A Framework for Agent-Based Computational Economics in Economic Geography

By Tom Schenk

Abstract

Economic geography is the study of how economic agents organize themselves in the economy. The name suggests that economists and geographers have been working together to build models. However, this is contrary to the fact. A dissonance has arisen between economists and geographers in the last decade. The source of the problem is methodological differences. The difference are vast enough where it is difficult to merge the methodology of economists with those of a geographer. However, recent advancement in agent--based computational economics (ACE) allows us to build a framework that meets the needs of economists and geographers. This paper develops an ACE framework where economists and geographers can collaborate.

1 Introduction

In 1990, Bentonville, Arkansas was a small, traditional southern city with 11,000 inhabitants. A drive through present-day Bentonville and one will realize the city's industrial parks are turgid with regional offices for companies like Newell--Rubbermaid, Tyson Foods, Proctor & Gamble, and other Fortune 1000 companies. At the same time, the population has increased to more than 26,000 in 2003. What has caused this immense gravitational pull towards Bentonville? Wal-Mart, the nation's largest retailer, started and is currently headquartered in Bentonville. As the company grew, suppliers relocated near the headquarters to reduce costs. Like the gravitational pull of Wal-Mart, economic geography studies how and why firms choose their locations.

Bentonville is an example of an agglomeration, where people and firms are highly concentrated. Agglomeration commonly refers to a specific industry. Detroit, for example, is highly concentrated with auto manufacturers. Agglomeration can also occur in an entire region. A night time satellite photo of Europe shows a dense collection of lights between London, Amsterdam, Paris, and Brussels.

Where there are examples of agglomeration, there is a complimentary dispersion of population. Returning to the night time satellite photo, lights are sparsely distributed in the former Soviet states (e.g. Balkans, Baltic states). Likewise, the density of industry in the United States gradiates from highly condensed in the Northeast[1] to sparsely populated beyond the Ohio Valley.

Using simple assumptions of the behavior of firms and people, economic geography is able to explicate the forces of agglomeration and dispersion. However, a dissonance has arisen between

economists and geographers. Throughout the 1990s, renowned economists applied sophisticated international trade, endogenous growth, and urban and regional economic theory to economic geography. The subject, consequently, became very technical and required an advanced understanding of economics and mathematics. However, the increase of advanced methods accompanied the need to develop some more assumptions; meanwhile, the theories of social scientists and geographers were being ignored.

While the subject's popularity was growing, geographers were being deprecated from the literature. Recently, some geographers have tried to ignore economists. These calls are not in retribution for being ignored, instead, some geographers reject the methodology and assumptions used by economists. Economists cannot, some argue, incorporate "untraded interdependencies" in the mathematical models. However, there is an internal debate between geographers about the role of economists in economic geography.[2] Economists, meanwhile, have not responded. Thus, economic geography is a divided subject. Heated writings have been tempered, but the source of the dissonance has not been resolved.

The purpose of this study is to propose a framework that accommodates the needs of the economists and geographers. Specifically, this paper presents a model that uses agent-based computational economics (ACE). This tool is currently being used by economists [e.g. Duffy and Bullard,1999] and geographers [e.g. Dibble and Feldman, 2000] for various studies, but is not being used for economic geography.

This paper touches on a number of subjects—economics, geography, philosophy, sociology, and computer science. The computer science portion (e.g. learning algorithms, code syntax) of this paper may seem underdeveloped to a programmer. This, however, is intentional as this paper attempts only to outline the computational framework. It would be brash of this paper to speak esoterically of computer science so to only attract the attention of non-economists and non-geographers. It should be noted that this paper only offers a framework. That is, it does not show a working model.[3]

The next section briefly reviews economic geography from the economists' perspective and the geographers' protest. Section 3 shows how a computational framework can be used as a common tool for

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[1] Sociologists refer to the Northeast as an example of a Megalopolis: a region containing a number of cities and their surrounding suburbs [Gottman, 1961] to sparsely populated beyond the Ohio Valley.

[2] An entire issue of *Antipode* was devoted to economic geography in 2001. Most of the articles dealt with the geographers relationship with economists. Economists, meanwhile, have not responded. Thus, economic geography is a divided subject. Heated writings have been tempered, but the source of the dissonance has not been resolved.

geographers and economists; section 4 gives a detailed narration of the framework; and lastly, section 5 will conclude.

2 Antecedents of Economic Geography

2.1 Brief Review of New Economic Geography

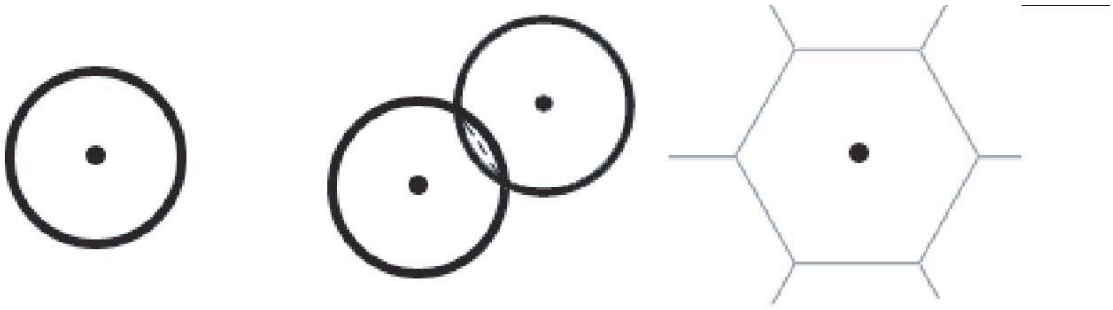
The introductory section outlined a few examples of systematic agglomeration. Economic geography, however, is not an *ex post facto* science. Using some basic economic principles, one can predict the effects of agglomeration. This section will show a succinct example of applied economic geography. However, most economic geography models are very complex and mathematical. The rest of the section will review economic geography, but will ignore the fine, rarefied details.

For a moment, let's consider the characteristics of a firm wanting to ship its products to consumers. One of the first decisions is to choose its location. Optimally, it will want to be near its consumer base. Then, let's assume another firm selling the same product is also choosing a location. Where should the second firm be located? Next to the other firm where it can compete for the same customers? Perhaps as far away as possible?

First, a firm must decide how far away it can effectively ship. Shipping is usually rated on mileage. Thus, shipping great distances may become expensive. For simplicity, assume both firms charge $10 for the product and shipping costs $1 per mile. Thus, a firm will ship up to ten miles before it becomes too costly. Consequently, each firm will service a 31,400 square mile circle around their location. Second, a firm will need to decide where to position itself in relation to another. Since the firms are selling the same product (i.e. perfect substitutes) they will not want to directly compete. Direct and perfect competition will lower prices where each firm is only making enough to cover variable costs—that is, both firms will be losing money. Figure 1 shows how firms will locate. If the circles are only tangent, then many customers will not be serviced, thus creating an opportunity cost. However, slightly overlapping the circles is more efficient. The overlapping portions can be evenly divided, which creates new market coverage for both firms who can now profitably sell their product. When seven or more firms are in the market, a firm's market area is transformed from a circle to a hexagon. So, by looking at price,

[3] A working model is in the works; however, the importance of an accepted framework precedes the need to show a working model. When it becomes available, the program and source code will be made available.

transportation costs, and some knowledge about perfectly competitive markets, this model shows how firms are located.[4]



I. Single Firm II. Two Firms III. Nested Hexagons (7 firms)

The reader might be quick to notice that the above model does not explain agglomeration. Instead, according to the model, similar firms will be equally spaced. However, this is contrary to what actually happens in the real world. Similar firms tend to be highly concentrated in a small area (e.g. malls or business districts) or in a region (e.g. auto industry in Detroit, insurance in Des Moines). How can similar firms coexist without negating each other's profits?

Hotelling [1929], the first modern economic geography model, found that slightly differentiated products permits firms to locate near each other. That is, product differences will appeal to certain tastes, thus creating a downward sloping demand curve allowing firms to charge different prices. In the case of the shopping malls, slight differences between products and consumer tastes will let similar, but not perfectly competitive, firms be located in a small area.

A slight product difference (i.e. monopolistic competition) plays a crucial role in economic geography. A century after the first monopolistic competition model, the topic was simultaneously revived by Robinson [1933] and Chamberlin [1934]. Dixit and Stiglitz [1977] is an empirically tractable model of Chamberlin [1934] that has escaped the problem of assuming economic growth. It is, however, representative of a special case. Notwithstanding, it has become a favorite model in international trade and economic geography literature.

[4] This specific model is called the ``nested hexagon model." Different industries usually have different prices and transportation costs. So when the hexagons from different industries are laid on the paper, different sized hexagons create nested hexagons.

The simple model presented earlier is also insufficient because it looks only at firms selling final goods. There are actually two types of firms: those selling products meant for consumers (final goods) and those selling products that are transformed into final goods (intermediate goods). Both types of firms are interdependent insofar as lowering the price of intermediate goods will lower the price of final goods and the sales of intermediate goods depend on their inclusion in final goods. Thus, there is a "circular causation" where firms selling final goods tend to locate near firms selling intermediate goods (to lower costs) and firms selling intermediate goods will locate near firms selling final goods (to increase sales) [Myrdal, 1957]. It can be broken down into two instances: "forward" and "backward" linkages [Hirschman,1958]. A forward linkage is where an intermediate good's plant encourages a plant that produces final goods to move closer. Conversely, a backward linkage is where a final good's firm encourages an intermediate good's plant to move closer. Thus, both instances create agglomeration. Bentonville, the booming Arkansas city discussed in the introduction, is an instance of a backward linkage. Wal-Mart, the retailer of final goods, has caused a gravitational pull[5] to compel suppliers to move closer.[6]

The final major contribution to economic geography is "new" international trade theory—namely, the seminal work of Krugman [1980] which created a simple two region economic model. The economy contained two types of industries—one enjoyed increasing returns to scale (that is, the value of the firms outputs is greater than its inputs) and one had constant returns to scale (the value of the inputs equals the value of its outputs). In addition, labor, the only factor of production, is immobile and cannot migrate between the two regions. Trade can be guaranteed because of increasing returns to scale and differences of tastes; society can be guaranteed to benefit from trade because of the greater variety of goods produced (which is a consequence of trade and the Dixit-Stiglitz monopolistic competition model). A notable outcome of this model is the home-market effect, where large dissimilarities of tastes will cause goods to be produced where they are preferred most. As a consequence, if a good is preferred more in one region, that region will have a concentration of manufacturers of that good; likewise, it will become a net-exporter of said good. In essence, production of a good will concentrate in one region where it is preferred most.

[5] Gravitational pull" is being used as a double-entendre. An early model used in economic geography adapted Newton's Law of Gravitation to firms. People and firms are like planetary bodies that caused a gravitational pull on the other.

[6] This is not a perfect example because circular causation and linkages often refers to producers. Wal-Mart is only a retail and does not produce any goods. However, the inference to the interaction between two firms is clear.

Thus, by certain characteristics of taste, technology, and factor endowments (TTFE), firms will agglomerate in a region. When "new" international trade theory is combined with the concepts of Hotelling, Myrdal, and Hirschman (among other authors not covered here)[7], the self-described "new" economic geography is formed. Krugman [1991a,b], Grossman and Helpman [1991] were the first works of "new" economic geography. A typical model resembles Krugman [1980]; however, a couple of restrictions have been lifted. The mobility of labor now depends on the sector that employers them: immobile for the agriculture sector (a sector with constant returns to scale) or the manufacturing sector (a sector that enjoys increasing returns to scale). Some models included more regions [Krugman 1991b] and assumed there were transportation costs between regions but no costs when shipping within a region. By this time, more economists were directly contributing to new economic geography, which was transformed from relatively simple models into sophisticated mathematical models.

Fujita et al. [1999] is a monograph of the aforementioned literature. They stressed the stability of equilibrium in a spatial economy, which boiled down to "centrifugal" and "centripetal" forces in the economy. Low nominal wages or a close proximity to other firms (when transportation costs are high) drive firms to agglomerate. On the other hand, high nominal wages or low transportation costs will compel firms to agglomerate somewhere else or space themselves out farther away from each other. These contrapositive forces will eventually balance themselves into equilibrium.

New economic geography has transformed early models into sophisticated general equilibrium models which are both explanatory and predictive.[8] Notwithstanding the specific components of a model, economists have discovered that agglomeration depends on TTFE—tastes, technology, and factor endowments—and the tug of war between backward and forward linkages. Since Fujita et al. [1999], the number of articles has quickly declined, signaling that economists were satisfied with their models. Meanwhile, geographers were largely ignored during the robust economic geography movement. The next section will review some of the fervor raised by geographers and attempts by other geographers to figure out how to incorporate geography into the sophisticated economic models.

A "Cultural Turn"' from New Economic Geography

[7] See for example, Henderson[1974] and Romer[1986].
[8] For more extensive review of `new' economic geography, Lehner and Maier[see2001].

"New" economic geography is the product of three decades of economic theory. The last decade has lent itself to merging monopolistic competition, urban economics, regional economics, New Growth and New Trade Theory into a single theory for economic geography. As a result, economists have moved the field away from social interaction toward a mathematical model. Unfortunately, geographers are not ready to wholly accept the assumptions of economists, nor ready to bequeath the field to economists.

The catalyst was Amin and Thrift's [2000] call for a "cultural turn" away from economists. While their argument is not against economists, *per se*, it is a dispute against their methodologies.[9] Namely, exploring the spatial relationships, as economists do, ignores the learning processes of firms and people. To thoroughly understand this process, the subject must "appreciate the anthropology of communities of practice in firms." Thus, economic geographers need to let economists focus on the spatial allocations and let economic geographers contribute theories of how firms and people learn and improve institutions.

As it turned out, other social scientists were ready to run with Amin and Thrift's commentary. For instance, Perrons [2001] suggested that Amin and Thrift did not go far enough. Instead, there is a false *de facto* assumption that economic geography needs to analyze the behavior of the firm. Firms, she argues, only play a minor role in the development of regions. Analyzing firms leads to analysis of "developments within regions rather than the development of the region as a whole." Thus, economic geography's level of analysis should be people and nation-states instead of firms.[10]

How will the "cultural turn" away from economic methods affect economic geography? In other words, where will economic geography be without economics? Despite the preceding arguments, some geographers are not ready to leave economists entirely. One of the strongest points for the geographers is the economists need for the axiom of individual rational choice. Economists, in order for their models to be explanatory, need to assume, to a certain extent, that individuals and firms are perfectly informed rational economic agents. That is, when choosing between two perfectly substitutable goods, the individual will always buy the lower priced good.[11] Likewise, if product A is preferred more than product B, then an

[9] There is an overall tone that some of the rejection originates from geographers being self--conscious of their status in relation to economists [Amin and Thrift 2000 ,Sheppard 2001]. I do not, however, believe this an accurate perception of geographer's arguments. While there are some geographers who are quick to dismiss the mathematical models simply because they do not care for the tedious work, there are geographers who have raised pertinent methodological questions. The critiques presented in this section, in my belief, are critiques of the economists methods.

[10] An excellent example of how much economic geography focuses on the firm, \citet[see][]{Maskell01} who carefully defines what qualifies as a firm.

[11] An individual can also rank goods if they are equally priced and preferred. The well--known Buridan's Ass paradox, created by 14th century philosopher Jean Buridan, placed a ``rational ass'' between the same two stacks of hay. Unable to rank (prefer) one stack more

individual will never pay more for *B*. Geographers, however, simply do not view this as a realistic assumption. There are many examples in which individuals do not behave rationally, and it is rare to find any who are perfectly informed. Thus, geographers argue, the use of unrealistic assumptions creates models that do not "increase our understanding of the real space economy, but more from their role as a statement of faith in such techniques to eventually produce some profound insights" [Sunley, 2001].

Overall, the assertions of geographers are to push toward a "relational" theory of economic geography. Notwithstanding the suggestions of Perrons [2001], economic geography is the study of how economic agents interact in space. Relational economic geography rests on three propositions [Bathelt, 2003]: *contextuality*, *path--dependence*, and *contingency*. To a certain extent, the behavior of economic agents needs to be understood in the context of their social and institutional relationships [see also Granovetter, 1985].[12] In addition, yesterday's actions will constrain the menu of choices today. At the same time, they are contingent on the strategies of others.

Thus, Bathelt and Gluckler [2003] propose that economic geography incorporates the following concepts:

1. *Organization* Firms also face problems with organization. For instance, one must choose its suppliers which can be a product of experience as much as a function of profit.
2. *Evolution* Economic agents interact over time. Everything operates independently, but they reflexively adjust to the surrounding economy. That is, agents must adapt to changing needs, possibly experimenting with new strategies.
3. *Innovation* New technologies may depend on how companies are vertically integrated. In addition, nation--states may encourage new technologies with institutional support. The development, however, is in coordination with evolution where firms are given feedback by other agents during the development.
4. *Interaction* This plays an important role because learning is often dependent on interaction. The ability to communicate, in turn, is dependent on technology and space. Thus, the organization of agents can be a function of the need for interaction. In addition, similar to evolution, interaction is closely related to evolution, where interaction will create the need for adaption.

These four concepts can be viewed as levels of analysis. Each one of these concepts incorporates at least one of the three research propositions. All three propositions are then necessary and sufficient conditions for the four research concepts.

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than the other, the ass will starve to death. However, in actuality, the ass could choose either stacks of hay without violating the rationality assumption.

[12] The social relativity that this suggests is philosophically worrisome [Belcher,2005]. However, I am not suggesting an absolute relatitivism. Although contextual analysis makes sense to some degree, it is not necessary. An economic agent is analogous to a ball flying through the air. The ball's current location does indeed depend on its previous location, angle, and velocity. However, proper scientific analysis demands that we are able to plot its future course, which in turn, the previous location, angle, and velocity is negligible. Likewise, an economic agent's current situation requires a contextual analysis; nevertheless, the meat of the analysis is making projections.

Using Bathelt and Gluckler's [2003] alternative framework for relational economic geography, the aim of this paper is to deter disparages between economists and geographers. By combining the main concepts of relational economic geography with new economic geography, it is possible to divert any further disparages between economists and geographers. Specifically, agent-based computational methods allow the experimenter to incorporate contextuality, path-dependence, and contingency. Likewise, they are also able to dissolve the need for the rational actor assumption and even the Walraisian Auctioneer. Thus, by meeting the criteria of geographers, while maintaining the tenants of economists, it is possible to have a tool accepted by both subjects. The next section briefly introduces agent-based computational economics and how this new model permits more "realistic" models. In addition, it will review the cleavages between economists and geographers as well as why it would be difficult to combine the aforementioned research paradigms.

2.3 Agent--Based Computational Economics

2.3.1 What is Agent--Based Computational Economics?

Agent-based Computational Economics (ACE) is a relatively new tool in economics. Computational models (e.g. MATLAB, Mathematica, or GAMS) are not new to economics or geography. These models traditionally used fixed algorithms that ran repeatedly over time. Agent-based computational economics, however, is distinctly different because it uses an evolutionary approach. While a model may contain several "fixed" algorithms, agents are allowed to make decisions using learning algorithms. These algorithms, which vary in sophistication, permit agents to arrive at decisions based on their previous experience.

Models are constructed using new programming techniques, namely, object-oriented programming. The researcher programs an economy which is simulated and displayed visually on the screen. The visual display may be a map of the location of economic agents or graphs displaying statistics. These techniques permit more extensive and realistic models in several key ways [Tesfatsion, 2001]. First, such models permit interaction between heterogeneous agents. Interaction is driven by individual preferences, internalized social norms, and behavior rules. Consequently, the economic agent accrues data on its experience, which forms a basis for further interaction.

Second, agents adapt to their surroundings to satisfy their wants. Agents may need to adapt to the behaviors and strategy of other agents or to a new environment. That is, an agent's strategy may change in response to its surroundings. This is in contrast to traditional game theoretic literature which normally posits a constant strategy.[13]

Lastly, models are Darwinist insofar as they incorporate evolution and natural selection. They are intrinsically evolutionary since agents continually adapt to their surroundings and seek to better themselves. This also posits a form of natural selection since agents may be forced to adapt to the new surroundings or accept inferior conditions.[14] Thus, these models do not explicitly adhere to population laws, but to implicit laws of survivability.

ACE modelling is new and exciting; however, it is also important for well-designed models. While models may show regularities arising from decentralized activities, it is more important to constructively show why regularities exist. Thus, models must be rooted in theory; thus, ACE is only a tool which must be verified. Nevertheless, it provides some trenchant insights which can promote further study.

2.3.2 Using ACE in Economic Geography

A new framework in economic geography will need to combine the basic tenants of geography and economics. Relational economic geography rests on three propositions: contextuality, path dependence, and contingency. New economic geography, on the other hand, rests on utility maximization and equilibrium analysis. Thus, any new framework would need to incorporate "soft"[15] analysis with the more mathematical economic analysis.

This paper suggests ACE modelling permits the research paradigms of geographers and economists can be combined into a single tool. Yet, is it necessary to find another tool? Is there any way to reconcile both disciplines within the current framework? One needs only to look at the geographers' need to incorporate path dependency.

Path dependency postulates that one must consider individuals previous actions because any action will limit or open future decisions. Some economists have mulled over the path dependency of

[13] There are, however, exceptions in the field of evolutionary game theory. For examples, see Samuelson [1997], Gintis [2000].
[14] In this specific model agents may perish if they do not meet minimum needs.
[15] I am not using this as a pejorative. Several geographers have used this term to describe their analysis in relation to the analysis of economists, for example Perrons [2001].

economics. For instance, David [1985], an economist, uses the QWERTY keyboard layout as an example. The first letters for any computer or typewriter keyboard reads "Q W E R T Y." The layout was not determined because of optimal typing speed, but actually to reduce the early typewriters from jamming by slowing down typing speeds. The problem has since been fixed and, of course, computers cannot have the same problem. Nevertheless, the QWERTY keyboard is the *de facto* standard despite more efficient layouts (DORVAK, for example). It remains the standard because path dependency led us to a point where it is costly to retrain all typists.

Nevertheless, most economists believe this cannot fit within the framework of economic analysis. Krugman [1991b] directly countered the path dependency argument:

> ``Most important to my mind, however, is the support that the study of economic geography offers for a basic rethinking of economics. In spite of growing interest in 'path dependence,' most economic analysis remains dominated by a style of model that I like to think of a TTFE: the idea that the economy's behavior is basically determined by its (exogenously given) tastes, technology, and factor endowments…
>
> ``Many economists find QWERTY deeply disturbing and troubling. Like Paul David, Brian Arthur, and others before them, I find it exciting and inspiring. But what I conclude even from this preliminary study of economic geography that is does not matter whether you find path dependence appealing or appalling. For at least insofar as the location of economic activity in space is concerned, the idea that an economy's form is largely shaped by historical contingency is not metaphysical hypothesis; it is simply the obvious truth."

Although the remarks do not dismiss path dependency as incorrect, they largely ignore their impact due to econometric (statistical analysis) concerns. Incorporating path dependency into a new economic geography model is difficult; nevertheless, it remains an issue.

Whereas new economic geography cannot incorporate path dependency, ACE models are intrinsically set up to handle this problem. By setting the initial conditions, one may view economic growth on the computer screen. Each agent's past decision will affect the agent's future possibilities by increasing/decreasing money funds, heightening/limiting social interaction, or forcing agents to change their strategies.

Similarly, ACE models also incorporate contingency. Strategies are not predetermined universal laws; instead, strategies are forward-looking based on the need to survive. An agent's actions are contingent on the processes of others. A single strategy, otherwise known as a dominant strategy, can only be successful if others in the economy fail to adapt. Lastly, models incorporate contextuality. The interplay between path dependency and contingency requires that, to a certain extent, agents be analyzed in the context of their current environment.

Thus, the concepts of relational economic geography can also be integrated. The ACE model permits greater organizational analysis by granting more freedom to firms to choose internal behavior. For example, firms are allowed to determine the source of intermediate goods. While a firm is likely to choose lower price, negative experience might encourage firms to balance between price and guaranteed product availability.

Evolutionary analysis is embedded in agent-based modelling. Since the ability to successfully bargain is contingent on the nearby environment, an agent must evolve to adapt. Some evolutionary practices may be forced by a natural selection. That is, a poorly performing firm may need to completely readapt before succumbing to bankruptcy.

In brief, an agent-based computational framework for economic geography allows the model to permit path dependence, contingency, and contextuality. Thus, a researcher may analyze organization, evolution, innovation, and interaction within the economy. While learning plays a major role, some interaction is driven by economic theory (such as utility functions). Little attention was given to economic theory is this section. However, the next three sections are limited almost entirely to a discussion of economic theory. While it may seem that geography has been ignored, the resulting analysis fits into the aforementioned geographer's research paradigm.

The goal of the following sections is to outline an agent-based computational framework for economic geography that adheres to the preceding discussion. The next section briefly outlines how the economy would run. Following that, the literature becomes more mathematical as the precise details of the economy are explained.

3 Overview

The economy consists of three regions, two agent types—firms and individuals—and three produced goods—apples, bananas, and coconuts. Each region is equally spaced so transportation to one region is no more costly than the next. Individuals have the objective of earning enough income to survive. A firm’s sole goal is to maximize its profits.

Although there are multiple types of goods, the firms act as the manufacturer and retailer of their goods. That is, there are no intermediate producers.[16] Firms only produce one type of good and may only have one production location. Firms are allowed to sell the good locally and are allowed to export their goods to other regions at a cost. At the beginning of the model, firms are endowed with a positive sum of money. Each firm is also endowed with the same production function and has no advantage due to land fertility. Firms are expected to pay wages for laborers (the only input), a fixed cost, and if they choose to export, transportation cost.

Individuals have two roles: heterogeneous consumers and homogeneous workers. That is, as a consumer they each have different tastes. However, no individual is more productive than the next so in the face of firms, they are all equal. At the beginning of the model, each individual is endowed with a positive sum of money, a utility function, and a subsistence need. The primary goal of every individual is to earn enough money to meet their subsistence needs. Their secondary goal is to earn enough money to maximize utility. Not meeting their subsistence needs means the individual will parish. Additionally, consumers' utility functions are allotted so they have a weighted preference for one good. The origin of the good, however, does not play a role in their decision.

Firms and consumers have access to basic statistical information that will help them make decisions in each round. Firms know the number of other firms in each region, the price index of goods in each region, the population of each region, and the number of goods previously sold in each region. Consumers are also aware of the price index of goods of their home region and the average wage. Individuals may only work at one job within their region. They are, however, allowed to consume goods that are produced locally or imported into their region; they are not allowed to travel to consume goods.[17]

At the beginning of each round, firms choose a price and a quantity to produce for each region. The sum of the desired quantities in each region gives the entire production plan. Firms then post a wage offer in their home region to attract enough workers to actualize their production plan. If firms are not able to attract enough workers to produce their plan, the firm is still subject to the production function, the firm

[16] Their exclusion may seem curious, but they were omitted because they behave similar to a retailer. Thus, the primary importance is to establish the behavior of the firm in an ACE model. Then, any inclusion of intermediate firms is rather seamless.
[17] A counter to this is persons living on borders. For instance, the strong purchasing power of an American dollar in the Canadian economy attracts Americans living in northern Minnesota to buy goods in Canada and transport them back to America for personal consumption.

will be forced to produce a quantity lower than the initial plan. If the firm is faced with excess labor demand, then the firm will only hire enough to fulfil its plan.

An individual's labor is indivisible. Individuals can only work for one firm at a time. Since individuals are aware of their utility functions, subsistence needs, and price index, they will be able to estimate their minimum level of acceptable wages (i.e., reservation wage) in order to meet their subsistence needs. They are then able to search for jobs that offer wages equal to or greater than their reservation wage.

Firms that fail to sell enough goods to pay their costs will incur a negative profit. They will be forced to use a portion of their endowment to cover those costs. Firms that do not produce any output will be forced to pay their fixed costs. Individuals who are unable to earn enough money to buy enough goods to meet their minimum subsistence needs will be forced to use their endowment to consume up to their minimum subsistence level. A consumer will never use their savings to consume beyond their subsistence needs. If a firm fails to cover its costs, it will be forced into bankruptcy. The bankrupt firm will not be replaced, and the population of firms will be adjusted accordingly. Consumers that fail to consume their subsistence needs will perish. All of the existing endowment would have gone to their attempt to consume enough goods so there will be no remaining cash to redistribute or any outstanding debts. The expired individual will not be replaced, and the population will be adjusted accordingly.

Individuals are faced with a simple problem: they must earn enough wages to first meet their subsistence needs, and, if there is remaining cash, they will try to maximize their utility functions. Firms face a more complex problem: they must strategically set a price and quantity in each region that will not create a surplus or shortage of goods so they can minimize cost while maximizing profit. They must strategically choose wages so they are able to attract enough workers to meet their production quota, but they must not offer too much so they can maximize profits.

Although meeting minimum subsistence and budgetary needs seems trivial, maximization may be difficult. Regionally, firms use local labor to produce goods. In addition, firms attempt to maximize profits which may mean lowering wages. Consequently, suppressed wages may leave local individuals unable able to buy the goods they produced. Reliance on foreign produced goods may lead firms and

individuals to move to increase purchasing power. Thus, the maximization problem leads to a dynamic economy where agents are constantly moving.

In summary, agents in the economy must adhere to some procedural rules. However, individuals and firms are allowed to set certain parameters (such as price). This is where learning algorithms are used to make the decision. Notwithstanding their autonomy, both individuals and firms are given specific goals. Individuals must meet minimum subsistence needs and, if possible, maximize their utility. Firms, on the other hand, attempt to break even (where revenue equals costs) and, if possible, to maximize their profits. However, as previously mentioned, this simple goal may lead to a changing economy.

The next section repeats the above process in more mathematical detail. In addition, some unified modelling language (UML) diagrams are included to show the procedural steps.

4 Detailed Process

The model can be distinctly divided into distinct parts: overall economy, individuals, firms, and interactions. The overall economy does follow some basic protocols.

4.1 The Economy

The economy runs over a discrete time-period from T_0 to T_{max}. The entire economy consists of A_i apple firms, B_i banana firms, and C_i coconut firms. The economy also consists of P_i individuals. Each industry is equally distributed across the three regions. Each i^{th} firm is given $M(t)$ dollars at $t=0$ and a common production function. Each individual is given a utility function that varies by different utility weights. They are also given a minimum subsistence needs and an ordinal ranking of goods.

Each i^{th} firm has $M(t)$ that can be costlessly carried from one period to the next. Firms are not constrained by any production limit, but all firms adhere to the same production function.

$$Q = \bar{l}, 0 \leq \_ \leq 1 \tag{1}$$

Firms are not advantaged by technical efficiency, land fertility, or higher productivity of workers. (It should be noted that geographical heterogeneity is only an assumption in this model. One exciting possibility is allowing heterogeneous land fertility so one region may attract higher returns.) Consumers

are exogenously given a utility function, which includes a minimum subsistence utility level and an endowment. The utility function is a Cobb-Douglas function for all three goods:

$$U = (a^{\_} b^{\_} c^{\_}),\ U \geq u \tag{2}$$

where a, b, c are apples, bananas, and coconuts, respectively; _, _, _ are the utility weights assigned for each i^{th} individual, and u is the minimum subsistence need for that individual.

In the initial period, individuals are given a sum of money M(t) at $t=0$. The money allows consumers to purchase some goods if they are not employed. Savings will only be used to consume up to the minimum subsistence utility level; a consumer will never use their savings to maximize utility. Likewise, they will never use their money endowment to consume beyond their subsistence utility level.

4.2 Individuals

Individuals serve two roles: a consumer and a worker. The consumer role is still neoclassical. The role of the worker is to fulfil the role of the consumer. Income generated by a individual is through work and it directly finances their consumption. An individual has access to posted prices and is aware of her utility function. Given an average historical price and her subsistence need, the individual is able to calculate the minimum level of wage they must make to meet their subsistence need for that round.

Since an individual knows the minimum wage needed to live, she is able to eliminate jobs that do not post a sufficient wage. The only jobs that remain on the individuals list are firms that will pay a wage equal to or greater than the minimum acceptable wage. This final list of potential firms is then randomized.

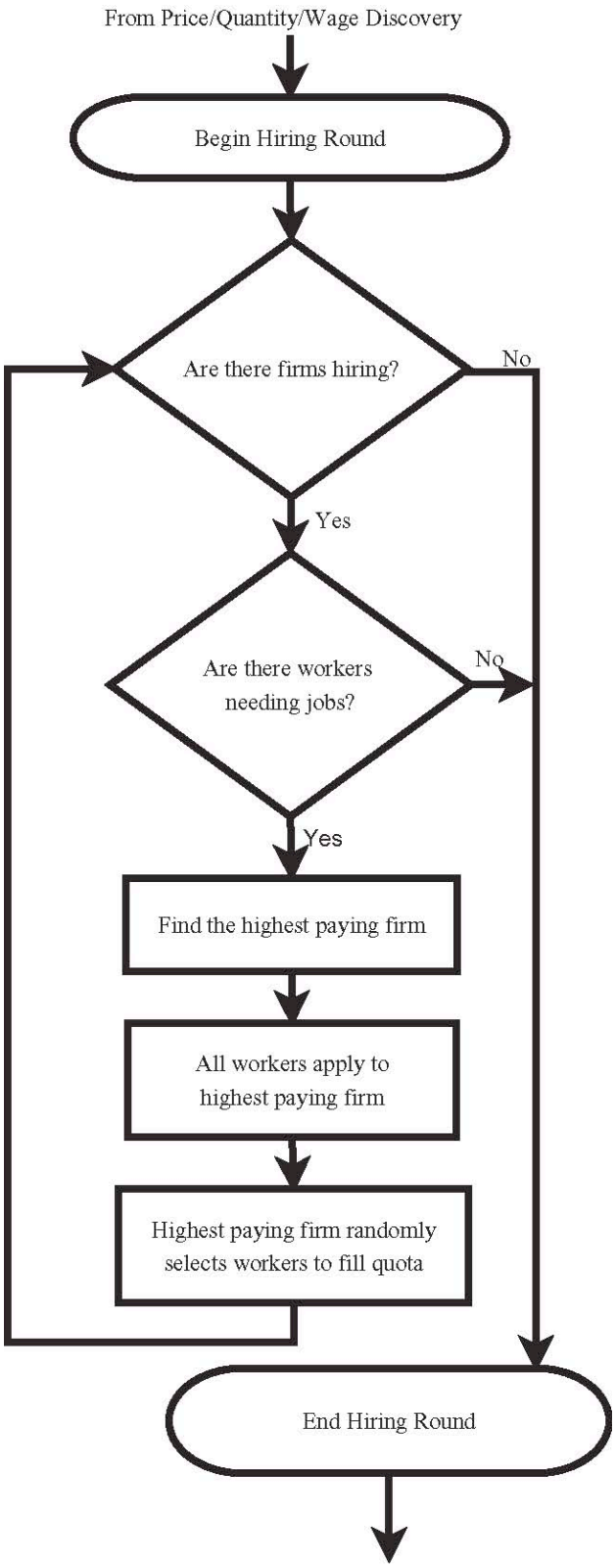
From Price/Quantity/Wage Discovery
Begin Hiring Round
Are there firms hiring?
No
Yes
Are there workers needing jobs?
No
Yes
Find the highest paying firm
All workers apply to highest paying firm
Highest paying firm randomly selects workers to fill quota
End Hiring Round

Figure 1

After their labour is completed, workers receive their paychecks. Products are also available to consumers. Individuals calculate their income and prices of goods available to them. First, they calculate whether or not they earned enough to achieve their minimum subsistence utility. Second, upon discovering that they have enough money to live, they attempt to maximize their utility functions.

4.3 Employment

Employment is the first time firms and individuals interact. Figure 1 shows the hiring process. First, labor demanded is determined by the firms need to produce goods. Firms have the ability set a desired quantity to be sold in each region. The sum of all quantities to be sold in each region is the total desired quantity. Once a firm decides its total desired quantity, it will solve the production function (1) to determine the amount of labor it needs to employ to produce the desired quantity. The firm also sets the price for the goods within each region. When a firm chooses the price and desired quantity, it can calculate the expected revenue (3). The firm can limit the range of possible wages using equation (5) so that it expects profit greater or equal to 0. After it has chosen its wages, it will post its wage offer to the market.

Once the wages have been posted to the market, individuals are able to view all of the available wages. At this point, individuals are responsible for applying to jobs so that they can earn income. Individuals are able to reduce the potential jobs by eliminating the ones that can't adequately pay them. The worker simply reduces the list by multiplying the wage by the past prices to determine how much wage she needs to meet her minimum subsistence. The remaining jobs are then placed on a list and randomly sorted.

Each individual simultaneously submits applications to all of the jobs on the list. Firms receive all of the applications and place them on a list. The list is then randomized and the first n workers are concurrently given offers to fill n positions. The offer the firm makes will be the same as the offer it posted. After workers have collected all offers, they choose the highest paying offer.

Consequently, some workers may not receive job offers and some firms may not have anyone accepting their offer. The remaining job seekers reapply to all firms that did not fulfil their hiring quota. Firms receive the applicants and randomly place each job seeker on a list. Again, firms extend offers for the first n_r individuals to fill n_r positions, where r is the round. As rounds continue, the firms are not allowed to adjust the offered wage from the initial posted wage. Rounds will cease as soon as either all

firms fill all positions or all job seekers find a job that meets his or her reservation wage. If the job market is in disequilibrium, the unemployed job seekers are those whose reservation is too high and/or excess labor supplied.

4.4 Firms and Production

Each firm controls several variables: the price it charges for its good in each region, the quantity produced for each region, and the wage they offer. A firm's production function, endowment, and transportation cost are given exogenously. The firms are not preset to attempt high profit, low quantity tactic; nor are they set to attempt a low margin, high quantity business model. The outcome is based on the dynamic economy.

The firm determines the amount it produces by determining how many goods it wants to ship to each region. The sum of quantities gives the production quota. The firm is allowed to use discriminatory pricing. The firm's revenue is:

$$\text{Revenue} = q_i^1 \cdot p_i^1 + q_i^2 \cdot p_i^2 + q_i^3 \cdot p_i \tag{3}$$

where each q^j and p^j are the quantity and price for the $j^\textrm{th}$ regions. In order to produce each good, a firm must pay a fixed cost, wages, and transportation costs for goods that it ships outside its home region. A firm's total cost is:

$$\text{Cost}(q^1, q^2, q^3, w) = F + w \cdot l(q^1 + q^2 + q^3) + T \cdot qe \tag{4}$$

where F is a fixed cost, w is the wages chosen by the firm, l is the labor hired to produce q^1, q^2, q^3 units, and T is the transportation cost for q_e exported goods. Figure 2 shows how a firm organizes its production.

Although a firm has control of price and quantity, its decisions restrict the domain for wages. If firms choose p and q for all regions, and labor is not considered yet, a firm will have a profit of $(q_i^1 \cdot p_i^1 + q_i^2 \cdot p_i^2 + q_i^3 \cdot p_i^3) \_ (F + w \cdot l(q^1 + q^2 + q^3) + (Tqe)$. To produce Q, a firm must solve the production function, which determines the amount of labor L. Since all labor is equally productive, the firm will pay the same wage to all employees. To consider how much to pay each employee, the firm restricts their choice to:

$$w \leq \frac{(p \bullet Q) - (F + Tq_e)}{l(q^1 + q^2 + q^3)} \tag{5}$$

Now the firm has p, Q, and a range for w that it can choose from. It can post these values so it can receive applications and sell goods.

4.5 Purchasing

The first instance of interaction between firms and individuals is employment. The second instance of interaction is during purchasing. Firms submit a price and a desired quantity. After choosing a wage and hiring workers, firms actualize their production. If firms are unable to hire planned n workers, their actualized production is in accordance with the production function. The total quantity is shipped to regions to be sold. Figure 3 maps the process of purchasing.

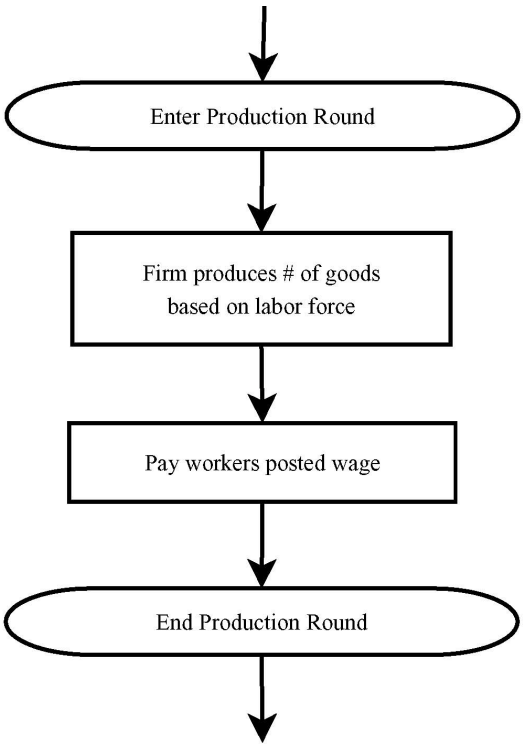

Figure 2

Firms are not allowed to adjust their price after their initial posting. Consumers have access to goods within their own region (including imported goods). Buyers submit orders to one firm in each industry. Buyers who do not have enough money to consume their subsistence needs will use their savings to meet those needs and buyers with adequate income will maximize their utility subject to their budget constraint.


Enter Consumption Round
Worker retrieves current prices for goods in respective region
Worker calculates possibile utility maximum with respect to budget
Worker submits orders to Firms for goods
Firm receives all orders
Random orders are filled within constrains of inventory
Does the worker still have money?
No
Worker exits market
Yes
Does the worker still have utility needs?
No
Yes
Does firm still have remaining inventory?
No
Firm exits market
Yes
Are there still workers and firms?
Yes
No
Exit Consumption Round

Figure 3

Once buyers submit their order to a firm, the firm collects all the orders and randomly arranges the consumers in a queue. Each firm progresses through the list, delivering the requested goods and collecting money from the consumer. No consumer is allowed to exit the line, change their request, or fail to pay. Once each firm completes the list or runs out of goods, each consumer calculates their utility. Some consumers may be unsuccessful in receiving some or all of their requested goods because of supply shortages from their particular choice. Remaining consumers who have not spent their income will remain in the market after they calculate their current utility.

Some firms may not have sold all of their goods due to lack of demand. The remaining consumers will calculate what they need to maximize their utility with their remaining budget constraint. Consumers will submit orders to one of the remaining firms in each industry. Firms will collect the orders and randomly assign consumers a position on the list. The round will end when all firms deplete their inventory or all consumers have received their goods. Further iterations will repeat this step. Any unsold inventory will perish.

5 Completion of the Iteration

At this point, firms have chosen a price, desired quantity (which was later actualized), and wages. Individuals have accepted jobs, received income, and consumed goods. Firms will calculate their revenues (3), costs (4), and profits. Individuals will calculate their utility from the goods consumed (1).

At the end of each round, if a firm's profits are negative and it does not have sufficient savings, it exits the market. If a consumer failed to meet their minimum subsistence need, they will perish. Surviving firms will be ranked according to profits. Firms will also have access to quantity demanded by consumers and quantities sold in each region. Likewise, firms will know the average wage of the region and the price index of each region. This information will be used in the next round to determine price, quantity, and wages. Figure 4 shows the entire process of the economy.

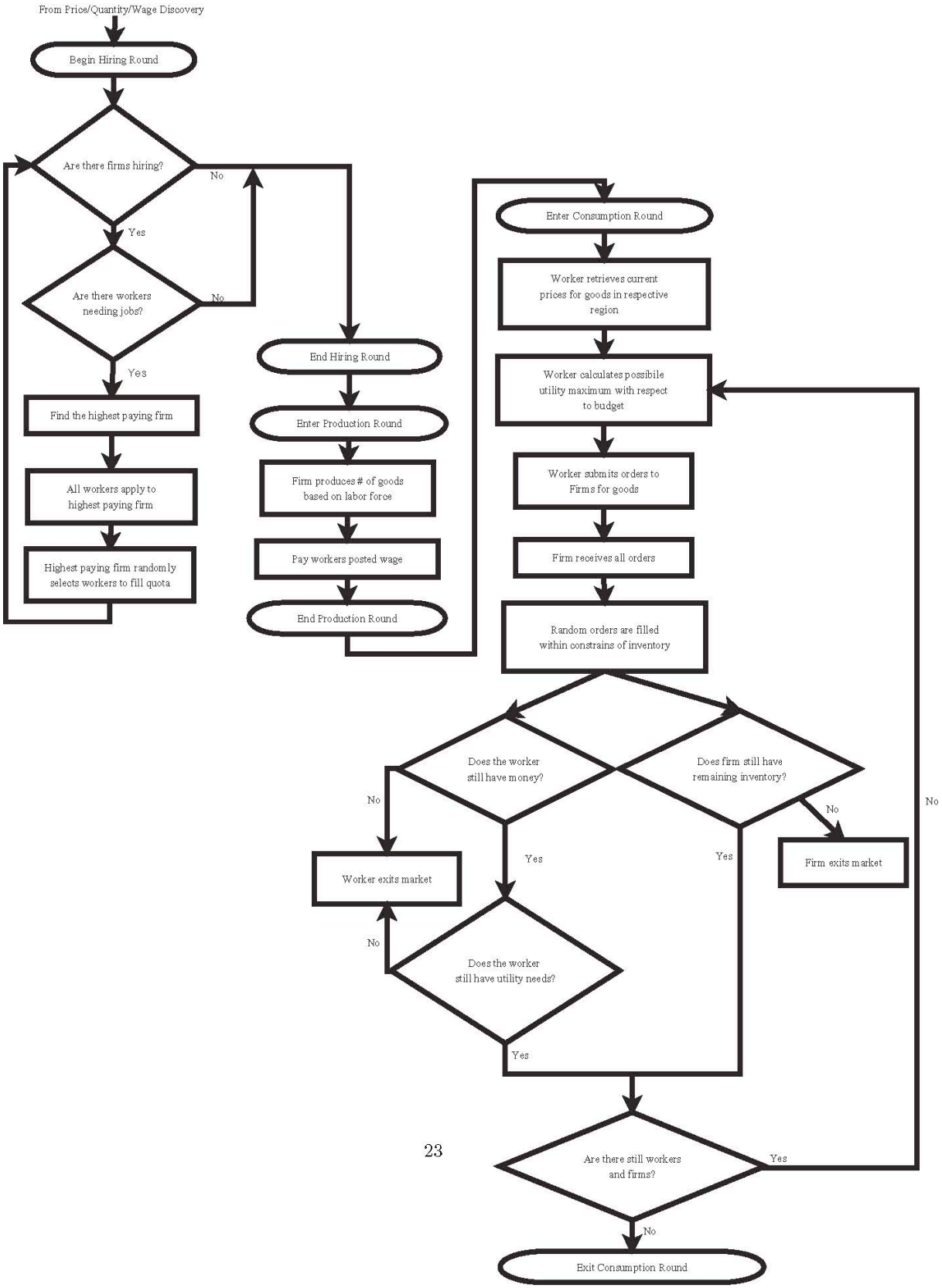
From Price/Quantity/Wage Discovery
Begin Hiring Round
Are there firms hiring?
No
Yes
Are there workers needing jobs?
No
Yes
Find the highest paying firm
All workers apply to highest paying firm
Highest paying firm randomly selects workers to fill quota
End Hiring Round
Enter Production Round
Firm produces # of goods based on labor force
Pay workers posted wage
End Production Round
Enter Consumption Round
Worker retrieves current prices for goods in respective region
Worker calculates possibile utility maximum with respect to budget
Worker submits orders to Firms for goods
Firm receives all orders
Random orders are filled within constrains of inventory
Does the worker still have money?
Does firm still have remaining inventory?
No
Yes
Yes
No
Worker exits market
Firm exits market
Does the worker still have utility needs?
No
Yes
Are there still workers and firms?
Yes
No
Exit Consumption Round

Figure 4

Conclusion

As economic geography has grown in popularity, economists and geographers have grown apart. Both disciplines have made drastic progress in the last decade, but have collaborated very little. A review of the literature reveals a well-defined list of research paradigms. As it turns out, ACE modeling is capable of handling "soft" research while borrowing significantly from economic theory.

This paper offers a framework for using agent-based computational economics in economic geography. This framework, of course, can be modified to explore other research areas. For instance, this framework uses heterogeneous space—that is, there is no inherent benefit in one region over another. However, this is contrary to the real economy. California, for example, offers higher yield for wine grapes, and vineyards subsequently face lower costs. Fortunately, an ACE framework can adapt to heterogeneous landscapes.

No other economic geography model uses minimum subsistence needs. This offers some interesting insights into the sustainability of the economy as well as its spatial development. In addition, this model reduces the need of a Walrasian Auctioneer. This deconstruction of a fictitious auctioneer was first suggested by Tesfatsion [2006a,b]. Consequently, this takes away from an assumed invisible hand and allows regularities arise from decentralized action.

This paper also suggests two points of interaction. First, individuals and firms should interact while hiring. Since an individual's working capability is heterogeneous across the economy, the hiring process is then able to be primarily based on random choosing of workers. Although this is unrealistic, it focuses on the ability of firms paying sustainable wages while producing a profit. Second, individuals and firms interact during the purchasing of goods. Some may argue that interaction must be more dynamic and continuous. While interaction between firms and individuals is constantly taking place, most interactions are within periods of purchasing or employment.

Lastly, an ACE framework for economic geography is not designed to compete with economists' and geographers' traditional methods. Instead, it is meant to allow for one to complement the other. Using these models, both disciplines can come together to work on a subject that bears their namesake. Thus, I hope this framework proves to be useful for all parties.

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