share of the economy's labor/employment between industries was used as criteria for designing and evaluating the model. More specifically, the model aims to reproduce the growth of an industry that outpaces other once dominant industries. Secondly, in order to help maintain a reasonable level of comparability to real world economies, the model was also designed and evaluated based on its ability to simulate a growing population. Thirdly, though not easily verified by someone observing the graphical output of this model, I also designed and evaluated the implementation of this model based on its ability to self-audit and verify that there are no financial discrepancies.

# 3 Entities, State variables, Scales

## 3.1 The Three Industry Agents

The model uses three industries to represent an entire economy. Each industry produces its own "consumable". Consumables are not tracked after they are purchased and used for their final use (they are then deemed to have been consumed). Table 1 lists the three consumable types along with the amount of that consumable that an employee can produce in a time unit at the start of the simulation when the *length of workday* is 100% and the *adjust production rate* is also at 100%. The table also indicates the amount of the raw material consumable that is needed to produce the listed "base quantity produced at once"; the ratio between these two values will always be the same regardless of the *length of workday* and *adjust production rate* values (which both affect the amount produced in a time step).

| Consumable | Base Qty Produced At Once | Input Raw Material Required For Production |
|---|---|---|
| Raw Material | 7 | 0 |
| Necessity | 16 | 5 |
| Discretionary | 16 | 1 |

Table 1: The three types of consumables in the model, which also represents the three industries in the model.

Near perfect competition is assumed to exist within each industry. The behavior of an industry as a whole therefore does not appear to seek the maximization of profits (Pettinger 2019, May 28).

For the purpose of minimization, administrative costs are not considered in the model; industries are the only employers in the model and employee pay does not vary or change.

The raw material industry produces the raw material consumable that is required for production within the other two industries. Raw material cannot be used or purchased by individual people. There is no limit on the amount of raw material that could be yielded except by the constraints imposed by productivity, finances, and a limited number of employees.

The consumable produced by the necessity industry is required for the survival of individual people in the model. A fixed amount of the raw material consumable is required to produce a unit of the necessity consumable (see table 1). This industry directly purchases raw material from the raw material industry. Because people need the necessity consumable and the necessity industry requires the raw material consumable for production, both the necessity and the raw industries are each considered an *essential industry.*

The consumable produced by the discretionary industry will be purchased by individuals that would still have enough of a financial safety net after purchasing the discretionary consumable. The more extra money people have, the more of the discretionary consumable people purchase. A fixed amount of the raw material consumable is required to produce a unit of the discretionary consumable (see table 1). This industry also directly purchases raw material from the raw material industry.

Table 2 lists the main industry state variables.

## 3.2 The Person Agent

A person is required as an employee in an industry in order to produce the industry's consumable. An adult person can be single or in a romantic relationship. People in a romantic relationship can have up to four children. Single adults each require a fixed amount of necessity each time step. The amount of the necessity consumable required for a couple in a relationship and their children is calculated together. A couple in a romantic relationship require slightly less of the necessity consumable than the two otherwise would require individually. Non-adult children of a couple require less than adults do.

Adults that have not reached retirement age will always seek to be employed. People that do not have enough funds to meet their necessity requirements will ask the government for assistance. If a person still doesn't have enough funds to meet their necessity requirements (or the industry doesn't have enough of the consumable) they will have failed to meet their needs and will have a fixed chance of dying (chosen at (pseudo) random).

Table 3 lists the main person state variables.

| Variable | Variable Type and Units | Meaning |
|---|---|---|
| Jobs | List of Jobs | This list contains all the open jobs in an industry |
| Industry Records | List of Records | This list is used both by the industry itself, the government, and for presenting data at the end of the simulation |
| Product Quantity | Real Number | Represents the inventory of the consumable that is sold as the industry's product |
| Product Type | Consumable | One of three product types that the industry produces |
| Product Sale Price | Integer | Current sale price of the industry's product |
| Input Consumable Quantity | Real Number | The inventory of the consumable required for production |
| Money | Integer | Monetary unit representing the balance of the industry |
| Daily Production | Real Number | Amount of product produced in the current time step |
| Daily Costs | Integer | Money spent in the current time step (includes wages, excludes tax) |
| Wages Paid | Integer | Money paid in wages in the current time step |
| Tax Paid | Integer | Money paid for taxes for the current time step |
| Revenue | Integer | Money received from selling product in the current time step |
| Met Demand(Qty Sold) | Integer | Quantity of product sold in current time step |
| Unmet Demand | Integer | Quantity of product requested that wasn't sold in current time step |
| Below Expectation | Boolean | Whether any employee did not produce in the current time step |

Table 2: The main state variables of each industry agent.

| Variable | Variable Type and Units | Meaning |
|---|---|---|
| Reproductive Gender | Reproductive Gender | One of two possible Reproductive Genders |
| Job | Job | A job ties a person to his or her industry of employment |
| Biological Relationships | List of biological relationships | Includes parents and children |
| Romantic Relationship | Romantic relationship | Ties a person to their significant other |
| Money | Integer | Monetary unit representing the balance of the individual |
| Time Initialized | Integer | Time initialized |
| Birth Time | Integer | Equal to time initialized minus age at initialization |
| Failed To Meet Needs | Boolean | Whether a person has failed to meet their needs |
| Alive | Boolean | Whether a person is still alive |
| Home | Home | A home has list of inhabitants and whether all of their needs in the time step have been paid for. |

Table 3: The main state variables for each person agent.

### 3.3 The Government Agent

The final type of agent in the model is the government. The government agent is intended to help the with economic stability of the model. The government collects taxes so that it can provide social security payments to people that have reached the designated retirement age as well as assistance to people that lack sufficient funds to afford their required necessities. The government will also reduce the retirement age or the *length of workday* for the model if unemployment is too high. Table 4 lists the main government state variables.

### 3.4 The World

The World entity could also be considered the environment. The world is the global point of access in which any of the models agents can be accessed. The world also keeps time. Table 5 lists the main state variables of the world entity.

### 3.5 Scale

The range of the person population in the model, which is derived by a number of factors, was calibrated keeping in mind reasonable growth rates, desired detail, and practical computational time-frames.

Desired detail and computational time was considered in choosing that a time step would represent one month.

The model simulation spans 230 years. The time span of the model was arrived at by the accumulation of a variety of factors. The time span needed to be long enough for the populated agents to arrive at their own more naturalized states (the statistics of the ages of the initial population, for example, will not match the more derivative tendencies of the agent population as time progresses) while still having ample time in the simulation for observation after that point. Some of the resulting output from running the model, for example, focuses just on changes within the middle 210 years of the simulation. While the model's level of minimization and generalization are such that it is not intended to be closely calibrated to match historical data, the time span was also chosen knowing that the results could loosely be compared to existing economic records.

| Variable | Variable Type and Units | Meaning |
|---|---|---|
| Money | Integer | Monetary unit representing the balance of the government |
| Income Tax Rate | Real Number | Used for collecting income tax |
| Profit Tax Rate | Real Number | Used for collecting profit tax |
| Sales Tax Rate | Real Number | Used for collecting sales tax |
| Inheritance Tax Rate | Real Number | Used for collecting inheritance tax |
| Revenue from Taxing Income | Integer | Revenue from taxing income the current time step |
| Revenue from Taxing Profit | Integer | Revenue from taxing profit the current time step |
| Revenue from Taxing Sales | Integer | Revenue from taxing sales the current time step |
| Revenue from Taxing Inheritance | Integer | Revenue from taxing Inheritance (includes 100% "death tax" in cases where a deceased person has no children) the current time step |
| Parent to a New Child Payment | Integer | The amount of money that is fabricated and paid to each parent when his or her new child is born |
| Retirement Age | integer | Age in years when individuals will stop working or stop looking for work |
| Money Added | Integer | Money added to the economy in the current time step |
| Last Total Scenario Money | Integer | Total scenario money at the end of the previous time step |
| Amount Paid to Assist People | Integer | Money the government paid in social security payments and for additional assistance than people needed for the current time step |
| Industry Asking For Help | Integer | Count of how many times the discretionary industry asked for assistance since last time it was given assistance |
| Financial Statistics Helper | Financial Statistics Helper | Object that sorts a list of each person's balance each time step to calculate financial information. |
| Government Records | List of government records | List of government records used both by the government itself and for presenting data after the simulation is completed |

Table 4: The main state variables of the government agent. See the "Observation" Section to see the full list of variables kept in the *government records* list.

| Variable | Variable Type and Units | Meaning |
|---|---|---|
| Industries | Industry List | This list contains the three industries. |
| People | Person list | This list contains all the living people in the model |
| The Government | Government | The government |
| Time | Integer | Current time step |
| Year | Integer | Current time step divided By 12 |
| Process Dead People List | Person with integer list | List of dead people each with a time in which their parents can be freed for deletion from memory (people are kept in memory to this point for tracing biological relation). |

Table 5: The main state variables of the world entity.

# 4 Process Overview, Scheduling

Time is represented in discrete steps, with each time step representing one month.

The model cycles through 7 steps each time step until the scenario time duration is met or there are no living people left:

1. **Update Relationships**
   (a) **Update Pregnancies** A list of existing romantic relationships is recreated each time step; the order of this list will match the order of the first person in each relationship in the globally accessible list of people.
      i. **Check If A Couple Becomes Pregnant**
      ii. **Add New People Born From A Relationship**
   (b) **Pair Individuals Into Relationships** The algorithm for this process is described in section 8.1.1 (under "Pairing individuals into relationships"). This algorithm relies on people being sorted into a list of single males and a list of single females. The order of these lists will be consistent with the order in which people were added to the model and the algorithm described will follow the same order of these lists.

2. **People Exercise Their Executive Function** The order that people are cycled for this process will be the reverse order than they where added to the model (the reason the order is reverse in this case has to do with the models code implementation and allows for the removal of people at this point in code execution upon).
    (a) **People Go To Work, Look For Work, Or Collect Social Security**
    (b) **People Satisfy Their Needs** Each person in a "home" (or, if they are a child, their first living parent) will ensure the required necessities for a home are paid for in a time step.
    (c) **Adults Seek To Satisfy Their Wants By Purchasing the Discretionary Consumable**
    (d) **People Who Have Failed To Meet their Needs Have a Chance Of Dying. People Who have Met Their Life Expectancy Die.**
3. **People Submit the Amount of Money They Have.** This is done in the order people were added to the model (but, as it happens, the order here could not be consequential).
4. **Industries Exercise Their Executive Functions.** The specific order here is the Raw Material, the Necessity, and then the Discretionary industries.
    (a) **Update Number Of Jobs**
    (b) **Check For Needed Raw Material**
    (c) **Update Sale Prices**
5. **Industries Pay Their Taxes and Update Records** The specific order here is Raw Material, Necessity, and then Discretionary.
6. **Government Exercises its Executive Function**
    (a) **Adjust Profit Tax Rate**
    (b) **Adjust Income Tax Rate**
    (c) **Adjust Sales Tax Rate**
    (d) **Adjust Length of Workday**
    (e) **Adjust Retirement Age**
    (f) **Adjust Parent to a New Child Payments**
    (g) **Update Records** (and verify the model has no financial discrepancies)
7. **Progress Time** (this is also where *adjust production rate* gets updated)

# 5 Design Concepts

## 5.1 Basic Principles

### 5.1.1 Serial Programming

This model was implemented to use standard serial programming; there was not sufficient cause to explore parallel programming.

### 5.1.2 Three Industries Representing an Entire Economy Compared to the Classical "Three-sector Model"

A classical three-sector model divides an economy into raw materials, manufacturing, and services (Zeder 2020, October 26). If specifically the three industry aspect of my model was viewed as a generalization/abstraction, the most important distinction between it and the classical three sector model is that my model doesn't distinguish between manufacturing and services and instead distinguishes between whether or not the final products/services of the two non-raw material industries (or sectors) are considered necessities.

## 5.2 Emergence

The models primary results emerge from an economy with an increasing production rate where industries create jobs based (directly or indirectly) on demand.

Since productivity is consistently increasing throughout the simulation, industries are able to reduce prices as the simulation progresses. The reduction of prices across the board where spending money remains about the same is deflation (Ashford 2020, December 16). This emerges as the result of the following factors:

- Productivity is consistently increasing throughout the simulation (this is directly imposed).
- The model never adjusts the numerical pay that employees receive.
- The industries are modeled to generally keep prices at what they can afford.

### 5.3 Adaptation

The government has three separate taxes that it may adjust based on unique thresholds and unique maximum change frequencies. If, for example, the government needs to quickly adjust its revenue several tax rates might be adjusted in a short amount of time. A fourth tax rate, inheritance tax, is not adjusted throughout the simulation (but in cases where a deceased person has no children 100% of the person's money goes to the government).

The government has multiple tiered thresholds that it uses for determining whether to reduce the *length of workday* or to reduce the retirement age and by how much. Unemployment rates are used in determining whether a smaller or larger change is made. This allows for quicker changes when the unemployment has been very high or more gradual changes when the unemployment has been moderately high. Both the retirement age and *length of workday* are used for affecting unemployment.

### 5.4 Agent Objectives

If I described agent behavior more generally as objectives, I would say that the objectives for an industry agent are to maintain a "Financial Standing" (equation 9) near one (or one thousand when converted for display on a graph) and a "Ratio Of Target Inventory" near one (equation 10); for the government agent are to keep people alive and help economic stability; and for the person agent are to survive and meet his or her own needs and, when able, to satisfy wants and reproduce.

### 5.5 Agent Learning

Agents in this model do not exhibit learning behavior.

### 5.6 Agent Predicting

Part of the design and implementation process involved iterative testing and experimentation with the aim of avoiding simulation instability. Agents do not explicitly predict what will happen, but industry and government agents could be considered predictive as their behavior considers past and present information. The person model only considers current model information in their behavior and is the least calculating of the three agents.

### 5.7 Agent Sensing

While the architecture of the model generally follows common best programming practices, functionally it does not impose significant limitations on the accessibility of current scenario information (which includes records from past time steps) from within individual agent models. Some of the information that agents use in the model are coded more as direct information access (for example, just "knowing" information) and some information that agents use is obtained/returned from other agents such as in some of the exchanges listed in table 6.

### 5.8 Interaction

Given enough time, at least collectively, all agents are bound to have at least indirect affects on all other agents. Since relationship pairing and reproduction are determined by a separate entity (the relationship helper), the model does not demonstrate any social communication. Table 6 lists a number of the model processes that involve direct agent interaction.

- Person $\overset{\text{look for work}}{\Longleftrightarrow}$ *Industry*
- Industry $\overset{\text{accept expected work}}{\Longleftrightarrow}$ *Person*
  - Person $\overset{\text{accept payment}}{\Longleftrightarrow}$ *Industry*
    - Government $\overset{\text{accept tax on income}}{\Longleftrightarrow}$ *Person*
- Government $\overset{\text{accept and provide assistance upon request}}{\Longleftrightarrow}$ *Person*
- Industry $\overset{\text{accept purchase of consumable}}{\Longleftrightarrow}$ Person Or Industry
  - Government $\overset{\text{accept sales tax}}{\Longleftrightarrow}$ *Industry*
- Industry $\overset{\text{pay profit tax}}{\Longleftrightarrow}$ *Government*
- Government $\overset{\text{help dying industry}}{\Longleftrightarrow}$ *Industry*

Table 6: Processes in the model that involve direct agent interaction.

## 5.9 Stochasticity

Stochasticity is intentionally used only sparingly in the model. The model does not implement its own random number generator. Randomly generated numbers are used to determine the outcome of chances/probabilities in the model. Random numbers that the model uses are determined by the implementation of the java.util.Random class.

Random values are used for the original initialization of the person population. Random values with an even distribution are used for determining initial ages of adults, how much money initialized people start with, pairing the initial individuals into relationships, determining if initial couples have children, determining gender, and determining the initial children's exact ages.

During the simulation random values are used for relationship matching, determining if couples become pregnant, and determining gender when new people are born. In the situation that a person needs to choose between the two essential industries (the raw material and necessity industries) for employment, a random value is used to determine which.

Stochasticity is also used for determining if someone dies when they fail to meet their needs.

## 5.10 Collectives

### 5.10.1 Romantic Relationships And Family Relation

A romantic relationship in the model is the basis from which a home may be shared and up to 4 children may be produced.

**Romantic Relationship:**

Male $\longleftrightarrow$ Female

$\Updownarrow$

Shared Home $\rightarrow$ *reduces required necessities*

$\Updownarrow$

Up To 4 Children

(Children share a home with their parents only up to adulthood)

**Effects of Family Relation:**

- When a parent dies his or her living children receive any money that he or she had minus inheritance tax
  (if a deceased person has no living children the government will collect all of the money he or she had).
- People that share parents, grandparents, or great-grandparents will not be paired into romantic relationships.

### 5.10.2 Industries And Their Employees

Depending on perspective, the industry agents could individually be considered collectives as they maintain a large number of jobs that people belong to. For the purpose of minimization, all jobs of an industry are the same and there are no administrative jobs. Other than employee's economic contributions and the fact that they are employed, they do not have any affect on an industry's executive functions.

### 5.10.3 Maybe Symbolically (...the government could be considered a collective, but...

For the purpose of minimization and easier verification there are no government or government funded jobs (therefore this model does not implement the government as a collective).

## 5.11 Observation

Records kept by the model allow for this information to be displayed after a simulation is run. A program wrote for running the simulation and observing results uses graphs to display the information (and a few select pieces of data are displayed as text). Most of the graphs used are line graphs. The ratios of the government's revenue, the share of employees by industry, and the proportions of total scenario money held by each type of agent are displayed in stacked area graphs (data from records are translated into percents for these graphs).

- Government Records Related To Finance
  - Revenue From Taxing Profit
  - Revenue From Taxing Income
  - Revenue From Sales Tax
  - Revenue From Inheritance Tax (includes 100% "death tax" from cases where a deceased person had no living children)
  - Amount Paid To Assist People
  - Rough Financial Standing
  - Adjust Production Rate

  - Profit Tax Rate
  - Income Tax Rate
  - Sales Tax Rate
  - Inheritance Tax Rate
  - Parent To A New Child Payments
  - Retirement Age
  - Length of Workday
- Government Population Records
  - Population
  - Retirement Age Population
  - Adult Population
  - Under 18 Population
  - Average Age
  - Unemployment Ratio
  - Average Person's Balance
  - Average Balance Of Top Quarter
  - Average Balance Of Bottom Quarter
  - Total Money That All People Have
- Records Kept By Each Industry
  - Money
  - Product Quantity
  - Input Consumable Quantity
  - Total Production
  - Product Met Demand (Quantity Sold)
  - Money Spent
  - Number Of Employees
  - Unfilled Positions
  - Unmet Demand
  - If Production was Below Expectation
  - Rough Financial Standing
  - Wages Paid
  - Tax Paid (Not Including Sales Tax)
  - Revenue
  - Sale Price

#### 5.11.1 Charts of the Final Test Simulation

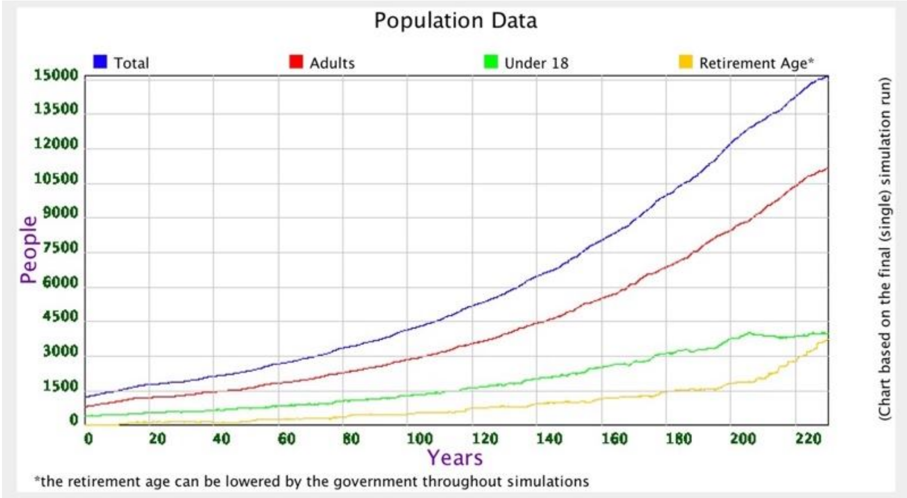


Figure 1: The population data from the final test simulation. Note that the adult population in this chart includes the retirement age population; also note that the designated retirement age changes throughout the simulation (see figure 7).

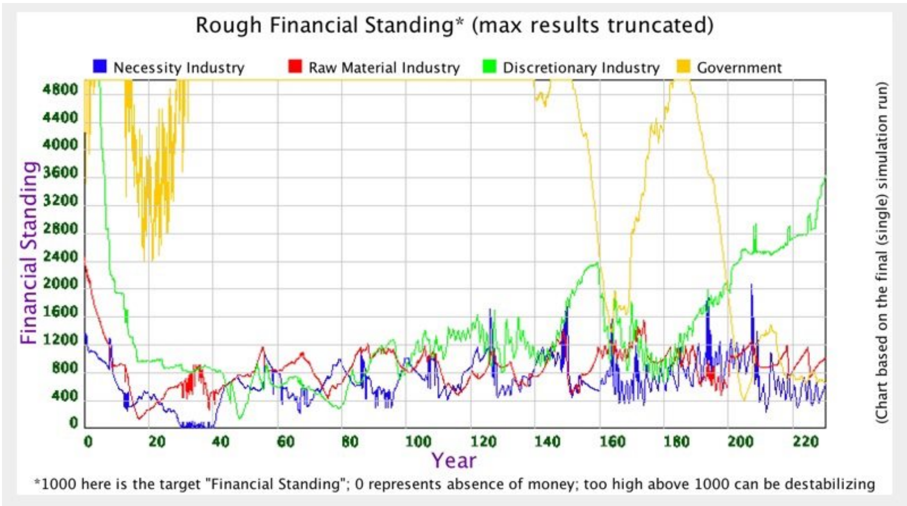


Figure 2: The rough financial standing values of the three industries and the government from the final test simulation. The "rough financial standing" value (equation 9, using a sample size of one, multiplied by 1000 for compatibility with the graph) proved valuable for getting a general idea of how these economic agents fared throughout the final test simulation. The rough financial standing value is also used by these agents themselves for making decisions.

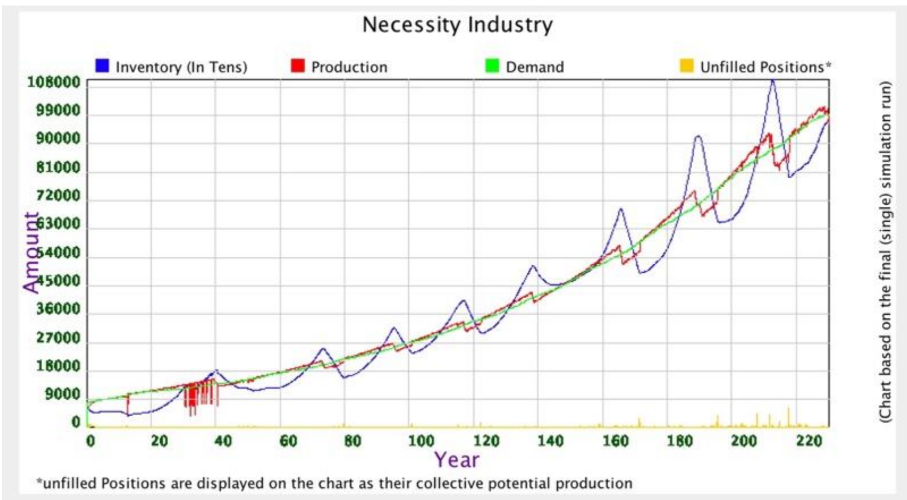


Figure 3: The inventory, production, demand of the Raw Material Industry throughout the final test simulation.

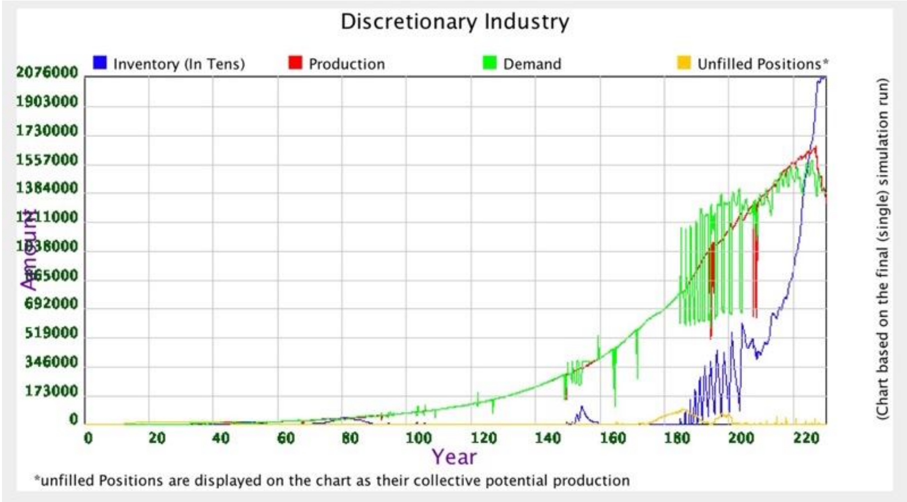


Figure 4: The inventory, production, demand of the Discretionary Industry throughout the final test simulation.

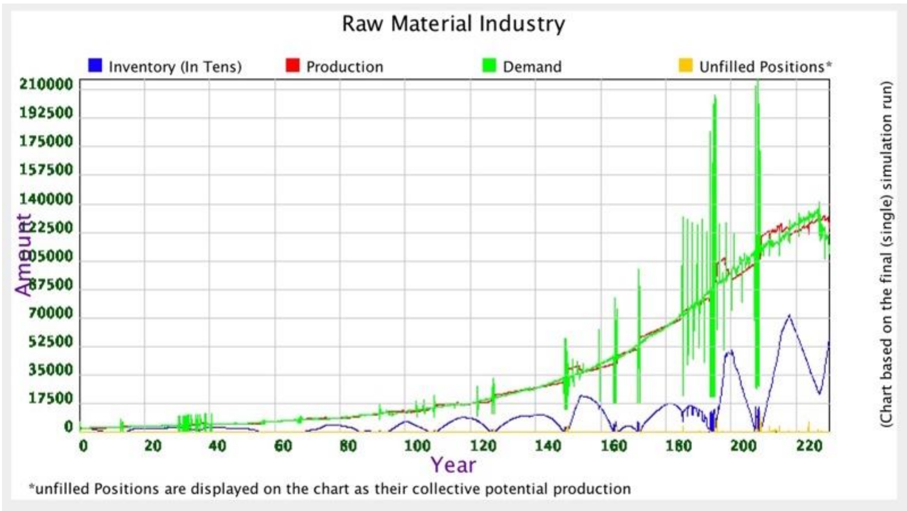


Figure 5: The inventory, production, demand of the Raw Material Industry throughout the final test simulation.


Figure 6: The relative base production rate throughout the simulation(s). Note that the production rate change is directly imposed by the model and will be consistent from one simulation run to the next.


Figure 7: The retirement age as adjusted by the government throughout the final test simulation.


Figure 8: The "length of workday" value as adjusted by the government throughout the final test simulation. This value depicts the relative amount of time an employed person works in a time step (for the same amount of pay).

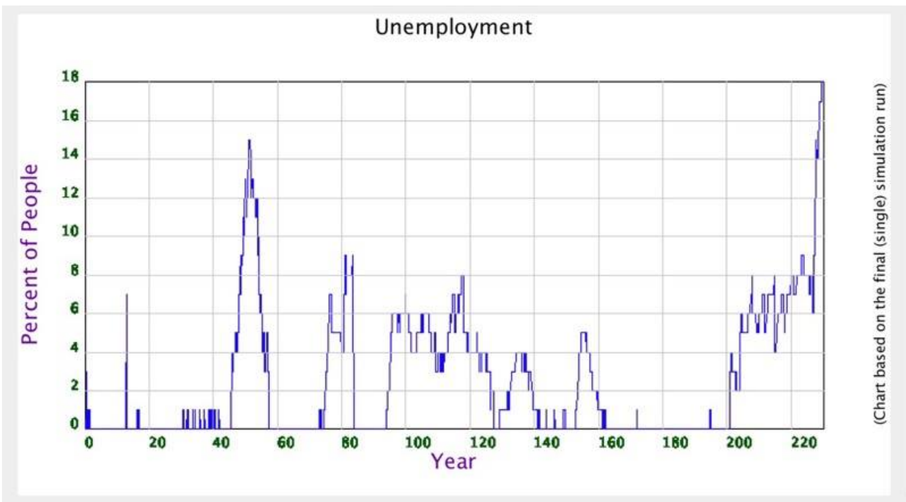


Figure 9: The unemployment rate throughout the final test simulation.


Figure 10: Consumable sale prices throughout the final test simulation. Note that monetary units in the model are discrete and there are no fractional prices between 1,2,3,4, ect.

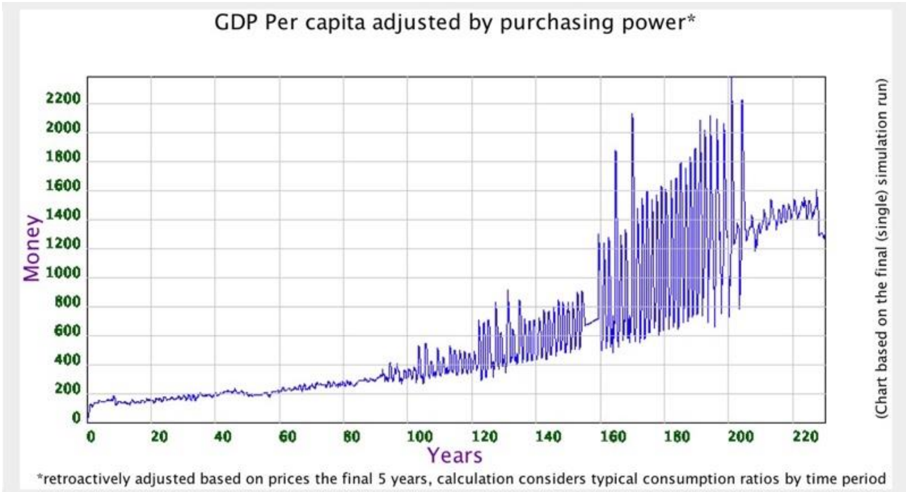


Figure 11: GDP per capita adjusted by purchasing power of the final test simulation. See equations 1 & 2 for how this value is calculated, which take into account typical consumption and is retroactively adjusted based on prices the last five years of the simulation. If you notice the significant fluctuation in this value particularly from the 160th - 200th year, the reason is that single monetary unit price changes are proportionately more significant towards the end of the simulation when prices are closer to zero.

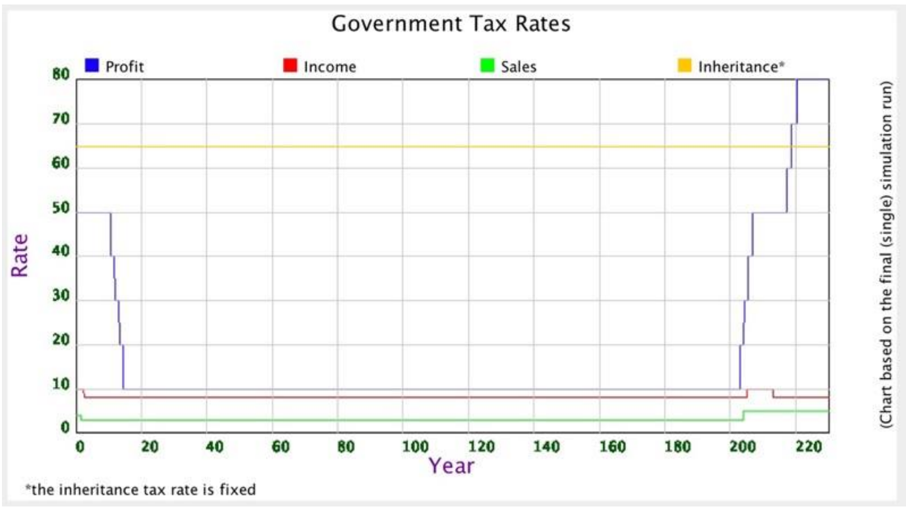


Figure 12: The government tax rates applied throughout the final test simulation.

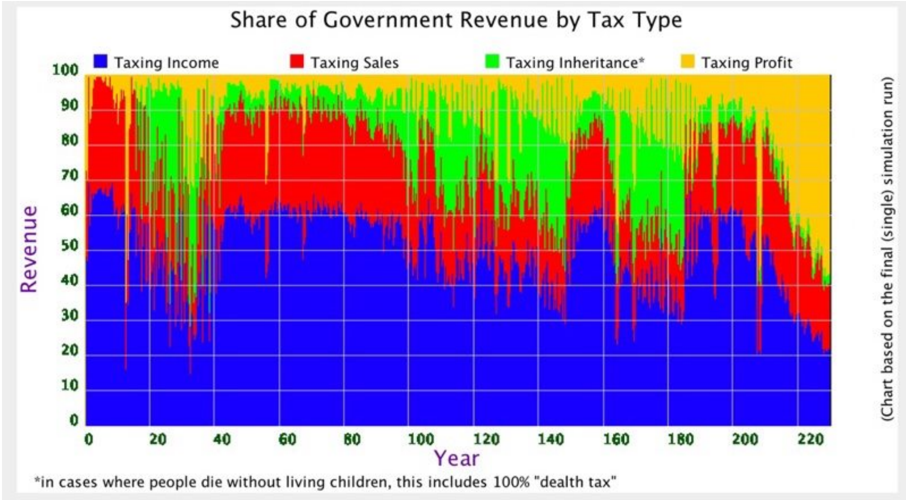


Figure 13: The relative proportion (out of 100%) of government revenue by tax type from the final test simulation.


Figure 14: The "Parent to a New Child Payment" amounts as adjusted by the government throughout the final test simulation. This value is the amount of money that is fabricated and given to each of the parents when a new person is born (this is the only process by which new money is introduced to an economy during a simulation).

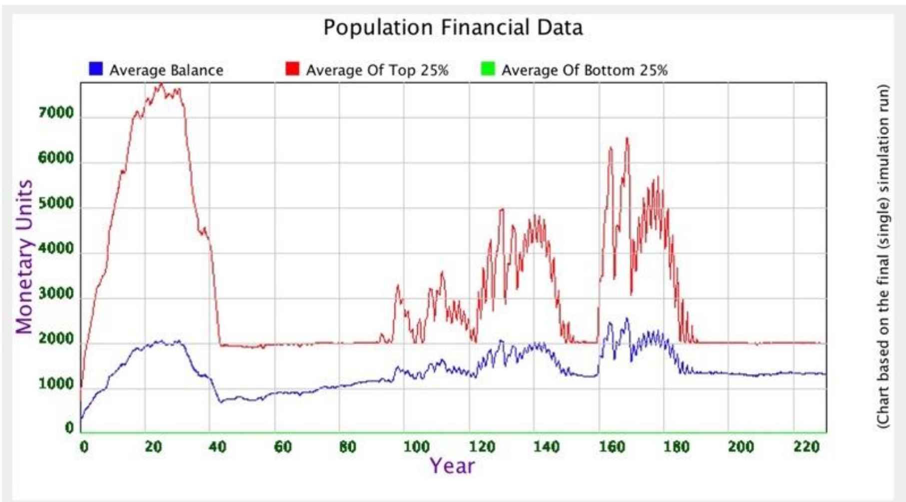


Figure 15: Population financial data of the final test simulation, which includes the average balance of the entire population, the average balance of the wealthiest 25% of the population, and the average balance of the least wealthy 25% of the population.

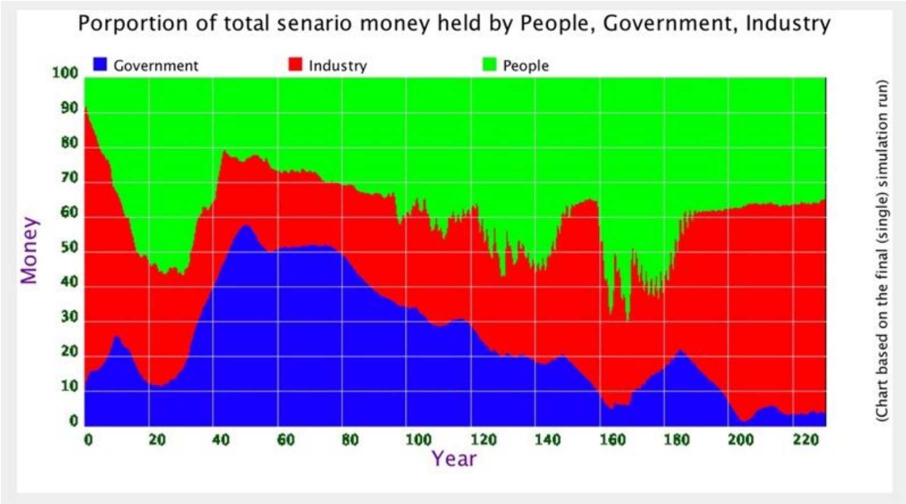


Figure 16: The proportion, out of 100%, of the scenario's total money held by each of the three agent types throughout the final test simulation.

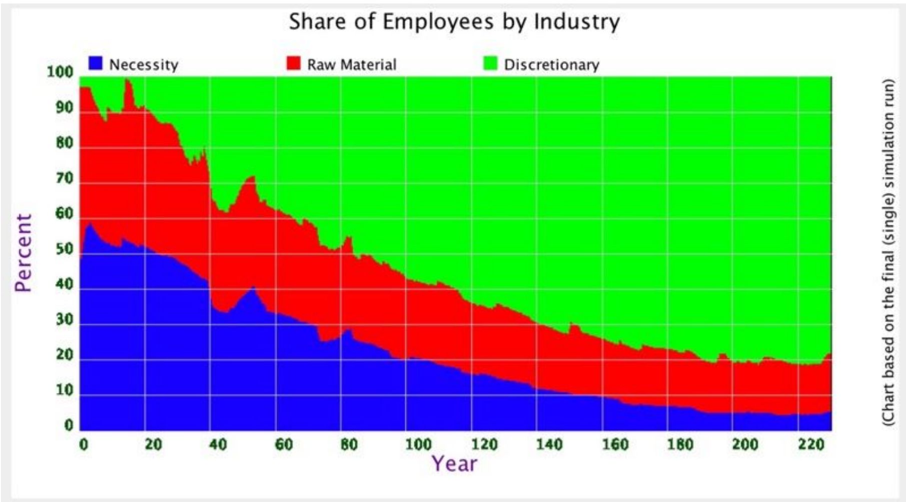


Figure 17: The proportion, out of 100%, of employees that work at each of the three industries throughout the final test simulation. The results displayed on the graph support the main purpose of this model as the results show the significant shift of the relative size (by number of employees) of each industry throughout the simulation.

#### 5.11.2 GDP per capita Retroactively Adjusted By Purchasing Power Based On Typical Consumption

One of the most illuminating graphs of observation is a line graph showing GPD per capita retroactively adjusted by purchasing power based on typical consumption (Banton 2020, November 30; Callen 2020, February 24; Hayes 2020, April 7). To determine this value the GDP per capita is first determined by adding the values of all produced final products in a year (Amadeo 2020, May 26) :

$$NP = NecessityProduction$$

$$NSP = NecessitySalePrice$$

$$DP = DiscretionaryProduction$$

$$DSP = DiscretionarySalePrice$$

$$GPC = GDPPerCapita = \sum_{i=t-11}^{t} \frac{NP_i * NSP_i + DP_i * DSP_i}{Population_i} \tag{1}$$

The average prices of the final products in the last 5 years of the simulation are used in comparison to the prices of each final product in each time step to retroactively adjust the per capita GDP by purchasing power based on typical consumption:

$$MT = MaximumTime$$

$$NSPA = NecessitySalePriceForAdjustment = \frac{1}{60} \sum_{i=MT-59}^{MT} NSP_i$$

$$DSPA = DiscretionarySalePriceForAdjustment = \frac{1}{60} \sum_{i=MT-59}^{MT} DSP_i$$

$$NS = NecessitySold$$

$$DS = DiscretionarySold$$

$$GDPPerCapitaAdjustedByPurchasingPowerBasedOnTypicalConsumption =$$

$$GPC * \left( \frac{NSPA}{NSP_i} * \frac{NS_i}{NS_i + DS_i} + \frac{DSPA}{DSP_i} * \frac{DS_i}{DS_i + NS_i} \right) \tag{2}$$

#### 5.11.3 Graphing and Viewing the Overlapping Results from Multiple Simulation Runs

At a certain point in the development process it became clear that viewing individual simulation runs wasn't always adequate for viewing the general behavior of the model. Viewing overlapping results on the same chart/graph offers an alternative way to informally discern rough statistical tendencies of the model. One disadvantage viewing the overlapping results (as opposed to viewing just the results of a single run) is that it can make it impossible to understand specific cause and effect events; for this reason I decided to include examples of both. All of the figures included in the article are from the same test (a single instance of the program running, which includes 10 simulation runs).

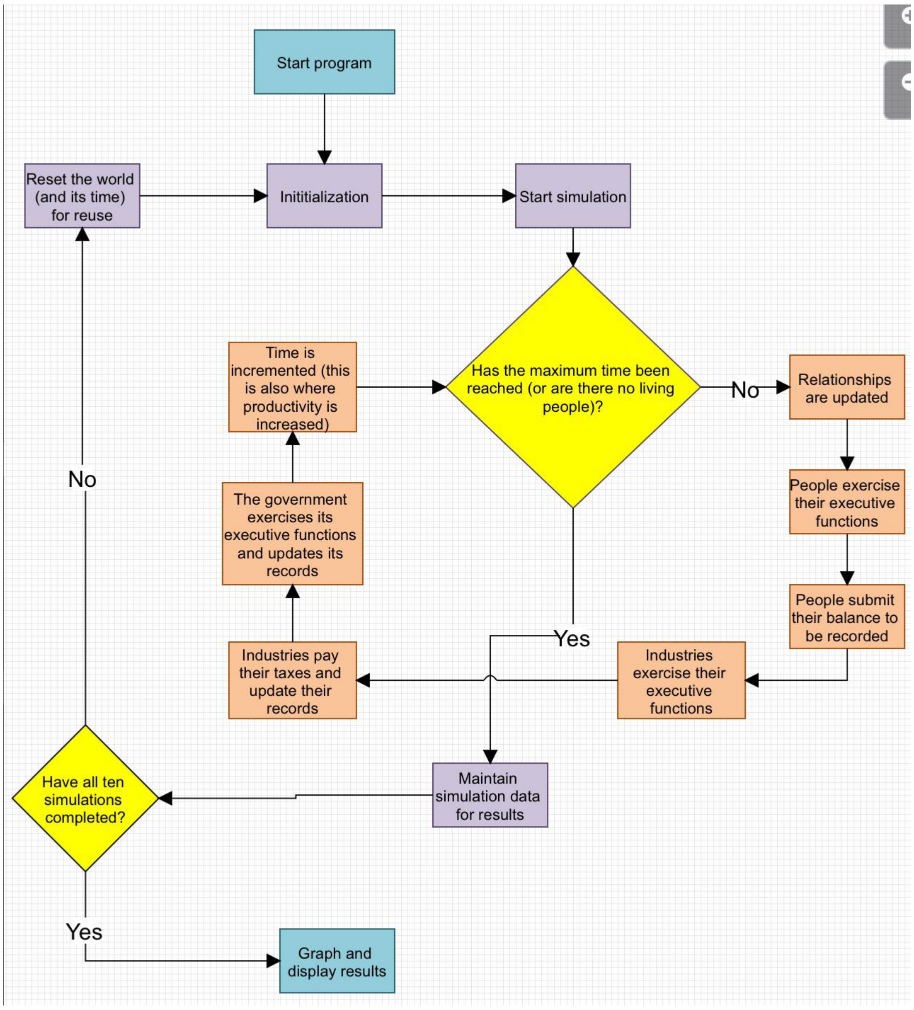


Figure 18: Flow chart of how overlapping results of ten simulations are collected for display.

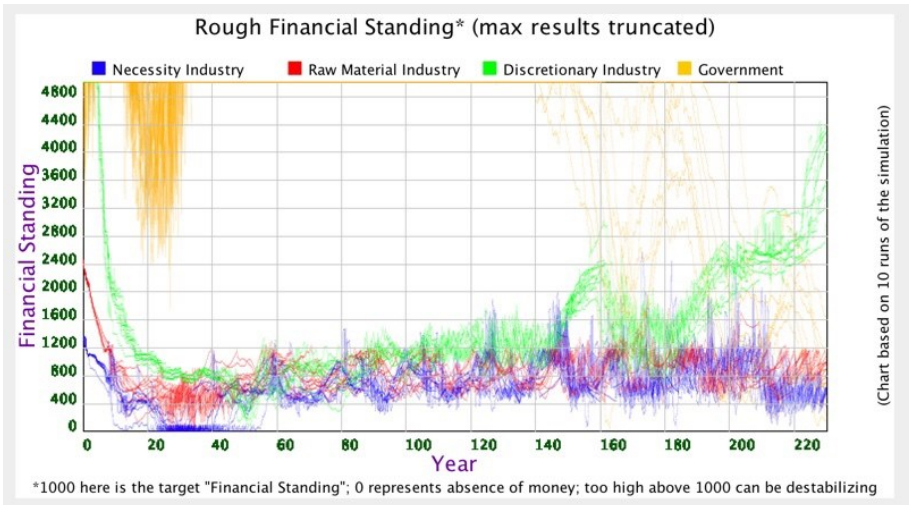


Figure 19: Overlapping results from all ten test simulations: the "rough financial standing" of all three industries and the government throughout the ten simulations. The rough financial standing value (equation 9, using a sample size of one, multiplied by 1000 for compatibility with the graph) proved valuable for getting a general idea of how these economic agents fared throughout the final test simulation. The rough financial standing value is also used by these agents themselves for making decisions. To view just the results of the final test simulation see figure 2.

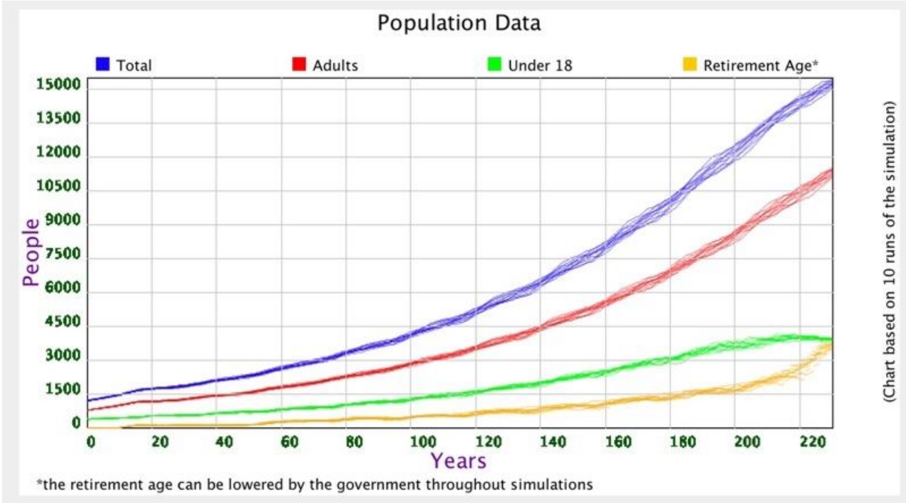


Figure 20: Population data from all ten simulations (note that the adult population in this chart includes the retirement age population). To view just the results of the final test simulation see figure 1.

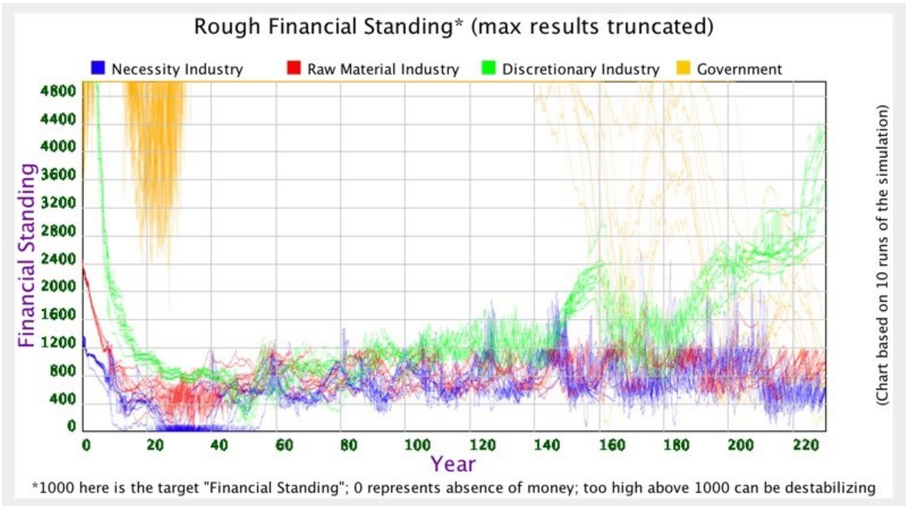


Figure 21: Overlapping results from all ten test simulations: the "rough financial standing" of all three industries and the government throughout the ten simulations. The rough financial standing value (equation 9, using a sample size of one, multiplied by 1000 for compatibility with the graph) proved valuable for getting a general idea of how these economic agents fared throughout the final test simulation. The rough financial standing value is also used by these agents themselves for making decisions. To view just the results of the final test simulation see figure 2.

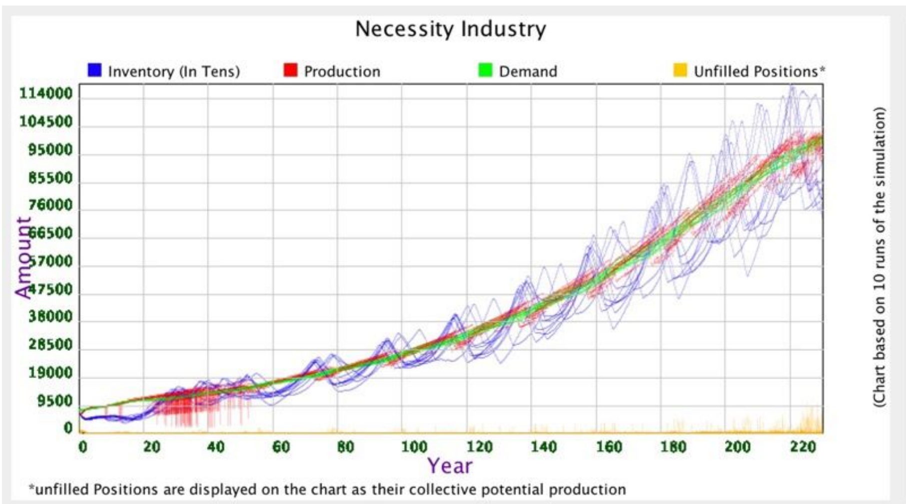


Figure 22: Overlapping results from all ten test simulations: the inventory, production, demand, and the potential production of unfilled positions of the necessity industry. To view just the results of the final test simulation see figure 3.

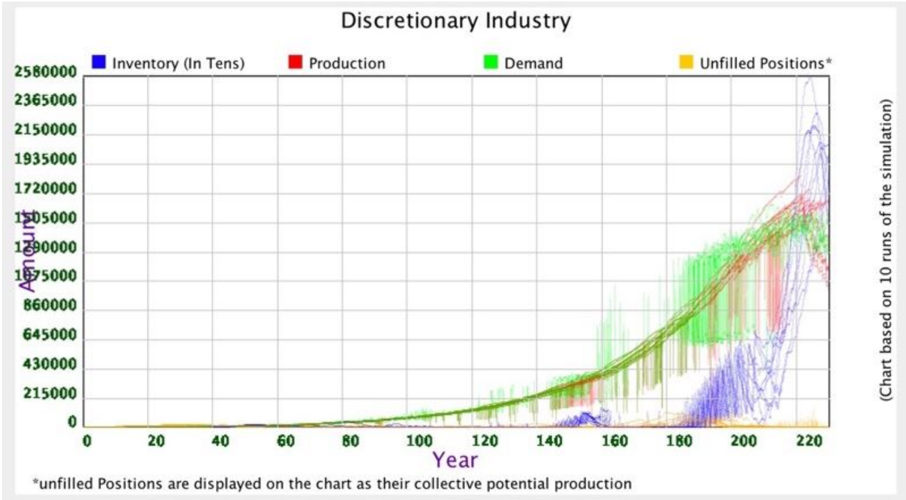


Figure 23: Overlapping results from all ten test simulations: the inventory, production, demand, and the potential production of unfilled positions of the discretionary industry. To view just the results of the final test simulation see figure 4.

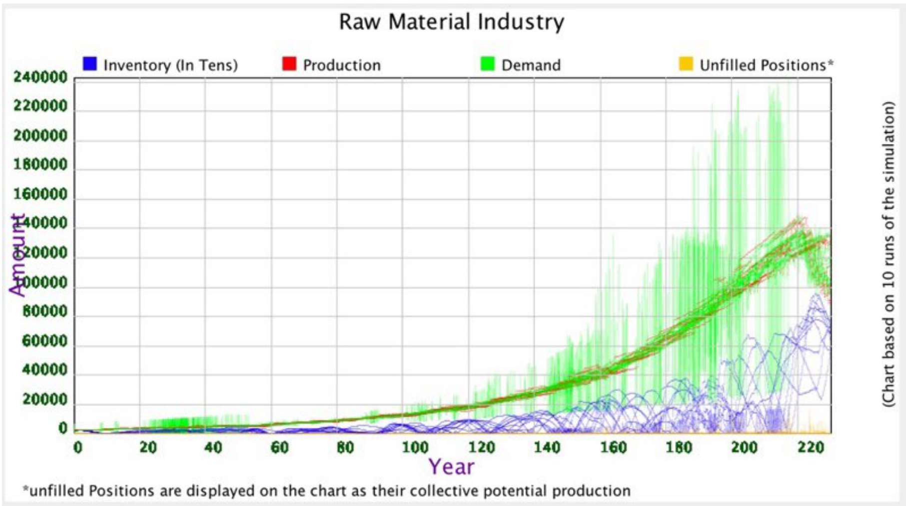


Figure 24: Overlapping results from all ten test simulations: the inventory, production, demand, and the potential production of unfilled positions of the raw material industry. To view just the results of the final test simulation see figure 5.

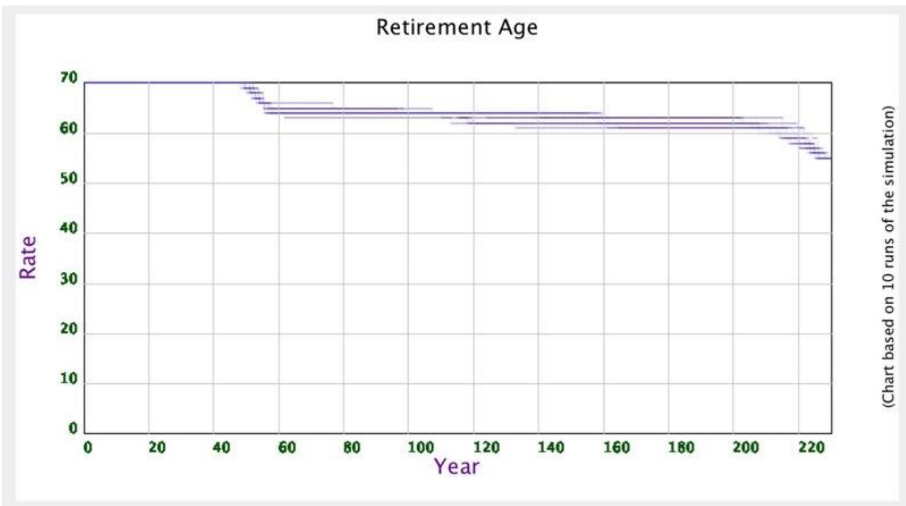


Figure 25: Overlapping results from all ten test simulations: the designated retirement age as adjusted by the government.

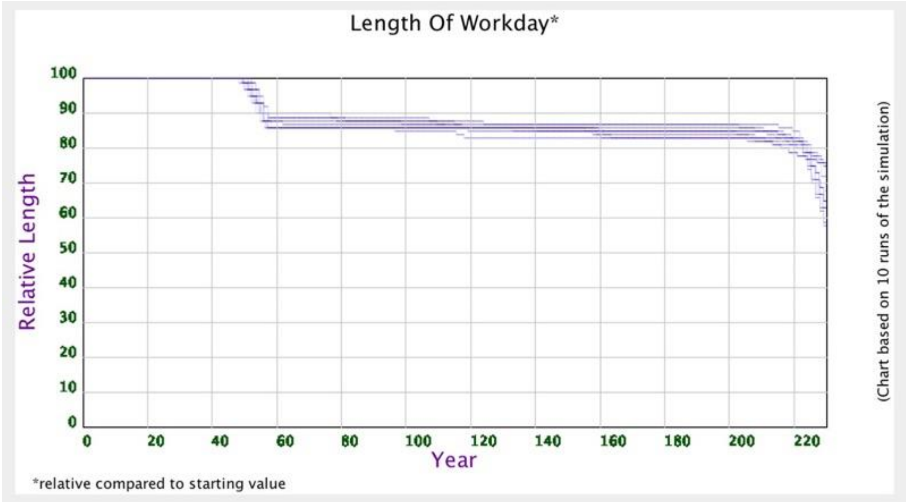


Figure 26: Overlapping results from all ten test simulations: the "length of workday" value as adjusted by the government. This value depicts the relative amount of time an employed person works in a time unit (for the same amount of pay).

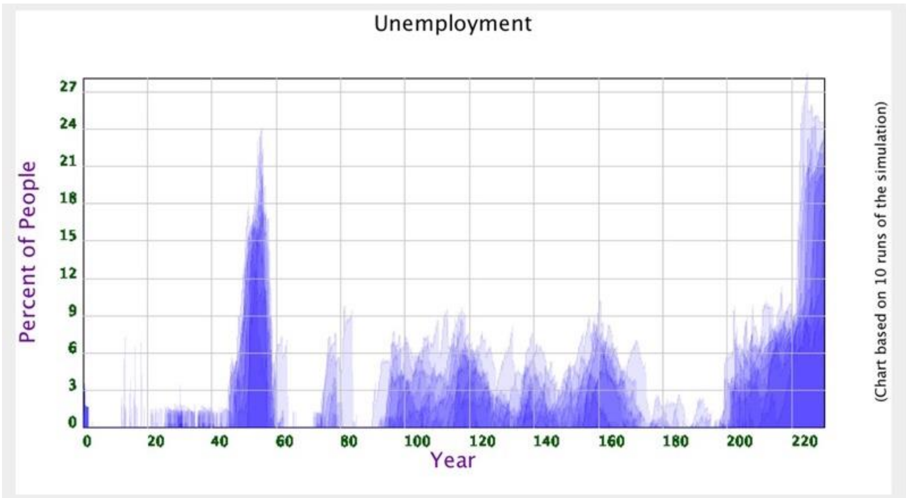


Figure 27: The unemployment rates throughout all ten test simulations displayed here on a "filled line graph" where the values below the unemployment rate are filled in. To view just the results of the final test simulation see figure 9.


Figure 28: Overlapping results from all ten test simulations: the sale prices of the three consumable types.

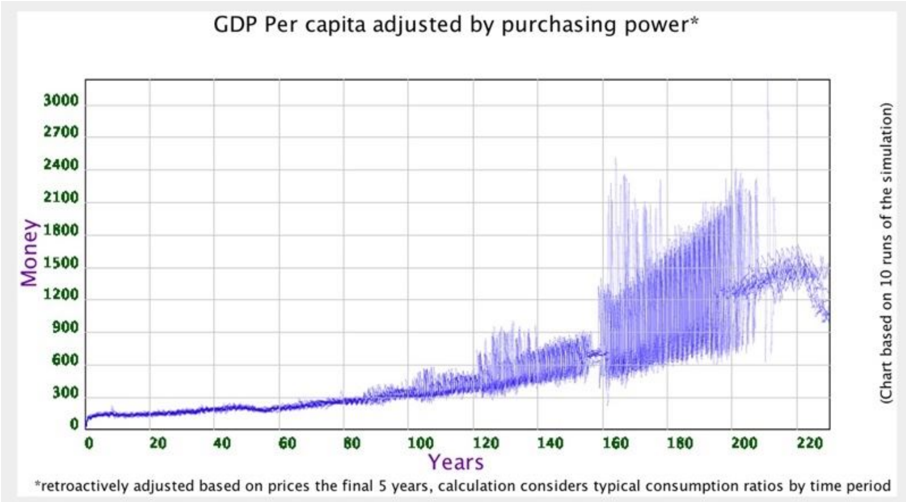


Figure 29: Overlapping results from all ten test simulations: the GDP per capita adjusted by purchasing power of the simulations. See equations 1 & 2 for how this value is calculated, which takes into account typical consumption and is retroactively adjusted based on prices the last five years of the simulation. If you notice the significant fluctuation in these value particularly from the years between 160 - 200, the reason is that single monetary unit price changes are proportionately more significant towards the end of the simulation (see figure 28). To view just the results of the final test simulation see figure 11.

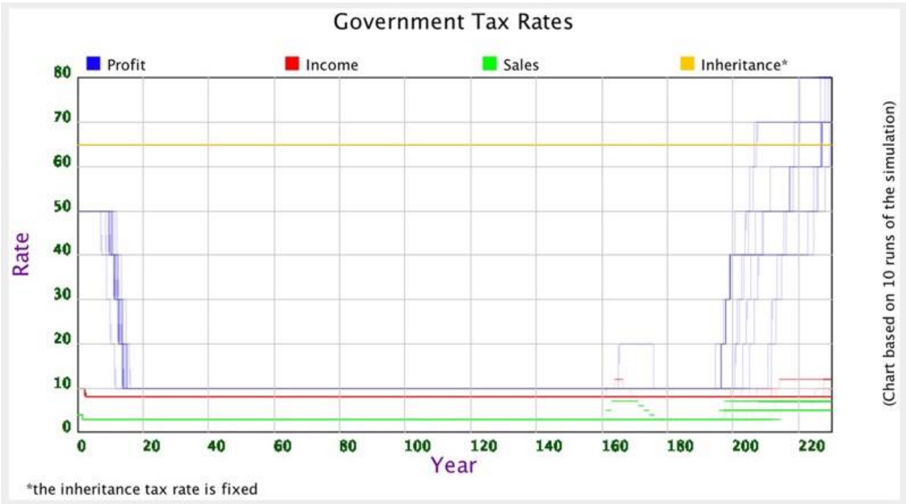


Figure 30: Overlapping results from all ten test simulations: the government tax rates applied throughout the simulations. To view just the results of the final test simulation see figure 12.

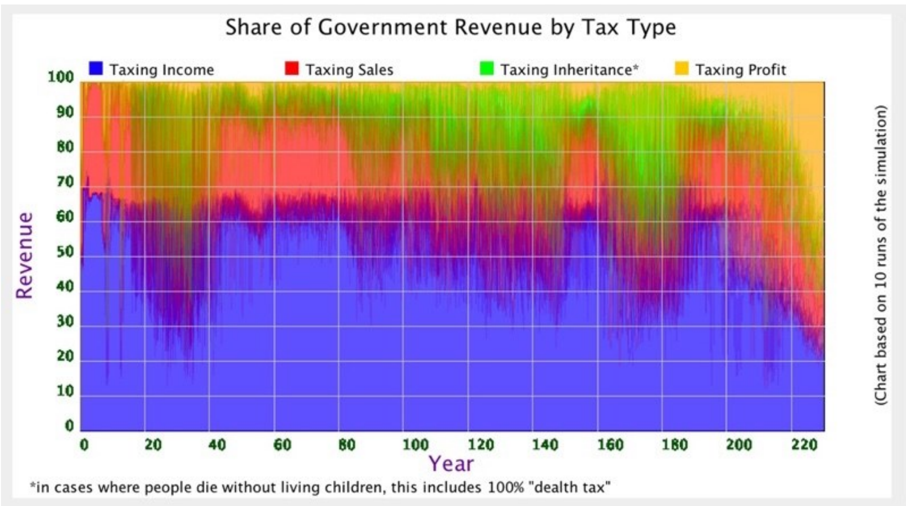


Figure 31: Overlapping results from all ten test simulations: the relative proportion (out of 100%) of government revenue by tax type throughout the simulations. To view just the results of the final test simulation see figure 13.


Figure 32: Overlapping results from all ten test simulations: the "Parent to a New Child Payment" amounts as adjusted by the government throughout the simulations. This value is the amount of money that is fabricated and given to each of the parents when a new person is born (this is the only process by which new money is introduced to an economy during a simulation). To view just the results of the final test simulation see figure 14.

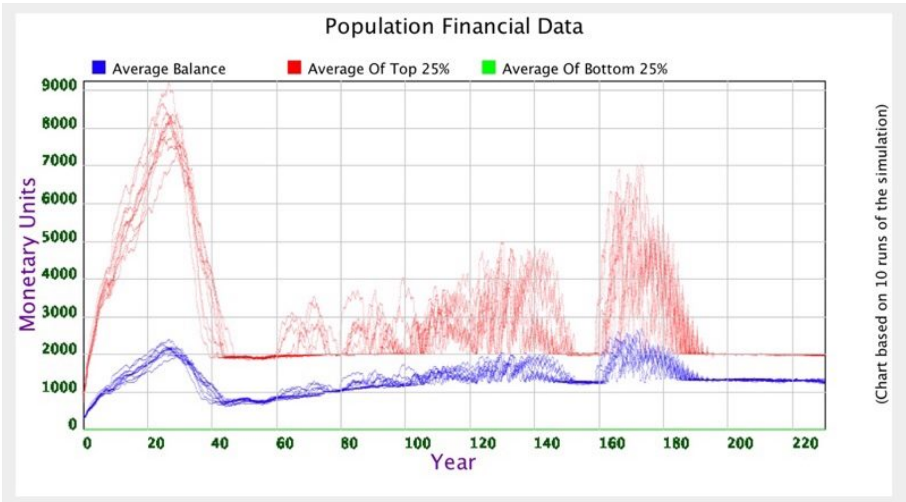


Figure 33: Overlapping results from all ten test simulations: the populations' financial data, which includes the average balance of the entire population, the average balance of the wealthiest 25% of the population, and the average balance of the least wealthy 25% of the population throughout the simulations. To view just the results of the final test simulation see figure 15.

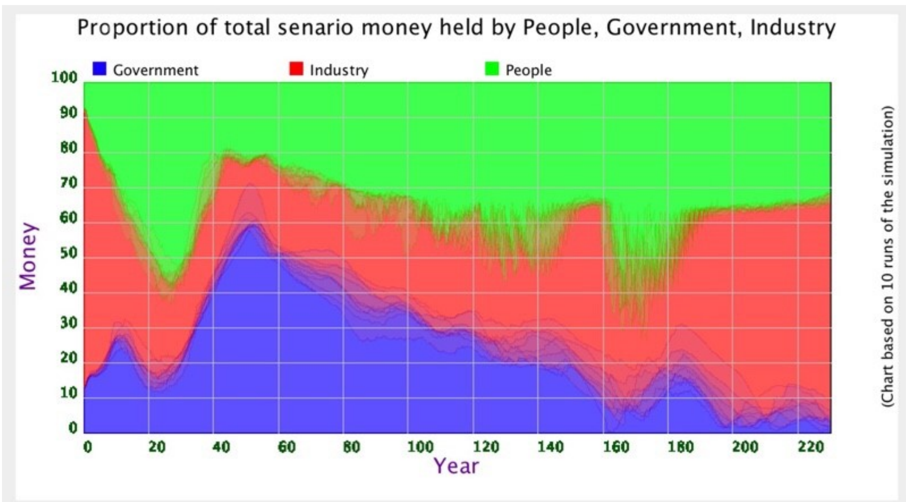


Figure 34: Overlapping results from all ten test simulations: the proportion, out of 100%, of the scenario's total money held by each of the three agent types throughout the simulations. To view just the results of the final test simulation see figure 16.

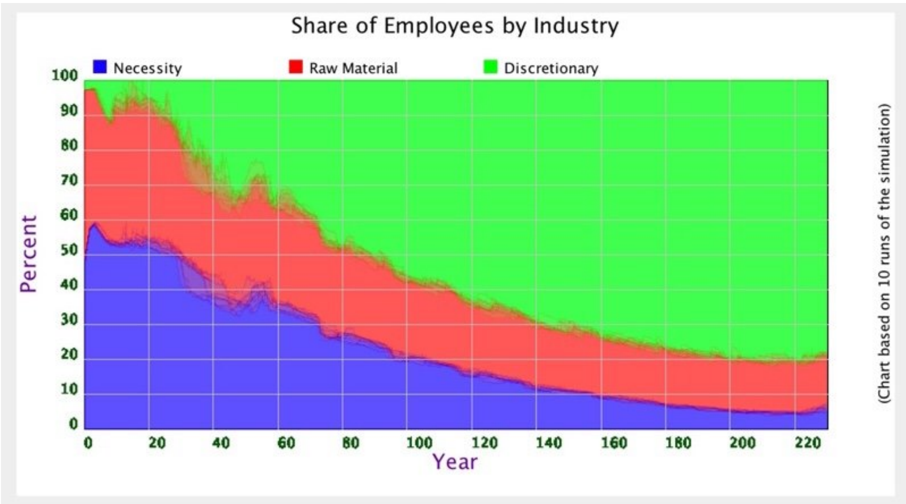


Figure 35: Overlapping results from all ten test simulations: the proportion, out of 100%, of employees that work at each of the three industries throughout the simulations.The results displayed on the graph support the main purpose of this model as the results show the significant shift of the relative size (by number of employees) of each industry throughout the simulation. To view just the results of the final test simulation see figure 17.

#### 5.11.4 Text Results

To help quantify results of this model I choose a few simple measures of the second and twenty-second decades from the ten simulation runs to output/display text results. Equations 3 and 4 detail the specific time steps (months) that represent these decades. In equations 3 and 4 $SR$ denotes the number of simulation runs from which data is being averaged (and the $h$ variable in the summation represents each specific simulation).

$$AverageValueSecondDecadeFromMultipleSimulations = \frac{1}{SR}\sum_{h=1}^{SR-1}\frac{1}{120}\sum_{i=120}^{239} Value_i \tag{3}$$

$$AverageValueTwentySecondDecadeFromMultipleSimulations = \frac{1}{SR}\sum_{h=1}^{SR-1}\frac{1}{120}\sum_{i=2520}^{2639} Value_i \tag{4}$$

These equations directly return the average values that are displayed for the population and sale price averages displayed in figure 36. To attain the share of workforce values the averages for the number of employees by industry (still using equations 3 and 4) are first attained and their combined value is used in calculating the average share of workforce by industry values that are also displayed in figure 36.

Test Results For 10 Simulation Runs

Average Population of second decade :1649.0
Average Population of twenty-second decade :13948.3
Average Share of workforce in RawMaterials for second decade :40.2%
Average Share of workforce in RawMaterials for twenty-second decade :15.1%
Average Share of workforce in Neccessities for second decade :53.7%
Average Share of workforce in Neccessities for twenty-second decade :4.9%
Average Share of workforce in Discretionaries for second decade :6.1%
Average Share of workforce in Discretionaries for twenty-second decade :80.0%
Average Raw Material Unit Sale Price for the second decade :24.8
Average Raw Material Unit Sale Price for twenty-second decade :2.0
Average Necessity Unit Sale Price for the second decade :18.8
Average Necessity Unit Sale Price for twenty-second decade :1.7
Average Discretionary Unit Sale Price for the second decade :11.4
Average Discretionary Unit Sale Price for twenty-second decade :1.0
Simulation ran 10 times in 74 seconds
( To see the results of just a single simulation run, scroll halfway --> )

Figure 36: Select values calculated from values from all ten test simulations displayed as text results. The calculations for these values use equations 3 and 4.

# 6 Initialization

The values used for initialization are to some degree arbitrary except in relation to each other such that they are intended to allow for a logical and stable economy as well as leave room for a growing population.

## 6.1 Government Initialization

The government is initialized with a balance of 640000. The initial parent to a new child payment is set at 250. The *length of workday* and *adjust production rate* values are both initialized to 1.

The tax rates are also initialized as indicated by table 7.

| Tax | Initial Rate |
|---|---|
| Sales Tax Rate | 0.04 |
| Profit Tax Rate | 0.5 |
| Income Tax Rate | 0.1 |
| Inheritance Tax Rate | 0.2 |

Table 7: Initial Tax Rates

## 6.2 Industry Initialization

The three industry agents are initialized with enough jobs, inventory, and money to support the model's initial population. These starting values are indicated in table 8.

| Industry | Balance | Sale Price | Product Inventory | Required Input Inventory | Initial Number of Jobs |
|---|---|---|---|---|---|
| Raw Materials | 1,600,000 | 30 | 20,000 | Not Applicable | 400 |
| Necessities | 1,600,000 | 20 | 80,000 | 400 | 400 |
| Discretionaries | 1,600,000 | 12 | 80 | 800 | 20 |

Table 8: Initial industry agent values

## 6.3 Person Initialization

The model is initialized with 840 working age adults, with their ages being selected at random (with an even probability distribution) from 18-62.

### 6.3.1 Pairing Adults into relationships for Initialization

The relationship helper pairs adults into relationships with a pairing algorithm similar to that described in section 8.1.1 (under "Pairing individuals into relationships") except that it instead uses a probability of 8% to determine if two are paired and the number of opportunities is not limited except by the number of single individuals.

### 6.3.2 Adding Children

The model uses ages in the process for determining whether a couple has children.

$$NumberofYearsIntoAdulthood = Min(AgeOfPersonOne, AgeOfPersonTwo) - 18$$

For each year that a couple is into adulthood minus 1, up to a maximum of 4 children, the model uses an 8.5% chance to determine if that couple has a child that age.

# 7 Input Data

The model does not use input from external sources.

# 8 Sub Models

## 8.1 Updating Relationships

First, relationships are updated. Updating relationships involves the pairing of individuals into relationships, determining whether couples become pregnant, and instantiating new people that are born from a relationship. This process, for reasons of simplicity, is not done at the individual level and is instead performed by the relationshipHelper class.

### 8.1.1 Pairing individuals into relationships

Age and gender are the only metrics used when pairing people into relationships because the model does not have any concept of location and does not detail the lives of people in the model. Relationships in the model are for the life of the people involved. It may go without saying that people and a population are required for there to exist a context in which an economy can exist (even a simulated economy). The specific way in which relationships and reproduction are modeled is not meant to be a key detail of this model but population and population growth are key details of any economy. This model spans a time frame of multiple generations and thus cannot be separated from a changing population.

The process of pairing individuals takes into consideration the age difference between individuals. A list of maximum age differences is used to prioritize the manner in which people are paired into relationships. In each time step either the males or females will each have up to four opportunities in which they may find a companion (the particular gender list used here each time is chosen at random to obscure the significance of which). Each single person of that particular gender has up to four opportunities in which they might find a pair. Until a pair is made, the opportunities are used up, or all the single adults of the opposite gender are cycled, there is a 2.6% chance that the next single person of the opposite gender within each age difference (starting with the smallest age difference) will become part of a new relationship (if they are not related within 3 generations). The age differences used in order are (up to) 3, 6, 9, 12, and 15. If either person being considered for a pair is under 24 only age differences up to 6 years are considered.

### 8.1.2 Check If A Couple Become Pregnant

The chance of a fertile couple that has not yet had the maximum number of children becoming pregnant is determined based on the current population. This chance is updated only once per time step. The chances of a person in a relationship becoming pregnant is reduced in order to start plateauing the population once it reaches 8150.

For the purpose of decreasing the population growth variance between simulations and increasing simulation stability it is also the case that if the ratio of children to adults exceeds a certain amount the chance of pregnancy is decreased and if it falls below a certain amount the chance of pregnancy is increased.

The calculations for determining the chance of a person within each couple becoming pregnant are detailed in equations 5 and 6.

$$PPA = PopulationPlateauAdjustment = Max(0, 1 - Max(0, \frac{Population - 8000}{150} * 0.011)) \quad (5)$$

$$ChanceCoupleBecomePregnant = \begin{cases} 0.012 * PPA * 1.4 & \frac{Children}{Adults} <= 0.13 \\ 0.012 * PPA & 0.13 < \frac{Children}{Adults} <= 0.45 \\ 0.012 * PPA * 0.65 & \frac{Children}{Adults} > 0.45 \end{cases} \quad (6)$$

### 8.1.3 Add New People Born From a Relationship

If a couple has been pregnant for 9 months a new person will be added to the model. At this time each parent will be given their $ParentToANewChildPayment$ that has been set by the government (this payment is the only mechanism in which new money can be introduced into the model).

## 8.2 People Exercise Their Executive Function (one person after another)

A person that has reached retirement age will request their social security payment; he or she will receive the payment if the government has enough funds.

A working age adult without a job will look for a job. A person that started a time step without a job will not work that time step even if they apply for and receive a job (industries will accept any working age applicant to fill a vacant job).

People that have a non essential job (in the discretionary industry) are modeled to check if there is a product shortage in either of the essential industries. If there is a shortage and a job opening in an essential industry a person will instead start working at an essential industry. The rationale for this is that the supply from the necessity and, by extension, the raw material industry is needed for people to survive. If both essential industries have a shortage and a job opening, a random value is used to determine which industry a person switches to. In this case, where a person as switched jobs because of a product shortage, the person will still work in the same time step.

The process of a person working is what produces the consumable for an industry. The *input raw material required for production* value from table 1 multiplied by the *adjust production rate* value multiplied by the *length of workday* value is the amount of raw material required for producing as much of an industry's consumable as a person can produce in a time step (as indicated by equation 7; note that for the raw material industry itself the resulting value will be zero).

$$AdjustedEmployeeRequiredInput = InputRequiredQuantity * AdjustProductionRate * LengthOfWorkday \quad (7)$$

If the industry a person works in has the required about of the raw material consumable (for production) and the required 210 monetary units to pay a person, the amount of the industry's consumable that a person produces is determined by equation 8. A person will pay their income taxes each time step they are payed.

$$QtyAPersonProducesatOnce = BaseQtyProducedAtOnce * AdjustProductionRate * LengthOfWorkday \quad (8)$$

People that have not reached adulthood (age 18) do not work.

People will also seek to satisfy their needs. For a non-Adult this merely means making sure that one of his or her parents has met the needs for their collective home. If an adult and his or her romantic partner do not have the funds required to purchase the necessity consumable required for a home he or she will ask the government for assistance. A single adult within a home requires 8 of the necessity consumable. If a second adult is within a home an additional 6.4 units are required to satisfy the requirements for the pair. For any children within a home an additional 5.4 units (each) are needed to meet the collective necessity requirements for a home (the sum of these requirements for a home are rounded down the the nearest whole number).

A person with sufficiently excess funds will purchase the discretionary consumable to satisfy his or her wants. A person will purchase as much of the discretionary consumable as he or she can obtain with a third any money he or she has above 1600 monetary units.

A person who has failed to meet his or her own needs will have a fixed chance of dying. A person that has reached his or her life expectancy will also die (yes, as expected).

## 8.3 People's Financial Information is Recorded

People's financial information is recorded. This is distinct from the other person agent updates in order to keep records of financial data consistent and free from discrepancies.

## 8.4 Industries Exercise Their Executive Function (one industry after another)

### 8.4.1 If lacking in money and product to sell, the discretionary industry will ask the government for assistance

If the discretionary industry that has become unable to function from lack of funds and lack of consumable to sell it will ask the government for assistance (this is the only industry that might benefit from this without the population dying). The need for the industry to ask for assistance is not a desired occurrence of the simulation and it should not occur often. The specific conditions for this is if the "Financial Standing" (using equation 9 with a Sample Size of 6) is below 0.01 and the industry also has less that ten units of the discretionary consumable. Once the industry has asked for government assistance at least ten times (since the last time it received assistance, if ever), if the government has a financial standing above one and has over 4800 monetary units, the government will give the industry 2400 monetary units and the industry number of jobs will be set to one.

### 8.4.2 Update Number Of Jobs

An industry updates its number of jobs based on a number of calculations and variables.

$SS$ denotes the sample size for calculating the financial standing, ratio of target inventory, and average demand in equations 9, 10, and 11 respectively.

$$FS = FinancialStanding = \frac{1}{SS}\sum_{i=t-(SS-1)}^{t}\frac{balance_i}{DailyExpenses_i * 8} \tag{9}$$

$$RTI = RatioOfTargetInventory = \frac{\sum_{i=t-(SS-1)}^{t} Quantity_i}{10 * (UnmetDemand_t + \sum_{i=t-(SS-1)}^{t} MetDemand_i)} \tag{10}$$

$$CalculatedDemand = UnmetDemand_t + \frac{1}{SS}\sum_{i=t-(SS-1)}^{t} MetDemand_i \tag{11}$$

If an industry's production in the current time step was below expectation it doesn't add or remove jobs because this is an indication that it didn't have enough resources and shouldn't make changes. An industry also will not make any changes to its number of jobs until the required amount of time has passed (4 months) since the last change. For the sake of maintaining stability of the simulation the discretionary industry will not adjust its number of jobs in the first 36 months of the simulation.

If the conditions listed in the previous paragraph favor a change and an industry has exceeded its target inventory by a specific threshold and it is producing more than the calculated demand (equation 11) or it reaches a relative inventory threshold compared to its target inventory and its production is exceeding the calculated demand by a specified amount, the industry will remove existing jobs.

$$ExcessNumberOfJobs = \frac{Production_t - CalcDemand}{Qty\ A\ Person\ Produces\ At\ Once} \tag{12}$$

If an industry has more than 50 employees and the calculated $ExcessNumberOfJobs$ (equation 12) is more than 4% of the industry's total jobs it will only remove 4% of its current jobs; otherwise, it will remove the total $ExcessNumberOfJobs$.

If an industry's production in the current time step was as expected, the required amount of time since the last change in the number of jobs has passed (4 months), its ratio of target inventory is below a specified threshold, its production is below its calculated demand, and, if it isn't an essential industry, it meets a specified financial standing, it will calculate the number of jobs to add.

$$JNeededByDemVsProd = JobsNeededByDemandVsProduction$$

$$JNeededByDemVsProd = \begin{cases} \frac{MetDemand_t - Production_t}{QtyAPersonProducesAtOnce} + 1 & RTI < .7 \wedge CalcDemand < MetDemand_t \\ \frac{CalcDemand - Demand_t}{QtyAPersonProducesAtOnce} + 1 & Otherwise \end{cases} \tag{13}$$

$$JobsNeededByTI = JobsNeededByTargetInventory = \frac{\frac{(1-RTI)*10*CalcDemand}{QtyAPersonProducesAtOnce}}{150} \tag{14}$$

The calculation for determining the number of jobs to add uses the sum of a value calculated based on the target inventory (equation 14) and a value based on demand versus production (equation 13). Any existing unfilled positions of an industry are subtracted from the total number of jobs that would be added (equation 15).

$$InProgJobsA = InProgressJobsToAddA$$

$$InProgJobsA = Max(JNeededByDemVsProd + JobsNeededByTI - UnfilledPositions, 0) \tag{15}$$

The number of additional jobs an industry would add will not be more than it could afford in a timestep (equation 16):

$$InProgJobsB = InProgressJobsToAddB$$

$$InProgJobsB = Min(InProgJobsA, NumberOfJobsAnIndustryCanAffordtoAdd) \tag{16}$$

If an industry has specified number of jobs the number of jobs it can add at once will be limited to a percent of its existing number of jobs as indicated by equation 17.

$$JobsAdded = \begin{cases} Min(InProgJobsB, .6\%OfEmployees) & Employees > 999 \wedge DiscretionaryIndustry \\ Min(InProgJobsB, 12\%OfEmployees) & 50 < Employees \wedge (Employees < 1000\vee \\ & \qquad \neg DiscretionaryIndustry) \\ InProgJobsB & Otherwise \end{cases} \tag{17}$$

### 8.4.3 Check For Needed Raw Material

Industries other than the raw material industry check to determine if they have an adequate amount of the raw material consumable. As long as an industry has enough money and the raw material industry has the desired quantity, a non-raw material industry will purchase enough raw material to maintain its *Target Raw Material Inventory* (equation 18).

$$TargetRawMaterialInventory = \frac{Max(Production_t, MetDemand_t)}{Qty\ A\ Person\ Produces\ At\ Once} + 1 * Adjusted\ Employee\ Required\ Input * 2.5 \tag{18}$$

### 8.4.4 Update Sale Prices

If the required amount of time (8 months) has passed since the last time a specific industry adjusted its sale price and the functions for calculating price (equations 19 and 20) would result in a different sale price, the sale price is updated accordingly.

$$CP = CostToProduce = \frac{Adjusted\ Employee\ Required\ Input * RawMaterialUnitCost + EmployeePay}{Qty\ A\ Person\ Produces\ At\ Once} \tag{19}$$

$$Price = \begin{cases} Max(CP * 0.8, 1) & FS > 3 \\ Max(CP * 0.8 + 0.5, 1) & 1.15 < FS <= 3 \\ CP + 0.5 & 0.6 < FS <= 1.15 \\ CP + 1 & (FS <= 0.6 \vee RatioOfTargetInventory < 0.1)\wedge \\ & \qquad (current)Price \neq CP + 1 \\ CP + 2.25 & (FS <= 0.45 \vee RatioOfTargetInventory < 0.01)\wedge \\ & \qquad (current)Price = CP + 1 \\ \text{(no change)} & \text{otherwise} \end{cases} \tag{20}$$

## 8.5 Industries Pay Their Required Taxes And Update Records (one industry after another)

Industries pay their required profit tax and update their records. Records are updated separately from the executive function of industries in order to prevent data discrepancies.

## 8.6 Government Exercises Its Executive Function and Updates Its Records

If the conditions are met for each individually, the government will adjust the profit tax rate, adjust the income tax rate, adjust the sales tax rate, adjust the length of Workday, adjust retirement age, adjust parent to a new child payments, and update its records.

### 8.6.1 Adjusting the Profit Tax Rate

If enough time has passed since the last change to the profit tax rate, the profit tax rate isn't at its maximum value, the government's financial standing goes below a certain threshold, and the essential industries both meet a minimum financial standing threshold, the government will raise the profit tax. The values for these conditions are listed in table 9.

If enough time has passed since the last change to the profit tax rate, the profit tax rate isn't at its minimum value, and the government's financial standing exceeds a specified threshold, and the financial standing of at least one of the essential industries falls below a specified threshold, the government will lower the profit tax rate. The values for these conditions are listed in table 9.

| Requirements To Raise Profit Tax By 10% | Requirements To Lower Profit Tax by 10% |
|---|---|
| At least 16 TU since last change | At least 16 TU since last change |
| Profit Tax is Below the 80% Maximum | Profit Tax is Above The 10% Minimum |
| Both Essential Industries have a FS of At Least 0.8 | The FS Of At Least One Essential Industry Falls Below 0.03 |

Table 9: Requirements for adjusting profit tax.

#### 8.6.2 Adjusting the Income Tax Rate

If enough time has passed since the last change to the income tax rate, the income tax rate isn't at its maximum value, and the government's financial standing goes below a certain threshold the government will raise the income tax. The values for these conditions are listed in table 10.

If enough time has passed since the last change to the income tax rate, the income tax rate isn't at its minimum value, and the government's financial standing exceeds a specified threshold, the government will lower the income tax rate. The values for these conditions are listed in table 10.

| Requirements To Raise Income Tax By 2% | Requirements To Lower Income Tax by 1% |
|---|---|
| At least 30 TU since last change | At least 30 TU since last change |
| Income tax is below 13% (by 2%) | Income tax is above the 7% minimum |
| The FS of the government falls below 0.4 | The FS of the government rises above 1.5 |

Table 10: Requirements for adjusting income tax.

#### 8.6.3 Adjusting the Sales Tax Rate

If enough time has passed since the last change to the sales tax rate, the sales tax rate isn't at its maximum value, the government's financial standing goes below a certain threshold, and the essential industries both meet a minimum financial standing threshold, the government will raise the sales tax. The values for these conditions are listed in table 11.

If enough time has passed since the last change to the sales tax rate, the sales tax rate isn't at its minimum value, and the government's financial standing exceeds a specified threshold, the government will lower the sales tax rate. The values for these conditions are also listed in table 11.

| Requirements To Raise Sales Tax By 2% | Requirements To Lower Sales Tax by 1% |
|---|---|
| At least 20 TU since last change | At least 20 TU since last change |
| Sales Tax is Below 8% (by 2%) | Sales Tax is Above The 3% Minimum |
| The Government's FS Falls Below 0.5 | The Government's Financial Standing Rises Above 4.5 |
| Both Essential Industries have a FS of At Least 0.3 | |

Table 11: Requirements for adjusting sales tax.

#### 8.6.4 Adjusting the Length of a Workday

Based on the average unemployment rate over a fixed number of time steps, if the minimum length of workday has not been reached, and enough time has passed since the last change in the length of the workday, the government will reduce the length of the workday as a means of reducing unemployment. $SS$ denotes the sample size for calculating the averages. Then:

$$AverageUnemployment = \frac{1}{SS} \sum_{i=t-(SS-1)}^{t} UnemploymentRate_i \tag{21}$$

There are three threshold tiers used to determine if the length of the workday will be reduced (table 12). The model checks for the conditions of each tier in order. If the $AverageUnemployement$ is above the threshold in a tier, the tier's required amount of time since the last length of the workday change has passed, and the minimum length of the workday has not yet been reached then the length of the workday is reduced by the amount indicated for that tier (only down to the minimum length of the workday).

| Tier | SS for Average | Average Unemployment Threshold | Time Steps Required Between Changes | Amount to Reduce Length of the Workday By |
|---|---|---|---|---|
| Tier 1 | 2 | 0.18 | 15 | 0.04 |
| Tier 2 | 6 | 0.09 | 15 | 0.02 |
| Tier 3 | 6 | 0.06 | 30 | 0.01 |

Table 12: Values for reducing length of the workday.

#### 8.6.5 Adjusting Retirement Age

Based on the average unemployment rate over a fixed number of time steps, if the minimum retirement age has not been reached, and enough time has passed since the last change in the retirement age, the government will reduce the retirement age as a means of reducing unemployment.

There are three threshold tiers used to determine if the retirement age will be reduced (table 13). The model checks for the conditions of each tier in order. If, using equation 21 with a $SS$ of 6, the $AverageUnemployement$ is above the threshold in a tier, the tier's required amount of time since the last retirement age change has passed, and the minimum requirement age has not yet been reached then the retirement age is reduced by the amount indicated for that tier (only down to the minimum retirement age).

| Tier | Average Unemployment Threshold | Time Steps Required Between Changes | Amount to Reduce Retirement Age By |
|---|---|---|---|
| Tier 1 | 0.15 | 18 | 2 |
| Tier 2 | 0.1 | 18 | 1 |
| Tier 3 | 0.06 | 36 | 1 |

Table 13: Values for reducing retirement age.

#### 8.6.6 Parent To A New Child Payments

The monetary transactions in the model are discrete. The only situation in which new money may be introduced into the model is when a new person is born. The model enforces an amount that will be given to individual parents with each new person born. The government entity will adjust this amount (between 0 and the maximum of 1100) based on the average of the average balance of people over the course of a fixed number of time steps.

If $SS$ denotes the sample size for calculating the average. Then:

$$AAPB = AverageAveragePersonalBalance = \frac{1}{SS} \sum_{i=t-(SS-1)}^{t} AveragePersonalBalance_i \tag{22}$$

The government may make a change to this amount, the *parent to a new child payment* amount, only once every 12 months. If this average value falls below 1550, enough time has passed since the last change, and the maximum value (1100) for this payment isn't currently reached, the government will raise it by 25. If this average personal balance rises above 1650, enough time has passed since the last change, and this payment is above zero, the government will lower this payment by 25.

This payment is meant to ensure that an increasing population during the simulation doesn't dilute the amount of money available relative to the population in the scenario.

#### 8.6.7 Updating Records (and verifying the model has no financial discrepancies)

Records are kept of the government's balance, revenue, expenses, tax rates, parent to a new child payment, the retirement age, and length of work day.

Population records are also kept to record the total population, retirement age population, adult population, under 18 population, unemployment rate, and people's financial information.

This is also the point in the model's execution that includes a basic check for financial discrepancies. This checks that the sum of all of the model's agents' money is equal to the previous time steps total scenario money plus any new scenario money that was added from *parent to a new child payments*. If this check failed the model would throw an exception and the program would not finish or display any graphs. The model and program has been debugged and tested enough that I am reasonably certain that this check will not fail.

## 8.7 Time is Progressed (this is also where the production rate gets updated)

Every third month the *adjust production rate* value is increased by about 0.35% which amounts to a 100% increase over a 50 year period. This *adjust production rate* value is directly applied, in combination with the *length of workday* value, to directly adjust the amount employees will produce in each time step.

Every five years the model checks for dead people it can dereference for release from memory. These references are kept until this point for people that had children in order that relationships can be checked for the enforcement of the incest taboo.

Finally, time is progressed and the current year is updated. These are the last updates of each cycle of the simulation.

# 9 Discussion

## 9.1 Sensitivity Analysis and the Potential for Undesired Results

Sensitivity analysis on the model was informal and executed via minor code changes that produced the relevant output . The model contains enough variables that there are computational time constraints such that variable variation testing had to be limited.

It is possible for the simulation to exhibit undesired behavior. On occasion, for example, insufficient necessities and or insufficient funds will cause a complete collapse of the population until no one is left which causes the simulation to end early. The results presented in this article are accurate and typical for that number of runs. At a larger number of runs a failure or two of this type is not unusual. This potential behavior is not intended to be the focus of this article (and I do not find this potential simulation result to be damning to the purpose of the model or the article). Out of 5000 single simulation runs this undesired result occurred twelve times ( 0.24% of cases ). In addition, there may also be cases in which the population significantly declined yet the simulation was able to stabilize (though, with the current values of the model, I have not yet visually observed this result). The easiest way to rule out that either such cases occurred, for anyone that might run the program implemented with this model, would be to check the population graph first (figure 20).

Many of the values used in this model have been adjusted to their current value for the purpose of reducing the likelihood of simulation population collapse.

The model has a maximum productivity rate adjustment of 25 times the initial productivity rates. That maximum would be hit if the simulation were to be run sufficiently past the coded default of 230 years. Having this maximum productivity rate adjustment prevents unstable and undesired results that would happen at higher productivity rates. It is difficult to program agents that can respond to exponential changes and the model as it is cannot handle further ranges in the rate at which productivity changes or in the resulting effective maximum productivity rates.

## 9.2 Notable Absences and Previous Considerations

As previously mentioned this model does not include loans, debt, interest, or dividends. To the extent that the model still exhibits economic characteristics such as consumption, employment, and the expansion of the existing money pool, this exclusion is a minimalist design feature that reduces the complexity of the model.

## 9.3 Computational Time

On a moderately high-end 2014 personal computer running the simulation 5000 times sequentially took eleven hours and 18 minutes or just over 8 seconds for each run (this excluded time that would have been required for calculating the adjusted GDP, basic math for calculating percents, and drawing graphs). On the same computer the program implemented on for running the model consistently takes around 90 seconds to finish its 10 simulation runs and graph their results.

## 9.4 Discussion of Results

All of the graphs/images included in this article are from the same simulation runs. As previously indicated, from each of the ten simulation tests, select calculated averages from the 2nd and 22nd decades were displayed as an alternative to purely graph data (figure 36). The 200 year period between these decades of the simulations offers a good picture of the economic change that the model is able to accommodate.

This model was not designed with the intention of demonstrating deflation, but key design decisions, in an approach that was a compromise between the KISS (Keep It Simple Stupid) and KIDS (Keep It Descriptive Stupid) approaches (Edmonds & Moss 2005), meant that this model would exhibit deflation. In each of the ten test simulations sales prices went down enough that the purchasing power, for example, of an employed person rose by more than 900%.

While this model was not calibrated to and not intended to represent any real world example, loose comparisons could still be useful; any comparisons ought to start by comparing population and production change rates. Data from the text results of the ten test simulations suggests a population increase rate of 70.5% every 50 years. The model described in this article imposes a production rate change that amounts to a 100% increase every 50 years. For comparison to a real world example, according to data from the United States Department of Commerce Bureau of the Census (1975, September), the average output per man-hour from the decade of 1910 to the average output per man-hour from the decade of 1960 increased by 264.1% and the average (US) population from the same time periods increased by 94%. The described real word example represents a production rate change that is approximately 1.82 times faster and a population change rate that is 1.13 times faster than the simulated model presented in this paper.

The discretionary industry, by economic share of employment, represented only 6.1% of the simulations' economies the second decade(s); the raw material industry more than 6.5 times this amount and the necessity industry more than 8. Over the course of 200 years the discretionary industry's share of the labor force consistently rose to 80%, a relative increase of more that 1200%.

An important aspect of this of this economic model is that its monetary transactions are discrete. Basic checks have verified that this is the case in the final implementation of this model.

Overall I find that this model fulfills its purpose.

### 9.5 Possible Future Directions

There are number of future directions this project may take depending on feedback, opportunity, and potential collaborators. If the passing of time suggests that features of this model prove to have sufficiently beneficial potential, a future iteration of development that builds a more robust and adaptable model may be warranted. Also, it would be worth considering exploration into any insights that might be illuminated by adapting this model for exploring the effect of trade between two nations. Lastly, the possibility of implementing a model that explores similar concepts that is instead designed to take full advantage of parallel computing would also be intriguing.

## 10 Source Code

The model was implemented in Java. The implementation of this model uses a GNU General Public License (2021).

The program requires java 8. An Apache Ant build file is included for compiling the program. The program itself was created for the purpose of demonstration and does not accept any input parameters. Running the program will open up a window that will run 10 simulations and display the results. The program does not write output to any files.

## 11 Acknowledgments

I found *Simulating Social Complexity* (Edmonds & Meyer 2013) to be indispensable to my introduction into the field of agent based modeling.

## 12 Appendix

### 12.1 Variables Unaffiliated With Specific Agents

**Adjust Production Rate :** Variable value representing the relative overall production rate in an economy. This value is used along with the *Base Qty Produced At Once* (for each consumable, table 1) and the *length of workday* value in calculating how much of a consumable can be produced by an employee in a time step (equation 8). This value is initialized to 1 at the beginning of a scenario and is incremented throughout the simulation.

**Length Of Workday :** A variable value representing the relative amount of time an employee will work within a time step. This value is used along with the *Base Qty Produced At Once* (for each consumable, table 1) and the *adjust production rate* value in calculating how much of a consumable can be produced by an employee in a time step (equation 8). This value is initialized to 1 at the beginning of a scenario and can be reduced by the Government agent throughout the simulation.

### 12.2 Abbreviations

| Abbreviation | Whole Word |
|---|---|
| Calc | Calculated |
| Dem | Demand |
| FS | Financial Standing |
| Prod | Production |
| Prog | Progress |
| Qty | Quantity |
| SR | (the Number of) Simulation Runs |
| SS | Sample Size (for average) |
| TI | Target Inventory |
| TU | Time Unit(s) |

Table 14: Abbreviations used in tables, variable names, and equations.

### 12.3 Notable Constants

| Value Name | Value |
|---|---|
| Employee Monthly Pay (any industry) | 210 |
| Social Security Payment Amount | 120 |
| Life Expectancy (in years) | 77 |
| Maximum Fertile Age (in years) | 52 |

Table 15: Notable constant values

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