Issues in Political Economy, Vol 24, 2015, 28-47

Knowledge Spillovers and Entrepreneurial Activity: An Agent-Based Approach to Modeling Schumpeterian Growth for Developing Countries

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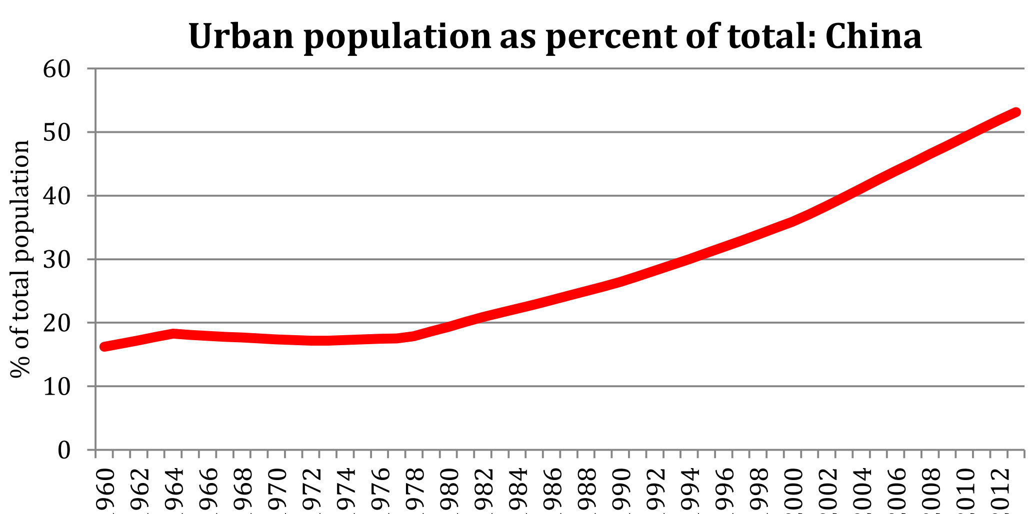
Though the process of knowledge spillovers was a prominent topic in the early endogenous growth models of Romer (1986) and Lucas (1988), more recent modeling has eschewed explicit knowledge spillover mechanisms in favor of a greater emphasis on innovation and research and development (R&D) expenditure. The Schumpeterian models of Aghion and Howitt (1992), among others, have identified innovative activity as the crucial link between R&D expenditure and total factor productivity (TFP) growth. However, the difficulty of including knowledge spillovers in conventional mathematical models has likely contributed to the topic's decreased presence in the growth literature. Despite this diminished focus, the topic of knowledge spillovers at a regional level has been preserved in the "new economics of urban and regional growth" recognized by Glaeser (2000). This channel of literature has consisted primarily of empirical studies investigating the link between the geographic density of productive activities and industry growth, though recent years have seen greater efforts to explore how spillovers can be converted into "economically meaningful" knowledge. Through these developments, the knowledge spillover literature has begun to align with the Schumpeterian approach through a shared emphasis on the role of entrepreneurs for engaging in innovative activities. It should be noted that the Schumpeterian growth models of Aghion and Howitt include implicit knowledge spillovers in the growth of a sector-wide "leading-edge" productivity parameter. However, they do not consider how spillover mechanics might lead to the rise of new entrepreneurs. In the "new economics" literature, knowledge spills over not only through R&D activity, but also through the interactions of individuals in densely populated areas such as cities. The "effectiveness" of these spillovers is dependent on those individuals who can capably apply this knowledge to productive activity such as entrepreneurship. Once again, the possibility of developing this process in growth models has likely been hindered by the incompatibility of conventional models to such complex patterns of interaction.



Source: World Bank

In this paper, I aim to tackle this obstacle by using agent-based computational economics (ACE) to create a model of economic growth that incorporates both Schumpeterian entrepreneurship and localized, individually based knowledge spillovers as a stimulus for the creation of new entrepreneurs. With multiple urban locations featuring distinct knowledge accumulation processes, the ACE approach allows me to model growth as a complex process driven by the innovative activity of individuals in these locations. From a policy standpoint, the primary theoretical merit of such an approach would be to model how certain regional dynamics might alter the path of growth. Thus, it is important to choose real world scenarios that provide a rich foundation for such possibilities. In this capacity, the developing world offers unique opportunity to explore how patterns of innovation can drive growth. While urban growth is a worldwide phenomenon, most developing countries feature large income disparities between urban and rural regions. Even rapidly evolving economies such as those of China and India, which have engaged in substantial R&D investment, still experience significant regional migration as a result of wage disparities. In China, for example, the percent of total population living in urban areas has risen by over 30 percentage points in the past 50 years (see above graph). The sheer magnitude of this change suggests that a dynamic urban population is an important feature of the rapid growth experienced by these countries. As such, my model includes internal migration as a significant feature of the growth process. This paper thus presents a theoretical foundation for internal migration as a key component of R&D led growth.

Empirical studies by Madsen, Saxena and Ang (2010) and Ang and Madsen (2011) have supported Schumpeterian growth theory as a viable model of R&D-driven growth in several Asian “miracle economies” (China, India, and the Korean Republic, among others), while most previous studies on knowledge spillovers, particularly those of the “new economics” variety, have focused largely on the developed world. As innovation is a key goal in the liberalization of urban policy in these developing economies, it seems reasonable that the patterns modeled for Europe and North America also occur in these regions. However, the developing world is distinguished by unique policy conditions and the more prominent population dynamics discussed above. With these differences in mind, this paper aims to both contribute to the growth literature and exercise a novel theoretical application in the knowledge spillover literature.

The main program models a three-sector economy that is comprised of several urban locations and a single rural location. Agents in the economy possess an initial location and productive role (either a farmer, worker, or entrepreneur). The rural location corresponds to a rural sector, while the urban centers all contribute to a manufacturing sector. Each urban center possesses an intermediate goods sector, which, as per Aghion and Howitt, serves as an input to the final goods sector. My model differs from their model in that the Schumpeterian component of growth, in which entrepreneurs engage in R&D activity in the pursuit of excess rents, occurs independently within each location. Additionally, while they characterize this rent as a monopoly rent, I model this rent as an excess market share over peer entrepreneurs. The arrival of innovations from R&D expenditure serves as the first source of endogenous growth in the model, as each innovation in a city effects an incremental increase in the total factor productivity (TFP) parameter for its final goods production. With this framework in place, agents make decisions in regard to their location and their role based on expected earnings. This allows for migration among locations and the creation of entrepreneurs in cities. Each agent possesses an exogenously determined initial level of human capital, which is the single input in the production of intermediate goods, which will determine their expected returns for being an entrepreneur. This process is facilitated through a knowledge accumulation process driven by local knowledge spillovers from other individuals. This serves as the second source of endogenous growth in the model.

One of the greatest advantages of ACE methodology is the ability to conduct normative experiments. To this effect, I use China as a template for exploring policy implications for the model. The primary goal of this paper is to present a theoretical framework for this particular flavor of endogenous growth. The model is thus not designed to apply exclusively to the case of China. Instead, the included policy experiments are presented with the intention of providing illustrative and qualitative examples of the model's usefulness. For these purposes, I run a simulation that models the effect of the Hukou household registration program in China, which serves as a significant barrier to rural-urban migration, on innovation-driven growth. While theoretical rigor is critical for any model, such experiments help provide tangible evidence of how theory can be utilized to motivate policy.

This paper is presented as follows. In Section 1, I provide an overview of the various channels of literature that inform the content of the paper, as well as China-specific literature used to formulate the included normative experiment. Section 2 is a thorough overview of the theoretical model. Sections 3 and 4 present simulation results, and Section 5 concludes.

I. LITERATURE REVIEW

The earliest examples of endogenous growth theory were primarily concerned with reconciling increasing returns to scale with market competition. Romer (1986) specified a long-run growth model that achieved this goal, but it did so under the broad assumption that knowledge accumulation creates externalities that allow for increasing returns. The spillover of knowledge is thus the essential component of growth, but such an unspecific definition does not explain how such externalities predispose growth. Within the growth theory literature, these models gave way to more rigorous approaches that provided precise mechanisms by which innovation could give way to increasing returns. As noted by Roberts and Setterfield (2007), Romer modeled knowledge accumulation as an accidental result of investment decisions, while later endogenous growth theories, such as the Schumpeterian approach of Aghion and Howitt (1992), modeled knowledge accumulation as the intended result of R&D. Though the spillover-centric relics of Romer were mostly discarded in mainstream growth literature, the central idea lived on in the "new economics" approach mentioned above. Roberts and Setterfield point to Lucas (1988) as the link between endogenous growth theory and regional growth literature. Lucas noted that the transmission of knowledge via spillovers would be highly dependent on the availability of direct human interaction and thus physical proximity. This line of reasoning leads quite naturally to the assumption that cities provide the ideal setting for knowledge spillovers. This argument was quickly adopted by Glaeser *et al.* (1992) in what can be considered the seminal paper in the "new economics" literature. The authors draw on the work of Romer and Lucas as well as early theoretical work by Alfred Marshall and Jane Jacobs to produce what became essential questions of the burgeoning knowledge spillover literature, namely, how degrees of firm diversification and market competitiveness might affect the impact of knowledge spillovers on innovation. Using data on industry growth in U.S. cities from 1957 to 1987, they found that urban variety and local competition led to employment growth in industries. As they note, however, these results should be treated cautiously, as their data was restricted to a period in which U.S. manufacturing industries were hindered by import competition, while it also only included data from “very mature cities.”

Following the example of Glaeser *et al*, studies on knowledge spillovers by Henderson, Kuncoro and Turner (1995), Feldman and Audretsch (1999), and Van Stel and Nieuwenhuijsen (2004) all focused on the central question of diversification vs. specialization, with mixed results. As suggested by the caveats provided by Glaeser *et al*, these differences can be largely attributed to the samples used in these papers. Henderson *et al*, using a data set comprising only computer and electronic industries, found that industry specialization promoted externality-led employment growth in cities. Additionally, they focus on the historical growth of industries as a driver of industry location (a topic that is outside the scope of this paper).

Though most works in the knowledge spillover literature seem to favor industry diversity as the ideal setting for knowledge spillovers, a central dilemma persists throughout. While the above approaches found extensive evidence of the “ideal” conditions for knowledge spillovers, these articles failed to address the specific mechanisms by which these spillovers operate. Feldman and Audretsch (1999) took a step in the right direction in this regard, using “innovative output” such as new products, rather than the rather poor proxy for technological growth of employment growth, as their outcome variable. This approach indeed considers technological growth more directly, but it still suffers from a lack of theoretical founding for which mechanisms, other than generalized regional proximity, might generate growth. In this sense, the question that dogged Romer and Lucas, namely that of how exactly spillovers might give rise to technological growth, has still loomed over the new economics literature.

Fortunately, recent studies have finally taken steps to address this theoretical gap. Braunerhjelm *et al*. (2010) draw more extensively on the R&D-centric models of growth theorists than that of the new economics approach. However, they provide a theoretical model that attempts to provide a “missing link” between knowledge spillovers and economic growth. They suggest that the main failing of previous knowledge-based growth theory is the assumption that knowledge that spills over automatically becomes economically useful knowledge. To address this shortcoming, they posit entrepreneurship as the critical component for accomplishing this transformation. In the theoretical model that they develop, entrepreneurially inclined individuals utilize existing knowledge stocks to develop novel products and business ideas. Thus, they suggest that knowledge spillovers can lead to the rise of new firms and innovations therein. In addition to this theoretical model, they include promising empirical results. As with previous spillover studies, their approach still suffers from a measurability problem, as the degree to which knowledge spillovers might lead to entrepreneurship is difficult to judge. However, using a data set for Organization for Economic Cooperation and Development (OECD) countries between 1981 and 2002, they find robust evidence that high levels of entrepreneurship contributed to national growth.

Desrochers and Leppälä (2011) apply a similar argument to address the previous new economics literature more directly. With a large body of empirical studies favoring inter-industry spillovers as the predominant flavor of localized externalities, they argue that the entrepreneur’s role as the “missing link” is in the creative combination of diverse stocks of knowledge. In order to avoid the measurability issue present in so much of the new economics, they take a qualitative approach consisting of a survey of Canadian inventors and case studies of spillover-driven firm-level innovation. Through this analysis, they find that many individuals who invented new products, started new firms, or engaged in other forms of innovative activity typically came from diverse career backgrounds, and their inventiveness often involved the combination of seemingly unrelated sets of knowledge in the creation of novel ideas. Though they take an unorthodox approach, two important insights can be gleaned from the work of Desrochers and Leppälä that are extremely relevant to this particular study. First, the incidence of creative combinations largely depends on the frequency with which an individual encounters diverse ideas. As they argue, creativity is dependent on both the availability of different ideas and the frequency with which an individual encounters such knowledge. These stylized facts point to the importance of both geographic proximity for facilitating face-to-face interactions and cities as a stock of diverse knowledge. Second, those individuals that successfully utilize knowledge typically possess a proclivity for creation. As Braunerhjelm *et al*. also suggest, this means that only select individuals will possess the necessary traits to transform spillovers into economically relevant knowledge through innovation or entrepreneurship.

With the basic foundations of the knowledge spillovers literature established, I now turn to the literature on endogenous growth theory that most closely resembles the approach of the new economics literature. After the work of Romer (1986) and Lucas (1988), mainstream endogenous growth split into two generally accepted approaches, the semi-endogenous models characterized by Jones (1995) and the Schumpeterian approach of Aghion and Howitt (1992). Broadly speaking, these two approaches differ in terms of their respective predictions regarding R&D expenditure and TFP growth. Both models were derived from the observation that since the 1950s, the growth rate of R&D labor in the U.S. has not produced the level of TFP growth predicted by early endogenous growth models. For this reason, the semi-endogenous models of Jones (1995) and Kortum (1997), for example, include diminishing returns to the knowledge stock produced by R&D. Thus, continued growth in R&D labor is a requirement for maintaining constant TFP growth. On the other hand, the Schumpeterian approach explains the observed trends by maintaining constant returns to the stock of knowledge in R&D with the caveat that increases in product variety dilute the effects of R&D expenditure, since a given stock of knowledge must be extended across varied sectors. Thus, R&D stock must only be kept in fixed proportion with the number of product lines in an economy to produce TFP growth (Ha and Howitt 2007).

The Schumpeterian model of Aghion and Howitt (1992) includes a theoretical framework that is particularly well suited to the approach of this paper. I will detail this framework in the next section. This model also benefits from significant empirical support in developing countries. In particular, several studies have noted the implications of R&D-led growth in “miracle” economies such as India and China. Madsen, Saxena and Ang (2010) use R&D data for India to test which of the aforementioned endogenous growth models best explains growth in India. While they acknowledge the importance of other factors in promoting growth, such as international R&D spillovers, technology catch-up and institutional reform, their results suggest that R&D activity also played an important role. In particular, they find that the picture of R&D led TFP growth predicted by the Schumpeterian approach accurately accounts for growth patterns in India since the 1950s. A study by Ang and Madsen (2011) finds similar results for six Asian “miracle” economies: China, India, Japan, Korea, Singapore and Taiwan, with Schumpeterian growth models best explaining growth paths in these countries. As an interesting parallel to the new economics literature, they favor a proxy for innovation, in this case patents, as their main outcome variable in favor of TFP growth, the more widely used variable of interest for previous growth literature. Additionally, while they concede that catch-up to the technology frontier might explain some of the observed growth patterns, they note that the R&D intensity of some countries in the study mirrors that of developed countries. Some of these, like China and India, are still far from the technology frontier, so R&D-led growth is still a viable model for predicting their growth in the future.

II. MODEL OVERVIEW

I adapt the Schumpeterian approach of Aghion (2004), which is itself an adaption of the canonical Schumpeterian model of Aghion and Howitt (1992), as the main production structure for my model. The Aghion model presents a single-good, closed economy in which the production of the final good is modeled by the function:

(1) $$Y = L^{1-\alpha} \int_0^1 A_i x_i^{\alpha} di$$

where L denotes labor input, x_i is the quantity of intermediate good i used in the production of the final output, and A_i is a parameter that measures the productivity of these intermediate inputs at a time t. When an innovation occurs in sector i, the innovator gains monopoly power in the sector until another innovation occurs, at which point the new innovator will replace this incumbent monopolist. Though I maintain the essential intermediate-final good framework in the model, I abstract away from modeling the intermediate goods input as a continuum of sectors. While the intermediate goods continuum allows for a mathematically tractable innovation process, it also confines these innovations to a black box in which innovations arise from the aggregate R&D expenditure in a sector and the intermediate firm that gains incumbent status is arbitrary. The intermediate goods sector instead produces a homogenous input, as opposed to the continuum of inputs used by Aghion. And as is fitting for the agent-based approach, I model the intermediate inputs sector as being composed of a finite, though flexible, number of entrepreneurs in each urban location. Like in Aghion, these entrepreneurs face a price schedule given by the marginal productivity of their inputs, but rather than gaining monopoly power, the incumbent innovator gains an exogenously determined excess market share over peer entrepreneurs. This sort of monopolistic competition is a necessary modification to allow non-incumbent to remain in the market. Thus, entrepreneurs commit a portion of their revenue to R&D in the pursuit of incumbent rents via innovation.

As noted before, this process constitutes the vertical innovation in the model- when an innovation occurs in the intermediate goods sector, total factor productivity in the manufacturing sector is increased by an exogenous increment. On the other hand, knowledge spillovers among workers in each urban center constitute the horizontal innovation emphasized by Romer. Finally, internal migration among locations is critically important for the nature of endogenous growth in the model. As I will show, vertical innovation serves to attract migration to urban centers via increased wages, while migration helps facilitate the incidence of horizontal innovation through an increased knowledge stock. What follows is a detailed description of these processes in the computational model.

A. Initial Conditions

I start with a time period T to denote the number of runs for the simulation and a fixed number J of locations, with one rural and J *-1* urban locations. The rural location begins with an initial TFP level A_R while each urban location begins with the same initial TFP A_U, such that $A_R < A_U$. Each location also possesses a fixed stock of land in order to place a restriction on returns to labor. This will prevent any one city's population from exploding while all other locations flounder. Initial populations are determined by N_R, the working population for the rural location, N_U, the economy-wide urban work force, and E, the economy-wide entrepreneurial force. N_U and E are then distributed amongst the urban locations according to the initial population vector $\boldsymbol{p} = \{P_1, P_2 \ldots P_{N-1}\}$, which randomly assigns these individuals to urban location i according to the weighted probability $P_i/\|\boldsymbol{p}\|$. With these populations established, wages and entrepreneurial returns are determined for each location.

While I assign agents a variety of qualities for programmatic purposes, they are primarily distinguished from one another by three initial traits. Each agent has a *role* - farmer, worker, or entrepreneur - determined by the initial population N_R, N_U or E from which they are assigned. Each agent possesses an initial knowledge stock – a normally distributed value $K_i \backsim N(\mu_j, \sigma^2)$, where the index j denotes the *role* of agent i, $K \geq \mu$, and $\mu_{Farmer} < \mu_{Worker} < \mu_{Entrepreneur}$. As I will discuss later, this knowledge is a direct input for intermediate good production, so it stands to reason that initial entrepreneurs will typically possess a greater knowledge level than the average worker. Moreover, these values also express the fact that in developing countries like China, education levels are generally higher in urban locations than in poorer rural areas (Knight and Shi, 1996). The third important initial trait is a propensity to learn, $\rho_i \sim N(\mu, \sigma^2)$ for each agent i. As this value is independent of role, it represents an individual's inherent aptitude for creativity and entrepreneurship, which determines their ability to improve their knowledge stock through spillovers. This idea follows from the conclusions of Desrochers and Leppälä (2011) discussed earlier. Though an agent's initial location will determine their wage or return to entrepreneurial knowledge, these three characteristics provide the primary impetus for the behavioral trends I will observe in the results section.

B. Production Framework

The three classes of agents correspond to the three sectors in the economy- farming, manufacturing, and intermediate goods. The following sections outlines the production technologies used in these sectors. I update output, prices, wages and rents each period, but for simplicity, I omit time subscripts from these equations. The single rural location produces farm goods according to the production technology:

(2) $$Y_R = A_R L^{\alpha} N_R^{1-\alpha}$$

where A, L, and N are defined as before and α is the return to land.

Though consumption of farming and manufacturing goods does not occur explicitly in the model, I assume economy-wide consumer preferences determined by the utility function:

(3) $$U_i = F^{\beta} M^{1-\beta}$$

where F is farming goods, M is manufacturing goods, and β is the returns to farming goods. Using this utility function, I derive the price of farming goods P_F as:

(4) $$P_F = \frac{\beta}{1-\beta} \cdot \frac{M}{F}$$

where M and F denote the economy-wide production of manufacturing and farming goods, respectively, and the price of manufacturing goods is normalized as $P_M = 1$. With these pieces established, the rural wage is determined by the return to labor multiplied by the price of farming goods:

(5) $$w_F = (1-\alpha) P_F A_F L^{\alpha} N^{-\alpha}$$

For an agent i with a *role* of farmer, the agent's *income* is equal to w_F.

Moving on to the manufacturing sector, each urban center operates according to the same production technology. However, unlike the single rural location, each urban location produces goods independently from other urban locations such that for location j:

(6) $$Y_M = A_j L^{\alpha} (\sum_{i=1}^{E_j} x_{i,j})^{\gamma} N_j^{1-\alpha-\gamma}$$

where A, L, and N are defined as before, $x_{i,j}$ is the intermediate goods production for entrepreneur i, E_j denotes the number of entrepreneurs in location j, and α and γ are the returns to land and intermediate inputs, respectively. The intermediate goods sector follows a simple production technology in which entrepreneurial knowledge is transformed directly into goods. For a given entrepreneur, her production of intermediate goods is:

(7) $$x_{i,j} = M_{i,j} K_i$$

Where K_i is the knowledge stock of agent i and $M_{i,j}$ is the market share for the given agent at location j. Before any innovations occur in the economy, this share will be equal for all entrepreneurs in the location, such that $M_j = 1/E_j$. However, if an entrepreneur creates an innovation, she attains incumbent status and receives an excess market share given by a factor m of the non-incumbent market share in her location. Unlike Aghion, in which each intermediate sector will only support one incumbent per period, multiple individuals can gain incumbent rent in a time period in the model. This follows from the fact that entrepreneurs engage in R&D individually and thus may arrive at innovations independently. In this case, I adjust the market share appropriately so that the ratio between incumbent and non-incumbent market share remains m.

As before, real wages in location j are determined by the return to labor multiplied by the price of manufacturing goods. Thus:

(8) $$w_j = (1-\alpha-\gamma) P_M A_j L^{\alpha} (\sum_{i=1}^{n_j} x_{i,j})^{\gamma} N^{-\alpha-\gamma}$$

where all variables are defined as before, and P_M is normalized to equal one. An agent in location j with a *role* of worker will have an *income* equal to w_j. Similarly, each entrepreneur's return to her production is determined by a rent schedule given by the return to intermediate goods in her location j:

$$e_i = \gamma A_j L^{\alpha}\left(\sum_{i=1}^{n_j} x_{i,j}\right)^{\gamma-1} N^{1-\alpha-\gamma} \qquad (9)$$

where all variables are defined as before. Thus, an entrepreneur i that produces x_i will have an *income* equal to $e_j x_i$.

C. Program Overview

I now turn to the program itself in detail, including the specific mechanisms for vertical and horizontal innovation. After the initialization described before, I begin the main program loop that repeats for T runs by first cycling through all agents in a random order, and consider the decisions for a fraction of all agents to move locations or change roles. Programmatically, this is necessary as I only update wages and rents after this first decision loop for agents. Thus, with no move costs, considering decisions for all agents at once would lead to all workers moving to the location with the highest wage, only to find their wage greatly diminished after production updates. Moreover, updating production after each agent's decision would create an unrealistic situation of perfect information. Thus, in this model, agents may not always choose the ideal decision in regards to their locations or roles.

For each agent i facing a decision, I first consider the agent's *role*. If the agent is a farmer, she observes the wage rate in each urban location, and compares each value to her current income plus the move cost associated with migrating to this location. She will then pick the highest expected income among these options and either move or remain in the rural location. For all agents, move cost includes a tangible cost of travel based on exogenously determined distances between locations, but as Zhao (1999) notes, rural-urban migration often involves high psychic costs associated with such a drastic change in lifestyle, so farmers will generally face a higher move cost than other agents in the model. I will discuss this issue more in the results section, but for the main program, I keep move costs relatively low for all agents.

If agent i is an urban worker, she will also compare the wage rate in each location to her current income plus the appropriate move cost. In addition, she also considers her knowledge stock K_i and her expected return to engaging in entrepreneurial activity based on the return to intermediate goods e_j and the market share for non-incumbents M_j for her location j. From among these options, she picks the highest expected return and either moves to the appropriate location or becomes an entrepreneur.

If agent i is an entrepreneur, she follows a similar behavioral rule as the other agent classes. However, she also considers her expected return as an entrepreneur in other cities and then makes a decision for her location and role. It should be noted that if agent i is an incumbent, she will compare her current earnings to the expected earnings of being a non-incumbent in other locations. However, she does not consider the fact that she will not maintain these earnings in subsequent periods unless she continues to innovate. Thus, non-incumbent entrepreneurs are more capable of achieving optimal outcomes for migration. I will return to this idea in the overview of the vertical innovation process, but it highlights a key feature of the Schumpeterian approach to growth theory- incumbent entrepreneurs face less pressure to continue innovating, and thus are more susceptible to being usurped by peer entrepreneurs. This concept of "creative destruction" largely drives the competitive process among entrepreneurs.

After agents have made migration and role decisions, I then update the innovative procedures in each urban sector, beginning with the knowledge spillover process. For urban location *j*, each agent *i* with location *j* accumulates knowledge according to the function:

(10) $$K_i' = K_i + \rho_i \sigma \sum_{h=1}^{n_j} Max[K_h - K_i, 0]^{\tau}$$

where K_i denotes the agent's initial knowledge stock, ρ_i denotes the agent's propensity to learn, σ is a fixed parameter that determines the fractional amount of knowledge available to the agent such that $0 < \sigma < 1$, and the index *h* denotes other workers with location *j*. I parameterize each agent's propensity to learn such that it is typically relatively small and almost always less than 1. A propensity greater than 1 is still possible, however, representing an individual whose creative capacities are such that she can obtain knowledge and actually create new knowledge from this increased stock. It is important to note that, as this parameter can be considered an inherent characteristic, it is homogenous across agents and thus not affected by educational attainment.

In words, this function states that an individual can add to her knowledge stock a maximum level of knowledge from other agents in her location, while the actual knowledge that spills over depends on her individual ability to absorb and implement this knowledge. Since knowledge is a homogenous input, I assume that an agent cannot learn from an individual with a knowledge stock lower than their own. Moreover, I also assume that, per Spencer (2012), cognitive distance impacts the effectiveness of spillovers. In terms of the model, this means that while an agent benefits from peer agents with higher knowledge stocks, spillovers become less effective as the distance between the peer's knowledge stock and her own increases. Essentially, this reflects the idea that an individual will be more capable of relating to and learning from an individual if that person's cognitive abilities are similar to her own. From a programmatic perspective, these assumptions are necessary in that they prevent individuals from achieving boundless knowledge. Thus, if a worker has a greater knowledge stock than all other workers in her location, than she will have effectively achieved her maximum knowledge stock until individuals with a higher knowledge stock move to her location. Moreover, it also prevents workers experiencing massive knowledge stock growth due simply to a low initial stock.

I now turn to the Schumpeterian growth process for entrepreneurial innovation. As in the Schumpeterian model of Aghion, producers in the intermediate goods sector commit a portion of their income to R&D in the pursuit of innovations. However, rather than modeling these decisions as the result of an expected value calculation, I opt for a less mechanical process of imitation among peer entrepreneurs. After assigning an initial R&D level to agents, each entrepreneur takes note of the R&D decisions of peer entrepreneur to assess the average R&D expenditure in her location. However, the R&D decisions of incumbents are weighted higher than those of non-incumbents. The entrepreneur then adjusts her R&D to better reflect this observed trend. This process helps imitate the creative destruction of the Schumpeterian model's namesake. While incumbents also assess the R&D levels around them, they do not tend to over evaluate this level unless other incumbents are present in their location. On the other hand, non-incumbents will tend to be more aggressive in their R&D decisions as they attempt to catch up to the innovative activity of the incumbents.

Like Aghion, I model the arrival of innovations as a Poisson process with an arrival rate determined by various factors. For each entrepreneur i, the arrival rate λ is given by:

$$\lambda_i = aR_i + bI_i + cR_iI_i + \xi \tag{11}$$

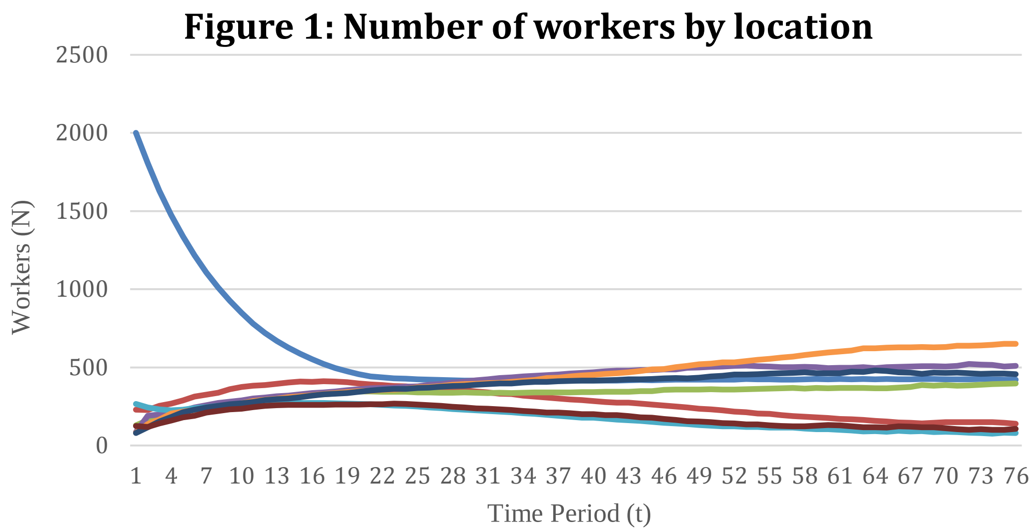
where R_i is the R&D committed by agent i; I_i is a counter for the number of innovations achieved by agent i; ξ is a random variable; and a, b, and c are exogenous parameters such that b, c < 0. This reflects the assumption that for a given entrepreneur, each successive innovation becomes increasingly difficult to attain. Moreover, the interaction term cR_iI_i ensures that the effectiveness of R&D diminishes as an entrepreneur continues to innovate. Again, these assumptions contribute to one of the underlying principles of Schumpeterian growth- namely, that incumbents will find it increasingly difficult to maintain an advantage over peers. While this means that an innovation will not benefit an entrepreneur in the future, as per Aghion, it does benefit the economy as a whole by advancing TFP for the final goods sector. For each location, the arrival of an innovation adds a fixed, incremental factor to that location's TFP parameter. After each entrepreneur's innovative process has been modeled, the program then takes note of the innovators in each location and updates market shares and TFPs appropriately. I then update production, wages, and returns to intermediate goods for each location. This completes the main loop, and the program then repeats this loop for the set number of runs.

IV. RESULTS

Here I present the findings of the simulation program. In the context of the model, I am primarily interested in cross-location measures such as wages, workers, and number of entrepreneurs in each location, as well as growth variables such as TFP and total production. While innovative activity in the model utilizes previous growth literature in the unique context of agent-based modeling, internal migration provides the greatest opportunity to illustrate novel paths for growth. As a standard for the model, I set the number of runs T to 75 for each simulation. In any one simulation, various outcomes can arise. Thus, I run the main program 50 times and average together the various metrics in the model to ensure that results are not simply driven by random outcomes of stochastic variables. Results are presented graphically, where individual data series represent the appropriate outcome for each individual location. Colored lines correspond to the same location across different figures. The blue data series represents the single rural location, while the other lines correspond to the seven urban locations.

A. Main Program

Figure 1 shows number of workers by location for the main program. As outlined in the previous section, these locations only differ by initial population and geographic location as determined by the distance matrix. Population differences, then, account entirely for initial wage differences among locations. Consistent with traditional migration theory, these differences in location wages lead to convergence over time as agents move in order to take advantage of excess wages in other locations. As equation (8) shows, increasing labor supply in a location serves to lower the location's wage rate. Thus, as workers move to take advantage of high wage rates, these rates gradually decrease until wages equalize and there no longer exists an incentive to move. In the initial few runs, the only factors preventing complete convergence are move costs and the imperfect information generated by the staggered production updating in the program. Figure 2 shows the complementary visual of wage convergence.



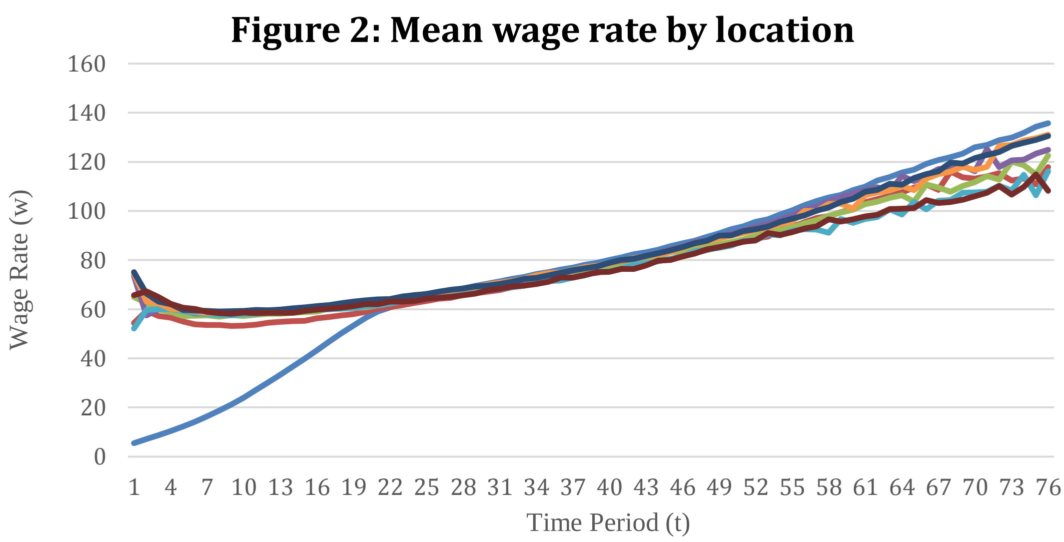
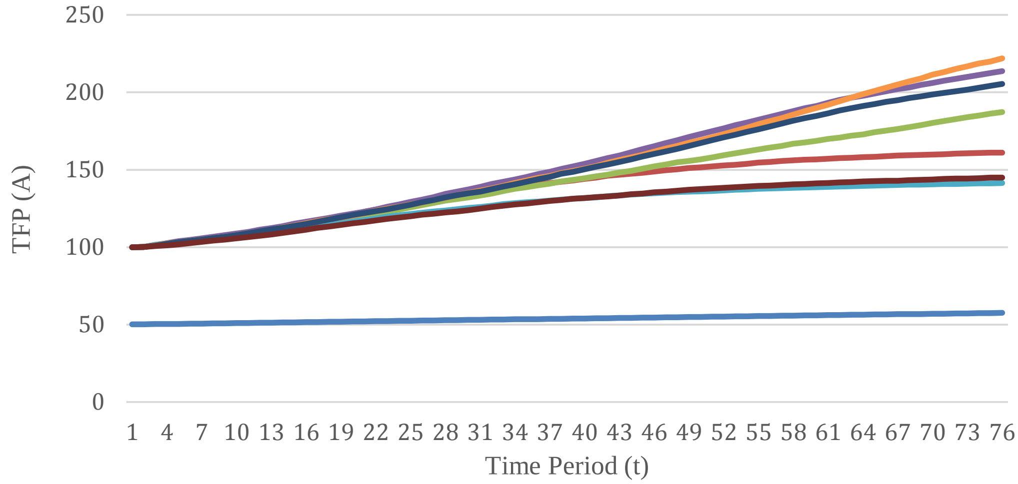


Figure 3: TFP by location



Because of the massive initial wage gap between the rural location and the urban locations, the number of rural workers fall and rural wages subsequently rise as these workers migrate en masse to the high-wage urban centers.

While these graphs generally show the expected picture for migration, they also include evidence that points to the impact of endogenous growth mechanisms. While wage convergence occurs rapidly, Figure 2 shows that for a longer time horizon, wages begin to slowly diverge. Moreover, while the equation above suggests that, *ceteris paribus*, high labor forces lead to lower wages, the high wage locations actually tend to correspond to the urban locations with the highest worker populations. Thus, increases in wages have come about due to changes in other variables in equation (8), particularly in TFP (A_i). Figure 3 shows TFP growth by location, which serves as a direct indicator of innovative activity by location. The three highest urban wages correspond directly to the most innovative city centers. With perfect information and no move costs, these dynamics would not necessarily serve as a barrier to wage convergence, as individuals could simply take advantage of rising wages as growth occurs. However, Figure 2 shows that this is clearly not the case, as wage rates converge before eventually diverging once more. Essentially, the rate of innovation exceeds the rate of migration in the model. Thus, while internal migration initially leads to an equitable distribution of wages across cities, the innovative processes modeled in the program can still give rise to regional inequality as certain cities rapidly innovate while others fail to do so.

On the following page, Figure 4, which displays entrepreneurs by location, shows another key dynamic present in the model. The most innovative locations are actually those with relatively fewer entrepreneurs. This suggests that a productive city center is best served by a few highly innovative firms. Additionally, it could be the case that these locations benefit from having a large, knowledgeable labor force that is capable of diversifying the entrepreneurial sector. On the other hand, locations that maintain large entrepreneurial sectors may tend to stagnate as the same firms struggle to maintain innovations over time. This reflects the model's assumption that individual entrepreneurs experience decreasing returns to R&D expenditures. It should also be noted that internal migration likely contributed to these growth paths. The three most successful locations were actually the three smallest initial population centers. Thus, they attracted a great deal of migration initially as individuals sought high wages in these locations. In the context of the model, it seems that cities that are active in migration processes tend to foster diverse sets of knowledge that lead to favorable growth outcomes. This might also be a product of the move cost functions, which discount psychic costs for those rural workers with a high propensity to learn.

A final point of analysis can be observed in the long run trends for both wage rates and number of entrepreneurs. As shown by Figure 2, wages become highly unstable in later periods. This suggests that worker mobility might be quite fluid. However, Figure 1 shows that these locations have relatively stable labor forces. Thus, wages must be changing due to changes in the entrepreneurial force. This can occur through either migration by entrepreneurs or workers becoming entrepreneurs (or vice versa). This observation again supports the hypothesis that a fluid entrepreneurial base most excels at innovation. Unlike the two locations with the largest entrepreneurial base, which create relatively fewer innovations, the most innovative locations not only tend to be smaller, but also tend to share similar wages, TFP levels, and entrepreneurial base sizes. This "clustering" can be observed in several of the data series, and it suggests that such locations could be engaged in competition over workers or entrepreneurs among one another. When wage rates or predicted entrepreneurial returns are close to one another among locations, small changes will tend to lead to either migration or changing role decisions. While some of these pairings clearly correspond to similar initial populations, the determinant of these clusters could, in the model, be in part due to geographic proximity. As mentioned before, move costs (even the relatively low ones observed in the main program) are computed according to a distance matrix, and in some cases, such as the green and purple locations in Figure 4, clustered locations have lower distances between them. While the emergence of regional economic centers was by no means a modeling goal for this study, this observation demonstrates the manner in which simple assumptions can lead to surprising results in the agent-based framework.

Figure 4: Number of entrepreneurs by location

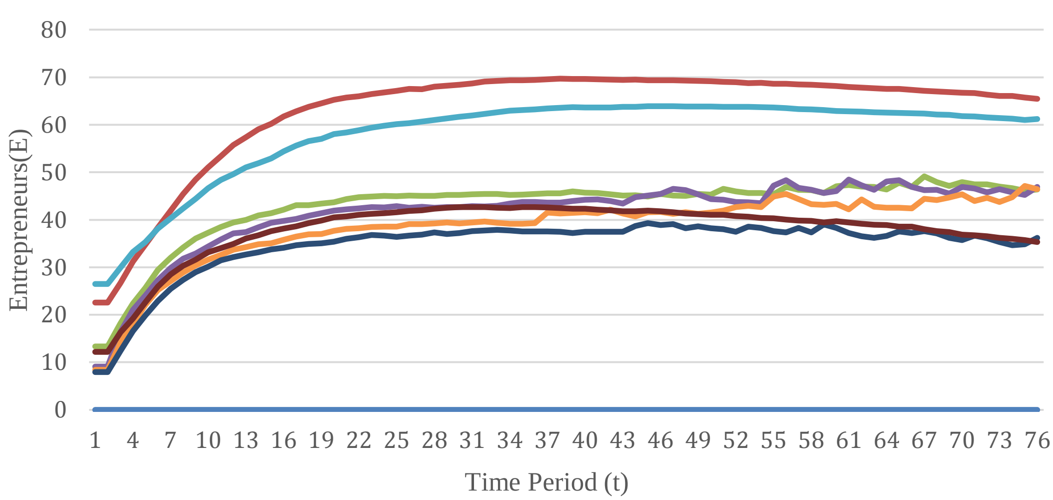


Figure 5: Number of workers by location - Hukou

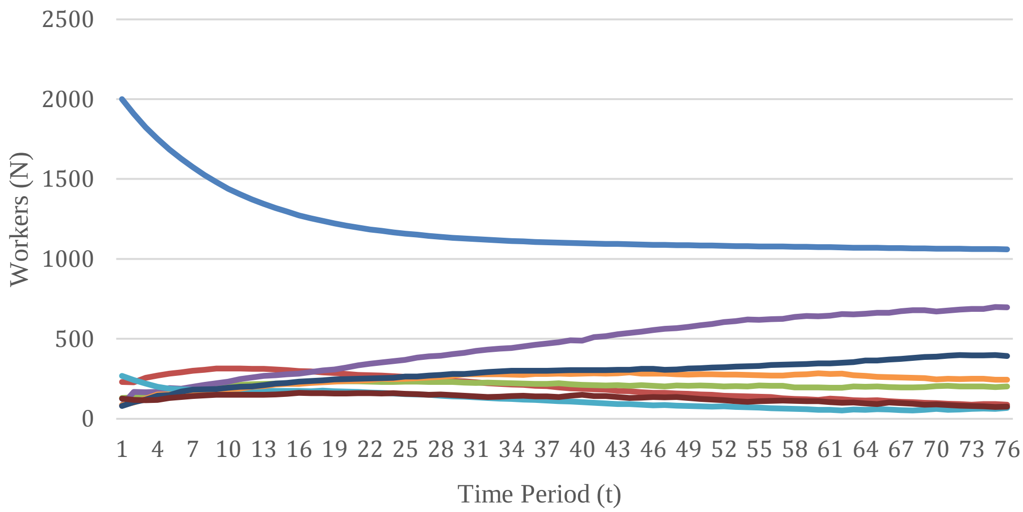


Figure 6: Mean wage rate by location- Hukou

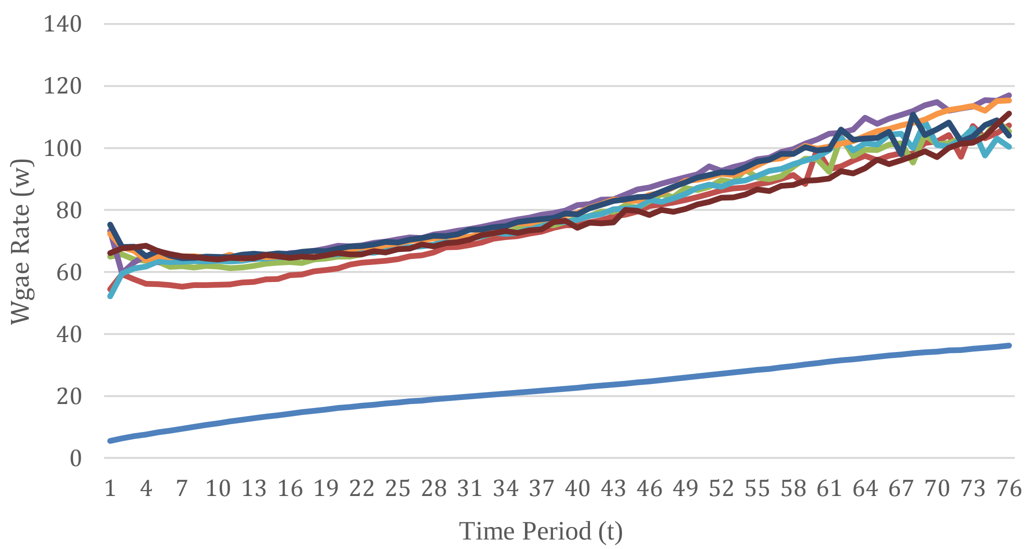


Figure 7: Number of entrepreneurs by location- Hukou

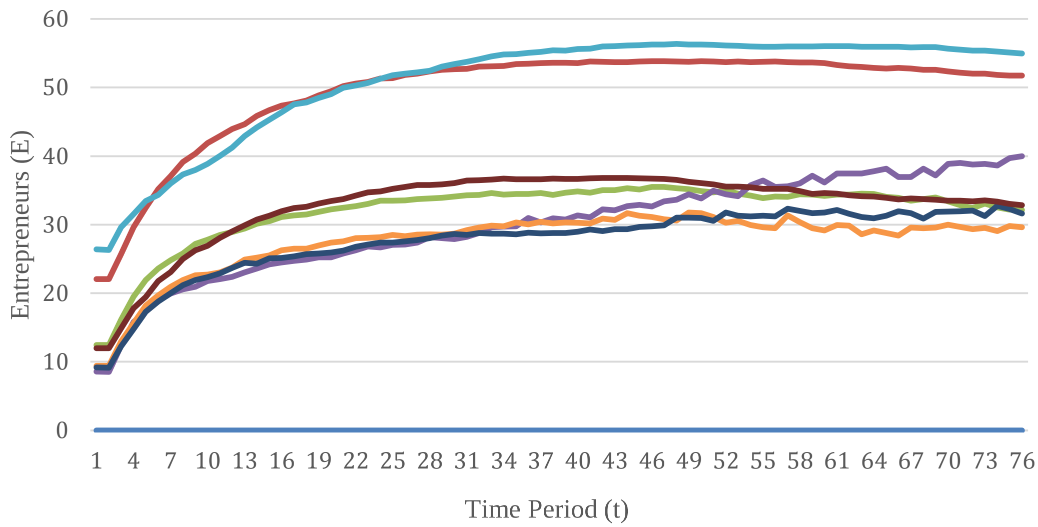


Figure 8: TFP by location - Hukou

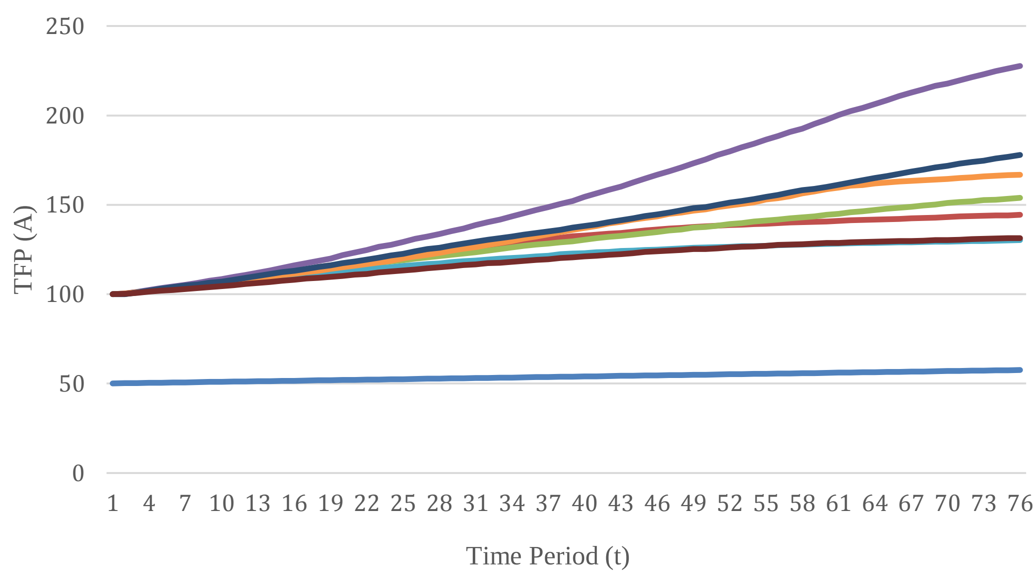
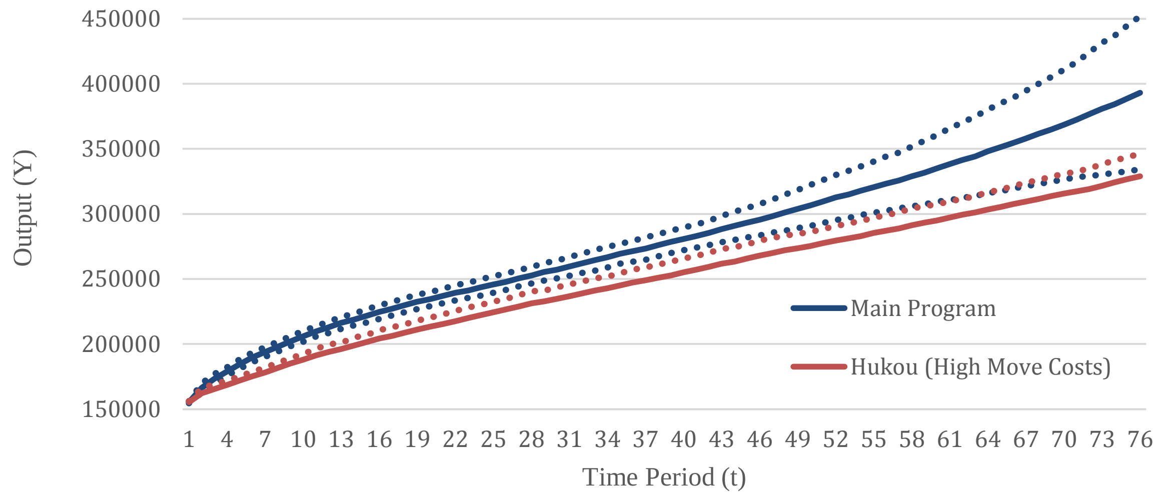


**Figure 9: Total Output over time
Dotted lines denote one standard deviation from mean line**



B. Hukou Experiment

As noted in the introduction, the ability to conduct normative experiments is one of the greatest assets of the agent-based approach. Here, I model a policy that has greatly affected internal migration patterns in China over the past several decades. China has a long history of restricting rural-urban migration, beginning with institutional rule following famines from 1959 to 1961. One such deterrent, the policy of *hukou* (household registration), has persisted into the 21st century. The system bars migration to urban centers by denying this household registration, which prevents migrants from benefiting from public goods and attaining employment legally. For the program, I model this policy in terms of extremely high move costs. One facet of this policy that Zhou (1999) notes is that despite the difficulty for migrants to cities, wage gaps are so significant that rural-urban migration persists. However, the *hukou* system often means that such migrants do not move to urban centers permanently, instead choosing to work temporarily and send home remittances. With this concept in mind, I also prevent rural migrants from becoming entrepreneurs, an implicit possibility in the full model in which low knowledge migrants could accumulate a sizeable knowledge stock.

As figures 5 and 6 show, internal migration greatly decreases with these high move costs. Many of the same observations from the main program, such as clustering and small, innovative entrepreneurial bases, still exist in this experiment. While inter-city migration remains viable for most agents, the growth of entrepreneurs and TFP (Figures 7 and 8) are relatively smaller in the presence of the *hukou* policy. Also, the effect of initial population becomes even more pronounced in this experiment, as each locations becomes virtually locked in to a specific growth path. In the context of the model, this reflects the fact that the *hukou* policy restricts one of the main sources of endogenous growth in the model – internal migration.

Figure 9 compares the total output for the economy in the main program compared to the *hukou* experiment (dotted lines denote one standard deviation). From a theoretical standpoint, the *hukou* system should decrease total output by imposing inefficiencies that prevent an optimal outlay of labor across the economy. This "uptick" in output can be observed in the first several periods. However, there is an added effect of the policy, as output growth clearly increases at a greater rate in the main program. As predicted by the model, this trend suggests that barriers to migration impose restrictions on the rate of innovation via a loss in total urban knowledge stock as well as potential entrepreneurs from rural areas. This hypothesis can be confirmed in the stunted TFP growth in Figure 8 relative to TFP growth in the main program. In the same vein, while growth clearly remains higher for the main program, it also experiences far more variability over time. By "locking in" growth patterns for cities, the *hukou* system tends to remove the possibility for more intricate growth patterns like those observed in the main program, such as broader innovative capabilities. In any event, empirical analysis is required to measure the magnitude of this effect, but the model provides a set of conditions in which it is possible.

V. CONCLUSION

This model presents an attempt to reconcile traditional endogenous growth theory with the microeconomic approach to modeling innovation in regionally bounded settings. Moreover, the use of ACE modeling represents a novel application to growth theory. While only one such experiment is presented in this paper, the model can be utilized to simulate and understand a variety of situations and policies relating to internal migration and innovation. With technological catch-up a primary goal for many developing nations, understanding how a highly stratified population impacts innovated potential could be crucial for properly implementing policy. As Zhou (2011) discusses, in the case of the *hukou* system in China, the barrier that exists between rural and urban regions has indeed lead to greater entrepreneurial activity in rural regions. An extension to the model could explore how this type of localized innovation may contribute to not only greater regional equity but also improved national growth. Theoretically, better technology and higher capital stock would suggest that a worker would better serve the economy in a city, *ceteris paribus*. However, understanding this dynamic more fully could motivate policies designed to promote the optimal balance of innovation throughout locations. In any event, since this model only presents qualitative findings, future applications should implement real-world data to a greater degree to achieve more accurate calibration, as well as stronger empirical support for the model's predictions, such as those detailed in Section IV. Still, this model presents a viable scenario in which regional growth dynamics such as internal migration serve as an important ingredient in existing growth models.

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