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Simulating the First Industrial Revolution: An Agent-Based Model of England's Industrial Revolution according to Robert Allen

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Simulating the First Industrial Revolution: An Agent-Based Model of England's Industrial Revolution according to Robert Allen

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Abstract

In this preliminary working paper I present a first modelization of Allen's argument on the British Industrial Revolution. To do so, I use a macroeconomic microfounded framework with heterogeneous agents – households, firms, institutions – which interact through a decentralized matching process presenting common features across five markets – labor, food, goods, services and government bonds. I study the dynamics of the model by means of computer simulation. Some macroeconomic properties emerge such as endogenous business cycles, nominal GDP growth, while reproducing important stylized economic facts like the Industrial Revolution and Engel's Pause in the right conditions.

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1 Introduction

There are some phenomena in human history whose consequences shaped world history forever. One of these is the British Industrial Revolution, whose importance is at par with the Neolitic Revolution in changing the lives of human being that lived ever since. For the first time, human beings were able to overcome the Malthusian forces that had limited them before, marking the beginning of the modern era, and fundamentally shifting the balance of power between man and nature.

There have been numerous attempt of both explaining and modelling this phenomena. This paper attempts a novel solution to the modelization of the Industrial Revolution, based on already existing theory. To be more precise, this work presents an Agent-Based Model of the First Industrial Revolution based on the theory of Robert Allen. The aim of such endeavour is to test whether Allen's theory can produce a working simulated economy that is able to industrialize under the described conditions.

Agent-Based Models in economics simulate different economic facts and events. They do so by creating a a stylized economy with different agents programmed to interact with each others, often in different markets and with different roles. These interaction simulate an economy, and the outcome is observed without intervention. These interaction give rise to emergent properties that reproduce a stylized version of real economic phenomenon. Given the difficulties encountered when testing economic history theories due to the lack of good data, such simulations can offer an alternative, as the qualitative argument can be translated to agents' behavior to be parameterized later through Monte-Carlo testing.

This methodology is quite recent, as it requires strong computational power, but it widely used among different scientific fields, from meteorology and physics to anthropology and history. Regarding the economic discipline, it is mostly employed in macroeconomics and finance studies, and it has been used to study technological diffusion from the macro-prospective. This also produced a branch of ABM studies studying the historical evolution of selected business sectors, but that seems to be the maximum extent the ABMs have been used in economic history.

As such, lacking an established literature, I have decided to focus on prioritizing the reproduction of real agents' behavior described in the economic history literature over the accuracy of historical data sources. Given the complexity of the phenomenon studied and the methodology utilized, this paper is mainly focused on the role of labor costs in incentivizing innovation. To do so, we create an open economy populated by different classes of agents.

Each agent interacts in some of four different markets, either as a Seller or a Buyer. They are placed on a randomly generated space with different characteristics. Some agents can cease to exist, or reproduce. This produces a stable pre-industrial economy with minimal GDP growth. At a certain point in the simulation we add the possibility for Firms to invest a sizeable amount for transitioning into an Industrial Firm with a much higher productivity. This is possible when Firms end a turn with a depleted Stock, meaning that labor costs are high compared to the quantity produced.

We then observe how different initial condition for labor price impact differently the development of the economy: with low initial labor costs, there isn't much of a transition, and the GDP-growth remains minimal; with higher initial labor costs, ceteris paribus, we observe a sustained economic growth and a rise in output and consumption of goods.

These preliminary results seems to indicate that Allen's theory on the causes of the Industrial Revolution can be validated by emerging behavior of agents programmed with simple economic behavior, given the right conditions. High initial wages also reproduce the Engel's Pause mentioned in Allen's work, as in real wages stagnation once the industrial revolutions begin.

This can be taken as first a validation of Allen's theory on the First Industrial revolution. Additionally, various macroeconomic phenomena emerge from the agents' behavior that mimic real world economies, like inflation and business cycles, together with market crashes from overproduction. A more sophisticated version of this model could also employ more historical data for a better verification.

This working paper is structured as follow: first, an overview of Agent-Based Models (ABM) is given, followed by an overview of Allen's work on the industrial revolution and other relevant historical literature, and how that literature is used in constructing the model. After that, the sequence of events is presented, and a more formal presentation of the different components of this model. Lastly, the Preliminary Results

2 Agent-Based Models: a literature review

2.1 What are Agent-Based Models

In what is probably one of the most useful recent contribution to the Agent-Based literature in economics, Caiani et al. (2016, pp. 4–5) describe the Agent-Based approach to economic modelization as a process that "conceives the economy as a complex adaptive system populated by heterogeneous locally interacting agents [where] even the simplest micro-economic behaviors may lead to complex systemic properties due to feed-backs, externalities, and other structural effects arising from agents disperse interactions".

In other words, ABMs allow for the modelization of complex economics events as emergent properties of agents interactions. These interaction follow the instructions programmed, but are not controlled by or interfered with by author of these models, who is a simple observant of the different possible outcomes. The initial instruction also contain different set of parameters, that allow for the comparison of different initial conditions.

As noted in Railsback and Grimm (2019, p. 10), we build ABMs when experiments or mathematical tractability are impossible, as it is often the case for the most complex phenomena. ABMs have the great benefits of representing the individual components of a system and their behaviors. These agents are different from each other (in location, starting resources, history ecc.), even when belonging to the same type, and interact with each other at the local level as they move in a geographical space. As they are autonomous, they "act independently of each other and pursue their own objectives". Finally, agents usually try to survive and reproduce, and they can do so only if they adapt their behaviors to the current state of other agents around them.

ABMs are particularly useful when representing problems of emergent phenomena, defined as "system dynamics that arise from how the system's individual components interact with and respond to each other and their environment" (ibid., p. 10); this is particularly useful when studying how individual components of a system can influence or even create its behavior. Lastly, ABMs are across-level models: unlike most modelization techniques, both the individuals and the system influence and are influenced by each other: we can observe what individual's behavior does to the system, and what the system's behavior does to the different individuals. They do not require simplification to be tractable or understood.

2.2 Relevant Literature

To my knowledge, there has not been any attempt of introducing Agent-Based Modelization to the field of economic history, although some ABM of historical events exist. This is probably because of the novelty of the methodology and the restricted number of practitioners in economics. Additionally, the required knowledge in statistics and programming are rarer in practitioners of economic history than those in economics, as different skill-sets are required for the different disciplines

This is also pointed out by Düring (2014, pp. 125–126), as they recognize how "most ABMs of historical events were not developed by trained historians but by computer scientists, anthropologists and epidemiologist". Most of the work done seems to concentrate in Archaeology and Prehistory, with less work done on historical process from the Medieval Age onward. The size and scope of the models is often smaller, too.

They also give an outline of the current use of ABMs in historical literature, which seems to share a number of features: a low number of influencing causal factors, a well-defined pre-existing hypothesis ready to be tested, stable and reproducible agents' settings, and detailed available information for the historical case studies. They also note how ABMs can contribute to check the robustness of qualitative arguments by subjecting them to test their compatibility with available data (ibid., pp. 131–133).

What is present, and quite worked on, is ABM economic literature on agriculture or technological innovation. One of such examples for agriculture is the work of Coronese et al. (2021): in it, farmers can perform a variety of improvements on land and technology used to compete by also imitating their more productive neighbours. On innovation, the literature is vast. "Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles" by Dosi, Fagiolo, and Roventini (2010) can be taken as an example: it's an ABM that bridges Keynesian theories of demand generation and Schumpeterian theories of technology-fueled economic growth. Recently this model has been expanded with the publication of "Mission-Oriented Policies and the "Entrepreneurial State" at Work: An Agent-Based Exploration" by Dosi et al. (2021), where

Mazzucato's arguments are studied and tested.

3 Characteristics of this model

The following section describes the background elements of this model, namely its purpose, the desired patterns it is intended to reproduce, the entities that populate them and the variables these entities. The world they populate is also discussed. This section is again based on Railsback and Grimm (2019, pp. 37–40), as their textbooks provide a clear guide in the structuring of ABMs papers using the Overview, Design concepts, and Details (ODD) protocol, and is in general an excellent introduction to the methodology.

This paper focuses on the modelization of the English Industrial Revolution, as described by Allen (2009) the first industrial revolution, specifically the mechanism of industrialization as a systemic response to high relative wages. To do so, it is necessary to create a stable pre-industrial economy composed of different classes.

To do so, we need a geographical space. This space is composed of different patches with different characteristics. Cities start out with a higher population, Coal patches allow nearby industries to access coal and Farmland patches allow for Food to be produced. This space is populated by a variety of Households, who buy good from and sometimes own Firms.

Since those owning the Firms did not work in them, we separate Workers Households from Bourgeoisie Households. These Firms can produce and sell goods based on the labor they are able to acquire from Workers. As it is a pre-industrial economies, Farms and Food is still a central part of the economy, and so it has to be included, as the class owning most of the land, the Nobility. A Government and Foreign Markets, while not strictly necessary, are also included to add sources of heterogeneity. The Banking System is not present in the model, as it had peculiar characteristic at the time and there is debate in the literature over its role in financing of the Industrial Revolution.

These agents all share an individual wealth. Some, like the Firms, can cease to exist if that goes under 0, while most don't. All agents desire to satisfy their needs, which can be of Food, Goods, Services, or Labor. Some produce item, usually based on the Labor they could acquire that turn, that usually accumulate in Stocks. Firms are the only producers that are characterized by two different production functions, as it is possible for them to switch to an industrial production when some conditions are satisfied. Bourgeoisie are the only Households who are also producers (of Services) when they do not own a Firm, and they do not require to hire Labor to do so.

The number of turns for each iterations, the size of the space, and the number of agents will be better determined with a parametric exploration of the properties of the model, which is planned in the near future. The idea is to perform a high number of Monte-Carlo runs to test the sensitivity of the model to different initial parameters.

These agents are able to reproduce a stable economy, where all the different agents are able to satisfy their needs. After an initial settling phase, a successful modelization would present some stylized facts of a macro-economy, namely inflation and business cycles. Once the possibility for transitioning to a industrial production is introduced to firms, the model aims at reproducing the industrial transition, as in the industrialization of a percentage of the firms present in the economy, together with Engel's Pause as described by Allen (2003), the rise of profitability of firms (Allen 2011, p. 373) and the consequent rise of the Bourgeoisie class wealth.

3.1 An agent based decentralized matching macroeconomic model: similarities and differences

This model is based on "An agent based decentralized matching macroeconomic model" by Riccetti, Russo, and Gallegati (2015). While the characteristics of the agents and their behavior are quite different in the original , as banks are included and agents don't use their geographical location to interact, the mechanism of agents matching is maintained almost unchanged. The price adjustment mechanism is also maintained.

The matching protocol is similar across the different markets composing this model, with one exception. In general, two classes of agents interact in each market, either on the supply or the demand side. One side observes a subset of potential counterparts and chooses a suitable partner based on market-specific criteria.

In most markets, the subset of potential counterpart is limited to those close in the assigned geographical space in the model, which is fixed as a parameter at the beginning of a simulation.

At the beginning of each new market phase in a turn, each agent on the demand side asks at the agent with the lower price either the demand of goods or services desired or what it can afford. The supply agent will either satisfy it or remove itself from the demand if it has no more supply. The demand agent will do the same if it has no more wealth or no more demand to satisfy.

Unlike Riccetti, Russo, and Gallegati (2015), here the Labor Market's Matching follows a different mechanism. Each Worker Household has a Price Labor, and each employee offers its own Labor Price. The employee will select a number of nearby Workers that ask for a lower or equal Labor Price than what is offered. This number is based on the available Capital and a maximum amount of workers that can be hired. Unemployed workers will migrate to a random direction at the end of each Turn.

Near the end of the Turn, all agents will adjust their prices. If a Worker is employed, there is a chance they will rise their Labor Price; if they're unemployed, they might reduce them. Producers might lower their Labor Price on the condition that they were able to hire the maximum amount of Labor possible, and vice versa. Producers will also set a higher Price for goods or services if they manage to sell all their Stocks (or all Services in the case of Bourgeoisie, as they do not create a Stock for obvious reasons).

Both models have a Government that issues Public Debt, which can be bought by rich Households. In Riccetti, Russo, and Gallegati (ibid.) the Government hires a fraction of Households on the Labor Market, and it would give the capital to create new Firms after each failure. This second feature is not maintained, as now Firms are created in a variety of ways: either by the lack of nearby firms noticed by a rich Bourgeoisie, or when a Firm accumulates enough capital to invest in creating another Firm with the same owner and characteristics.

4 Historical Sources and Model Design

As there is no establish literature on producing a macro-economic simulation of past economies, a heuristic was employed in the development of this model. Relevant literature has been used to design the different features of the model as it was developed. Historical features had to be adapted to the limits of modelization, and subjective judgment has been employed to do so.

Allen's work has been used when possible, especially the book "The British Industrial Revolution in Global Perspective" (Allen 2009), as this model is based on his works, and as such it represents a more cohesive view of the phenomenon studied. When this was impossible, other sources have been used.

4.1 Why was the Industrial Revolution British?

In his seminal paper Allen (2011, p. 359) argues that the Industrial Revolution began in Britain because of its peculiar wage and price structure which increased the demand for new products and created an economic incentive for substituting labor with capital and energy.

Allen argues that energy was uniquely cheaper than labor in Britain compared to other nation of the time, due to the early adoption of coal and its commercial diffusion. But this was coal low cost was true only in some part of the country, like the North-West and the city of Newcastle, where it was so abundantly available to be described as "inexpensive" (ibid., pp. 363–364) (Allen 2009, p. 7), and that "the Industrial revolution happened on the coalfields of [...] Britain] (Allen 2011, p. 366). This geographical availability and cheapness is adapted in the model by assigning some patches with the presence of coal. Any Firm close enough can access it, and only those with access can attempt an industrial transition.

Food was still central to workers' budget around the world at the time, and it still took an important part of a working household budget in Britain (ibid., p. 363). This historical fact is brought into the model by placing the Food Market before the Goods Market. Nevertheless, England's wages were higher than elsewhere, and Allen then argues that the high cost of labor created a demand for technology that could offset this cost with the inexpensive coal, as firms could compete internationally while having to pay those higher wages(ibid., p. 367).

This biased technological change is introduced in the model at Turn 100, as to give the model time to

stabilize in a pre-industrial economy before. At the beginning of each turn, each Firm is asked if they have access to Coal, the necessary quantity of Capital to pay for an industrial transition and if they have sold all their Stock in their previous turn. The reasoning behind the last condition it is that this signals the Firm that there is enough demand for them to produce more, and that labor is expensive for the quantity of Goods produced. Of course, this last condition is not always enough, as a random parameter must be satisfied for the transition to happen. The propensione to invest of an entrepreneur is represented as follow: . This should represent Allen (2011, p. 371) argument that "18^{th} century British invention were biased towards saving labor and using capital and energy. This biases meant that they were worth using at British factor prices but not [...] elsewhere". If the initial labor price parameters are set low, there should be no Industrial Revolution, and vice-versa.

Another characteristic of the Industrial Revolution, namely the technological advancement through micro-improvement described by Allen (ibid., pp. 373–374) and Juhász, Squicciarini, and Voigtländer (2020), is adapted through a process of neighbour imitation. Close Industrialized Firms have a small chance to improve their technological prowess every turn after their industrialization to represent Learning by Doing, with a higher chance of this happening the more industrialized firms surrounds them [1]

Lastly, a planned addition to this model is a machine-producing industry, as described by Allen (2011, p. 380), where he states that "the greates achievement of the British industrial revolution was the creation of the first large engineering industry that could mass-produce productivity-raising machinery". There are two reasons for the delay of this feature in the model: firstly, a similar mechanism is already described in Dosi, Fagiolo, and Roventini (2010); secondly, the focus of this paper is on the economic incentive for innovation, and such a system would only complicate establishing an effective test of this theory. For now, this industry is represented in the simple payment of a high cost by a Firm transitioning to an Industrial Firm.

4.2 Other Historical Sources

Creating a functioning model of a macro-economy requires a variety of design decisions. Allen's work is prioritized when making these, but other historical literature is employed when necessary. The following sections presents the literature employed to do so, although it is but a fraction of the literature consulted, and it is limited to some of the main features by time constraint.

Financing the Industrial Revolution: the banking system, or the absence thereof This model presents a very simplified view of the financial system of England at the time. Ventura and Voth (2015, p. 6) argue that the Nobility, the main capital holders of the time, had strong cultural resistances to investing in productive activity, preferring agriculture and state debt. As the British government introduced perpetual bonds in 1751 called *consols*, with a fixed 3% annual interest. The consequence was that "the new, dynamic sectors of the economy – cotton manufacturing, iron production, coal mining, ceramics – were initially starved of capital [...] almost no financial institution attempted to provide funds for entrepreneurs (ibid., pp. 9–10)".

This was because regulation made lending difficult to anyone but the safest borrower. Banks were limited in size, with a maximum of 6 partners, interest capped at 5% due to usury law, loans could not last more than 6 months and there was no Central Bank to provide liquidity during a crisis. Additionally, the Bubble Act prohibited firms from raising capital through equity unless they had a Royal Charter (ibid., p. 10). Nobles, on the other hand, could access safer investment through public debt and land investment, and preferred to do so. And since Britain's debt rose consistently in this period due to constant warfare, they had an easy time acquiring it(Temin and Voth 2005).

For these limitations on the banking system and for the structure of State financing at the time the State is modelled as a single agent, which each turn hires a fraction of workers (to simulate the warfare) and acquires a number of goods and foodstuff. It is financed through a minimal tax on sales, and it emits perpetual bonds when in deficit, which can be bought by Nobles and Bourgeois. The banking system is not present, as it did not participate in the financing of the revolution

Modelling The firm It is surprisingly difficult to obtain micro-data on Firms' characteristics for the period in question, especially if one is interested in the distribution of a firm's characteristics. One recent

[1] At this moment the mechanism described here is not working as intended

publication by Juhász, Squicciarini, and Voigtländer (2020, p. 23) presents one of such examples: by looking at firms that were mechanized in 1806 and 1840, the initial distribution is somewhat similar to a normal, while only productive firms have survived 34 years later. While the case studied is the French market, it is realistic to assume that such distribution could be found earlier in England, and that it followed a similar trajectory. Additionally, Juhász, Squicciarini, and Voigtländer (ibid., p. 26) show evidence that geographical proximity was responsible for technological improvement.

Society and Classes Population nearly tripled in this time period. Production could not keep up from 1770, and imports were not big enough to make up for it. Starvation was the norm (Allen 2009, p. 172). As for the workers, their wages are not differentiated between city and countryside according to Allen (ibid., p. 79).

5 Sequence of Events

This sections presents the precise sequence of events happening each period T of the model. Before that, the different classes of agents are created and placed into the geographical space of the model. This space is randomly generated, and so the disposition of coal, cities and the different agent is somewhat random. Cities have a higher number of starting agent close to them.

Once this initial setup phase is concluded, the sequence of events runs as follows:

1. Each Firm is asked whether they can switch to industrial mode of production based on past sales, access to coal and capital. The capital of the owner is considered to this goal, plus a safe zone to allow them to produce on the same turn. If they are successful they will switch their production to industrial from this turn.
2. The government spends on hiring a number of workers, which are employed at their asking labor price. Firms and Farms then hire workers in the labor market. The labor demand depends on their available capital and labor limits. These simulate the physical limitation of a business or of a tract of land, and they avoid the rise of mega-firms or mega-farms, unrealistic for the time. There is no requirement for firms to exhaust their cash reserves nor for firms to satisfy their labor demand. Some workers may remain unemployed.
3. Farms produce Food, and Firms produce consumption goods based on the amount of hired workers and their production function. This is added to their Stocks. Bourgeoisie produce a certain number of Services.
4. Households decide their desired consumption based on their wealth, with different preferences based on their class.
5. Buyers and Producers interact on the market. The different markets follow the hierarchy of human necessities: first is the Food Market, then the Good Market, then the Service Market. The Government also buys food and goods, while the Foreign Market only goods. There is no condition for buyers to satisfy their desired consumption, and so it may happen that some will remain with residual cash, and some companies may accumulate inventories. Each transaction is taxed.
6. If Households have unsatisfied demand, they can buy Foods and Goods from the Foreign Market, which are sold with a markup.
7. Firms calculate profit. Insolvent Farms ask their Noble owners for capital, insolvent Firms fail. Surviving Firms and Farms calculate profits and distribute dividends.
8. Agents update their prices: Workers higher their Labor Prices if employed, and vice versa. Employees higher their Labor Prices if they can't satisfy their demand of labor, and vice versa. Producers higher their prices if they sold all available stock. Services don't carry over next turn.
9. Workers and Bourgeoisie Households can reproduce if they are able to satisfy their food requirements for enough times. If they do, a new Household is born and it inherits half the wealth. Firms with a high capital can produce new firms with similar characteristic, and the capital is split evenly.

10. The Government pays interests on existing bonds, with a fixed rate of 3.5%. The government then emits new bonds of value equal to a 100 that are sold to Nobility and Bourgeoisie.

6 Markets

The following section better describes the various markets and procedures that compose this model. Before the first Turn, each agent is assigned a random value for each of its variables based on normal distribution. Each of these distribution are based on a parameter picked before the start of the simulation. This allows the model to be exposed to a variety of different possible combinations of starting values.

6.1 The production function transition

As per literature, I hypothesize that high labor costs caused the industrial transition. To represent this, firms may switch their production function when they exhaust their inventories, as this would signal an higher demand for their goods than they're capable to deliver at current production function and labor prices.

When a Firm may decide to invest, with an in-house development of the relevant machinery, at a cost of

$$c = ((1 + safe\_zone) \cdot (trans\_cost - (1 - (number\_industry/10)) \tag{1}$$

The constant $trans\_cost$ is a fixed initial cost, while $number\_industry$ is the number of close companies that have already switched production function, up to 5, and $safe\_zone$ is a parameters that prevent the firm from failing as a result of the transition. If successful, the firm will now use a different production function, and be able to hire more workers.

6.2 Labor Market and Production

In each period the government hires a fraction of Workers' Households, which is randomly picked by a random distribution with average $percent\_government\_workers$, a parameter. The remaining Worker Households can work at Firms and Farms. Farm's and Firms labor demand depends on the available capital and their maximum possible hiring limit, and its satisfaction depends on total capital available

$$Labor = max(capital/labor\_price; labor\_limit) \tag{2}$$

The parameter $labor\_limit$ is different for each firm and firm, and is assigned at the setup.

Firms and local workers interact according to the matching mechanism described earlier: the will pick up to $Labor$ workers that accept the offered wage. Each firms will end up with n workers and a residual of cash. Some workers may remain unemployed, and their wealth will update by around half the average wage to simulate them finding non-salaried work.

Farms and Firms then simply update their $stock$ with the following formula:

$$stock = stock_{t-1} + (labor \cdot productivity) \tag{3}$$

If a Firm has switched to an Industrial production mode, their $productivity$ will be higher.

6.3 Food, Good and Service Market

Here Households represent the demand side, while Farm, Firms and the Bourgeoisie who do not own a firm the supply side. Households set their consumption based on their class and their $wealth$. Each propensity is governed by a different parameter, as in $demand\_workers$, which sets a quota of income to be consumed each turn. That is compared to a minimum demand basket for each class.

Households then buy pick the Producer with the lower $Price$ to satisfy their demand. If that demand is not satisfied completely, they can ask another producer until none is available, or they have exhausted their income. The Government also buys a consistent quantity of Food and Goods. The sum of Household's and Government consumption makes the Aggregate Demand. If Household demand is not sated, they can satisfy it with the Foreign Market at a Markup.

6.4 Dividends and Price adjustments

As stated before, Farms with capital equal to 0 ask their owners for more capital, while Firms cease to exist. Surviving agents adjust their prices according to the following rule:

$$price_t = \begin{cases} price_{t-1} \cdot (1+\alpha) & \text{if } stock = 0 \text{ and } condition = true \\ price_{t-1} \cdot (1-\alpha) & \text{if } stock > 0 \text{ and } condition = true \end{cases} \tag{4}$$

Minimum price has to be at least equal to production costs. $alfa$ is the parameters that specifies the value of the price increase. *condition* is satisfied when a selected random number is lower than an assigned value.

The same is done for the Labor Price.

$$wage_t = \begin{cases} wage_{t-1} \cdot (1+\alpha) & \text{if } Worker \text{ is employed at time } t \text{ and } condition = true \\ wage_{t-1} \cdot (1-\alpha) & \text{if } Worker \text{ is unemployed at time } t \text{ and } condition = true \end{cases} \tag{5}$$

Dividends are calculated based on the difference between starting and final capital:

$$dividends = ((profits/2) + (\beta \cdot (profits/2)) \tag{6}$$

with $\beta <= 0.5$

Agent Reproduction The mechanism for reproduction is the same for Households and Firms. When a variable hits a certain number, a new agent of the same class is born, and both split the wealth while keeping the same characteristics. For Households, this condition is met when the variable *kids* reaches an assigned number. The initial value is given randomly up to the maximum value, and it increases by 1 when they can satisfy their need for Food. Firms, on the other hand, have a possibility to create offspring when their capital surpasses a certain threshold.

7 Preliminary Results

The empirical validation of this model has not been performed yet. What is a planned is an exploration of the parametric space, as in a Monte-Carlo simulation of each possible permutation of parameters values to explore how each of these parameter influence the model, and under which condition the model reproduces the desired phenomena. Sometimes an econometric analysis is performed to confirm that the causal link of the model. In this case, the exploration of the parametric space would allow the results to be compared to Allen's theory and data, and to

A first Validation of Allen's is already possible. Higher initial parameters for Labor-Price allow for a much higher and sustained Industrialization when the technology is introduced at Time 100, while low values produce either a slow industrialization or even fail at triggering it. First, we see an example of the world-map (Figure 1), and another from after a successful industrial revolution (Figure 2) (these are different runs, hence the differences).

Lastly, I present a series of a graph representing a successful industrialized economy. In Figure 3 we see the Gross GDP, in Figure 4 the Gross GD per Capita, in Figure 5 the Production by Sector; Figures 6 gives us the average Income by Class, and lastly figure 7 presents the different Prices and their evolution and lastly.

The interpretation of these figures is not easy, but some phenomena can be recognized: the fluctuations in Production and GDP represent business cycles. The growth of nominal GDP before industrialization can be interpreted as inflation. Figure 5 shows clearly a fundamental shift when the Industrialization technology becomes widespread, and that is represented in Figure 6 by the rise of the Industry Owner as the richest class. Figure 7 shows that a rise in Worker's salary is almost always matched by a rise in food prices, and can be interpreted as representing Engel's Pause.

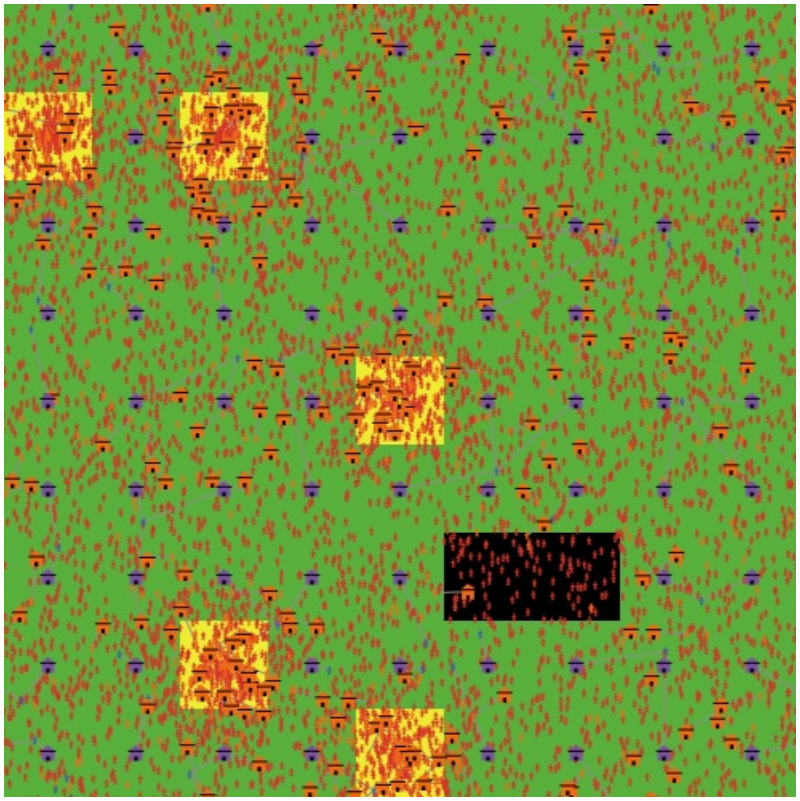

Figure 1: The world map at the beginning of a simulation

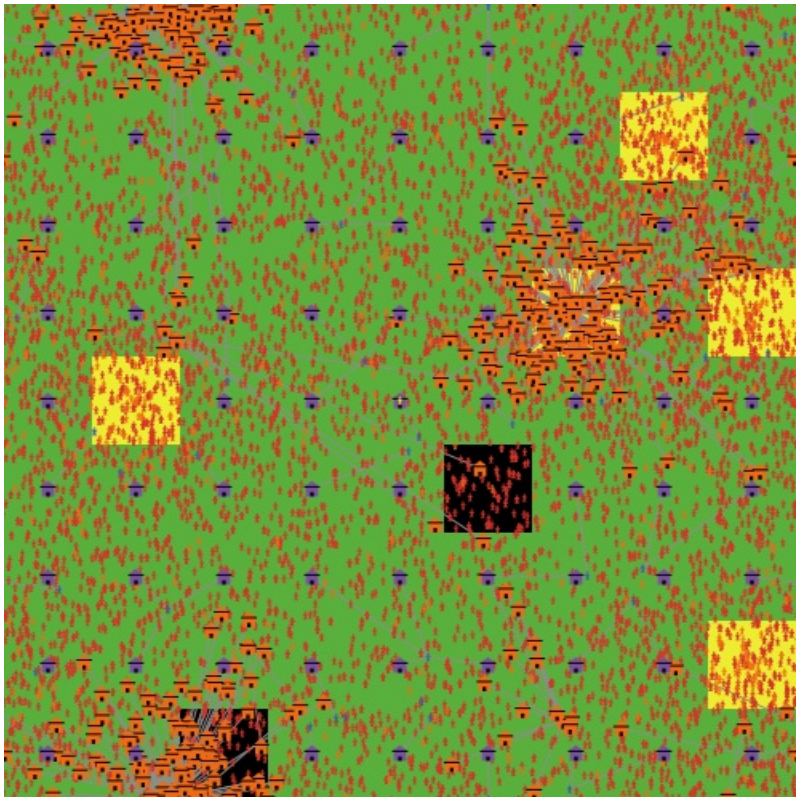

Figure 2: The world Map after an Industrial revolution

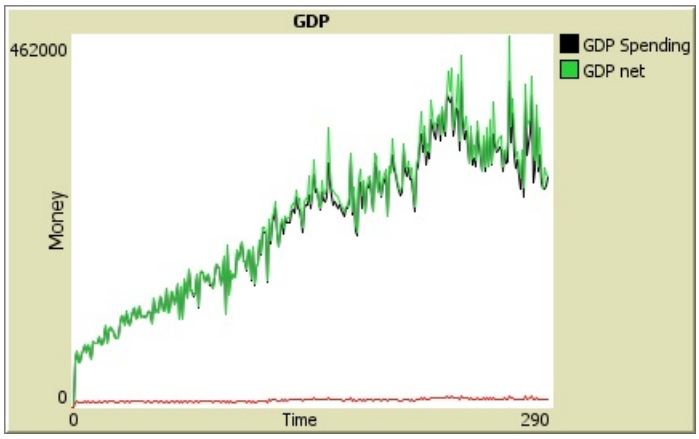

Figure 3: Gross GDP

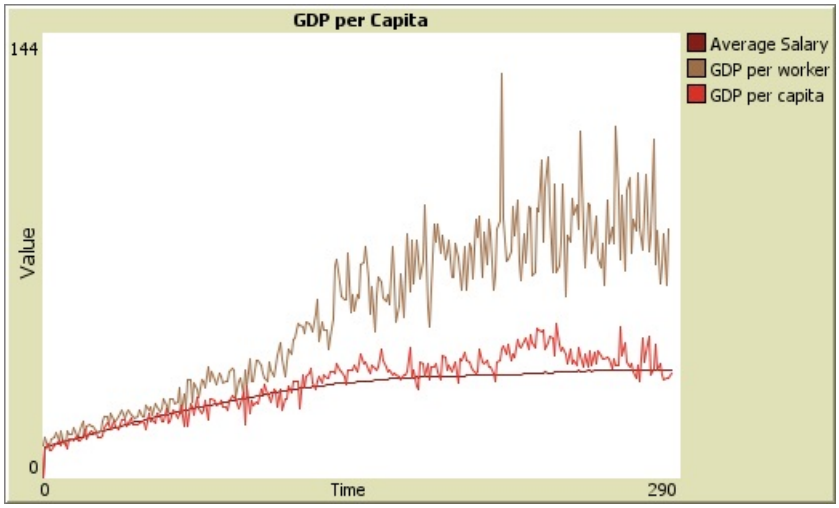

Figure 4: Gross GDP per Capita

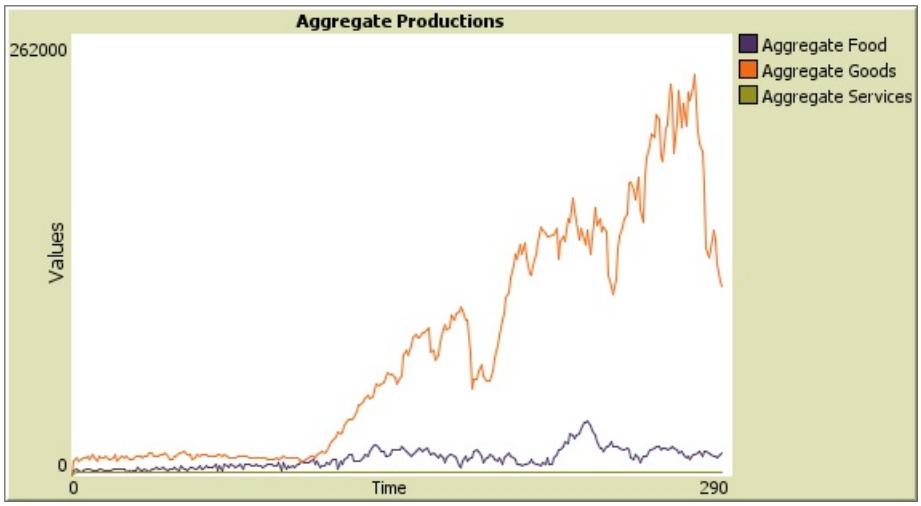

Figure 5: Production by Sector

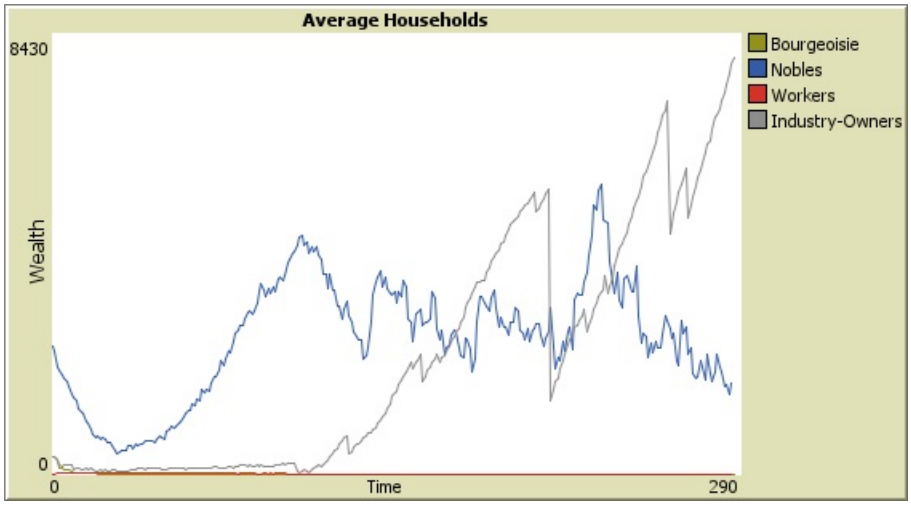

Figure 6: Average Income by Class

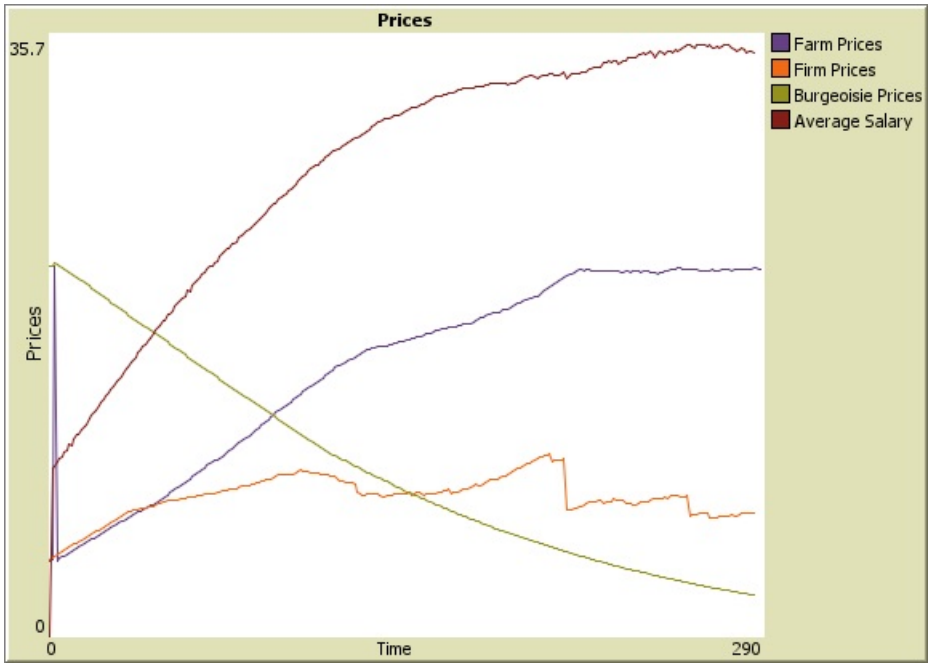

Figure 7: Prices

Missing and Future Features The behavior of the Bourgeoisie who do not own Firms is still unrealistic, and in dire needs of work, as the Service Market is probably not working as intended. Additionally, the technological improvements are not behaving as intended, and need fixing. As stated early, a further round of parametric exploration is missing.

Future iterations of this model could add a variety of new features, like n different goods with different degrees of possible industrialization, an explicit coal market, a proper financial system, a more sophisticated foreign market.

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