An Agent-Based Simulation of Heterogeneous Games and Social Systems in Politics, Fertility and Economic Development

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Abstract. This paper studies both the macro and micro level, as well as the linkage between the two, to answer the question of how economic, political, and demographic factors impact a country's development trajectory. Combining system dynamics, agent-based modeling, and evolutionary games in a complex adaptive system, I formalize a simulation framework of Politics of Fertility and Economic Development (POFED) to understand the relationship between those factors over time. I validate the original system dynamics model with updated data and measure, fuse the endogenous attributes with non-cooperative game theory in an agent-based framework, and simulate the heterogeneous interactions between individuals. This paper demonstrates the linkage between macro environment and micro behavior. Simulations of real world scenarios show network emergence under different environments. The results suggest policy implications for societies at different stages of development.

1 Introduction

Rooted in international political economy, POFED is a quantitative, trans-disciplinary approach to understanding growth and development through the lens of interdependent economic, demographic, social and political forces at multiple scales, from individuals to institutions and society as a whole. In each country's development path, macro structure provides political, social and economic environment that constrains or incentivizes micro level human behavior, while micro level human agency can act, react and interact, thus shapes macro environment.

Previous literature in this field mostly focuses at macro level. Countries are used as unit of analysis or specific cases. Empirical research uses macro structural, society level variables, like GDP, fertility rate, and literacy rate among others to test different theories. Each one of these indicators is the sum of millions of human choices, sampled at arbitrary annual frequencies from an imperfect data and population distribution. However, the micro level is very poorly studied, and the linkage between macro constraints and micro level choices remains undiscovered.

Therefore, this paper studies income level, fertility decision, and education at micro level of human agency, to better understand how individuals behave under different environments. Additionally, I investigate individual choice feedback mechanism on

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macro societal trends and conditions. The results confirm POFED theory, demonstrate individual strategy choice matters significantly to development, and offer policy implications for different societies.

2 POFED in Complex Adaptive Systems

Scholars in international political economy have done considerable research on development, focusing on the interrelationship between income, fertility, human capital, and political development, measured as political stability and political capacity [4, 8, 9, 12, 13]. Feng et al. [13] presents a formal model that characterizes the two trajectories of development – a poverty trap with persistent economic stagnation, and industrialization and rising incomes, and establishes that the interaction between politics and economics determines which path a nation travels. In more recent POFED literature, Feng et al. [12] presents a dynamic general equilibrium model that formalizes the political mechanisms that prompt demographic change and augment economic development. Abdollahian et al. [1] emphasizes the dynamic interrelationships between income, fertility, human capital, political effectiveness, and social stability. They show that fertility rates b depend on income level y; and that income depends on past income and political conditions. There is generational feedback on the creation of human capital h, as increased education would increase political capacity x and income, thus reduces political instability s. Instability also has a temporal feedback and impacts fertility decision. Their system of equations describes how the five main components work at society level, but is not empirically tested.

However, one major flaw associated with dynamic general equilibrium models is the assumption of a perfect world, which does not hold in reality [11]. Another general critique of formal or empirical macro level, structural analysis across most of social science is that aggregate structures often help explain or predict necessary, but not sufficient conditions of political, economic and social phenomena, as the emergent behavior is not captured [7, 11]. Policy makers often face information about complex systems different from what is assumed by traditional analysis [17]. Many individual level explanations, spanning positive political theory, microeconomics and game theoretic behavior might provide insights into human agency and thus offer the promise of theory sufficiency.

As macroscopic structures emerge from microscopic events lead to entrainment and modification of both, co-evolutionary processes are created over time. I posit a new approach where agency matters: individual game interactions, strategy decisions and outcome histories determine an individual's experience. These decisions are constrained or incentivized by the changing macroeconomic, demographic pattern, social and political environment via POFED theory, conditioned on individual attributes at any particular time. Emergent behavior results from individuals' current feasible choice set, conditioned upon macro environment. Conversely, progress on economic development, the level of internal instability, and population structure emerge from individuals' behavior interactions.

In order to create a simulation to capture the complexity of development, I extend Abdollahian et al.'s system dynamic representation of POFED theory towards integrated macro-micro scales in an agent-based framework. I first instantiate two systems of difference equations that are empirically validated using updated data from World Bank [26] and new measure from Fisunoglu [14] and Kugler and Tammen [16] using Three Stage Least Square estimation. This technique permits correlations of the unobserved disturbances across several equations, as well as restrictions among coefficients of different equations, and improves upon the efficiency of equation-by-equation estimation by taking into account such correlations across equations. Since understanding the interactive effects of macro-socio dynamics and individual agency in intra-societal transactions are key elements of a complex adaptive systems approach, I then fuse the system dynamic component to agent attribute changes with a non-cooperative Prisoner's Dilemma game following Axelrod [5, 6] and Nowak and Sigmund [20, 21]. This design allows the simulation of intro-societal economic transactions, which, in return, shapes the macro system where interactions take place. I finally explore the parameter space, conduct sensitivity test and simulate societies at different stages of development.

3 An Agent-Based Model

I propose an agent-based model in a complex adaptive system framework that captures both macro level changes and micro level behavior by incorporating system dynamics component and game theory component. Following the work by Abdollahian et al. [2, 3], my agent-based model has both the interactive effects and feedbacks between individual human agency as well as the macro constraints and opportunities that change over time for any given society. Individual decisions are affected by other individuals, social context, and system states. These elements have first and second order effects, given any particular system state or individual attributes. Such an approach attempts to increase both theoretical and empirical verisimilitude for some key elements of complexity processes, emergence, connectivity, interdependence and feedback found throughout several disciplines across all scales of modernization and human development. Figure 1 depicts the high level process and multi-module architecture. There are three modules in the agent-based model: micro agent process, macro society process, and heterogeneous evolutionary game process.

In micro agent process, individual agents behave as a system in terms of updating income, fertility and education decisions. Each individual agent carries all three variables that are randomized from the society's distribution. I maintain individual agent variable relationships and changes following the latest POFED literature [1]. Here I use empirically validated parameter values from Three Stage Least Square estimation as a good first approximation. This method has been widely used by many scholars [2, 3] to simulate the dynamic process at individual level. These endogenously derived individual agent variables impact how economic transaction games occur, based on society variables either increasing or decreasing individual wealth and ultimately societal productivity [6].

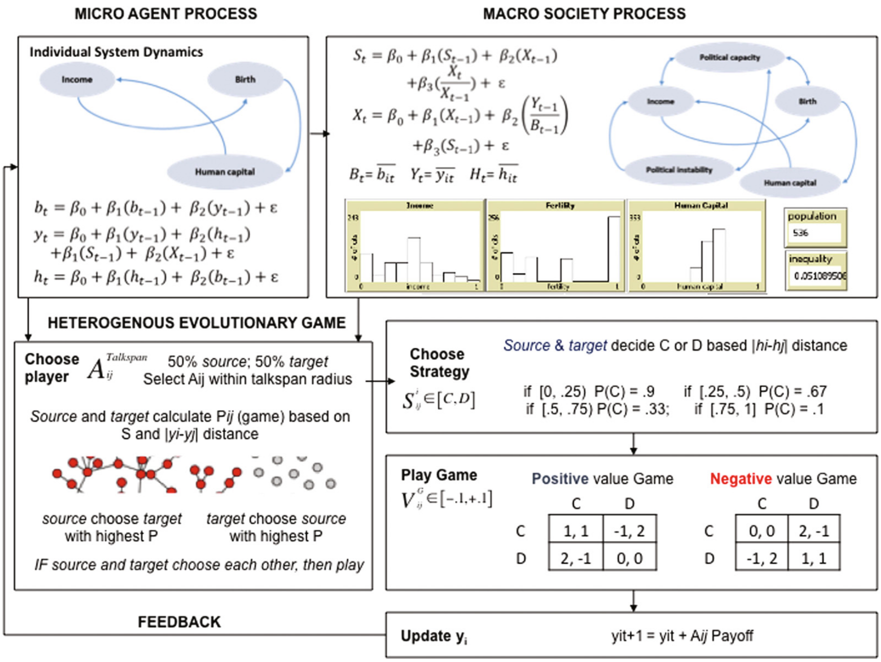

Fig. 1. Three-module agent-based model architecture.

In macro society process, instead of taking each individual agent as a system, this module takes the entire society as the system, with political instability, political capacity, economic condition, human capital, and fertility rate as main attributes. This module is critical as it connects micro individual level and macro society level. Society economic condition is aggregated from individual wealth by taking the mean. Human capital is aggregated from individual level of education, and fertility rate is also aggregated from individual level in the same way. The feedback loop is completed in the way that initial individual variables are randomized from the society distribution, get updated in micro agent process and evolutionary game process, then get aggregated at society level and interact with other society variables, while society variables also impact the evolutionary game process. I also use empirically validated parameter values from Three Stage Least Square estimation in this module. The updated instability is brought into the evolutionary game process to affect the probability that agents interact with each other. This feedback loop allows the study on how individual behavior changes macro environment, and how environment in turn impacts individual behavior.

In heterogeneous evolutionary game process, I choose to focus on non-cooperative game in the macro political stability environment. Prisoner Dilemma game is chosen because it allows agents to choice between maximizing individual benefit and mutual benefit. Evolutionary game theory provides insights into understanding individual, repeated societal transactions in heterogeneous populations (Sigmund, 1993). Social co-evolutionary systems allow each individual to either influence or be influenced by all other individuals as well as macro society [24, 27], perhaps eventually becoming coupled and quasi-path interdependent. To model communications and technology diffusion for frequency and social tie formation [18], I have agent i evaluate the likelihood of conducting a simple socio-economic transaction with agent j based on similarity of income level $|y_i - y_j|$, stability of the environment, and physical distance, which reflects level of technology the society obtains. Each agent will choose the one with the highest likelihood to conduct the socio-economic transaction game, and the interaction will take place only when both agents choose each other. This approach reflects recent work on the importance of both dynamic strategies and updating rules based on agent attributes affecting co-evolution [2, 3, 15, 19].

Once agents decide to play, they choose strategies based on $|h_i - h_j|$, since messages close to a receiver's position has little effect, while those far from a receiver's position are likely to be rejected [22]. Small difference of human capital leads to high probability of cooperation, while large difference results in high probability of defective strategy. Following Abdollahian et al. [2, 3], I specifically model socio-economic transaction games as producing either positive or negative values as I want to capture behavioral outcomes from games with both upside gains or downside losses. Subsequently, A^{ij} games' V^{ij} outcomes condition agent y^i_{t-1} values, modeling realized costs or benefits from any particular interaction. The relative payoff for each agent is calculated based on simple PD, non-cooperative game theory [10, 20, 21, 23] where T > R>P > S. The updated $y^i_{t-1} = y^i_t + A^{ij}$ game payoff for each agent then gets added to the individual's variables for the next iteration. I then repeat individual endogenous processing, aggregated up to society as a whole and repeat the game processes for $t + n$ iterations, where n is the last iterate. In this module, Ai strategies are adaptive, which affect A^{ij} pairs locally within an approximate radius as first order effects. Other agents, within the society but outside the reaching radius, are impacted through cascading higher orders.

4 Results

I implement the agent-based model in NetLogo [25]. The baseline initial population is 500 to represent a sample of any given population. The state variables for this model are fertility decision, education, and income. Global variables are level of instability and relative political capacity, which are setup at society level. Since society variables do not change on a daily basis, I approximate one time step as one month given data calibration for a simulated time span. This design allows me to study the dynamics of the key variables with reasonable frequency, and the 20-year period is also proper for a cycle in the study of political economy. In order to make generalizable model inferences, I conducted a quasi-global sensitivity with parameter for fertility, income, human capital, political capacity, political instability, and technology at low, medium, and high levels, resulting in over 17,000 runs across 240 time steps.

I compare the pooled OLS results from baseline model that only includes macro level variables and models that include both macro and micro level variables. With aggregated income as dependent variable, macro level variables only explain 20 % of the variance. With the number of micro level interactions added, the new model adds explanatory power by 2.6 %. The dramatic increase in model fit comes from individual choice. When using number of cooperation as the additional independent variable, adjusted R^2 more than doubles to 54.3 %; while counting both cooperative strategies and defective strategies gives the best model fit of 55.3 %. The sensitivity test also confirms the original POFED theory that negative value of instability significantly speeds the pace of economic development, while technology has a positive impact, as increasing individual agents' ability to reach other like-minded agents spurs cooperation. More importantly, the results demonstrate that micro level behavior helps explain macro level dynamics. While individuals communicate and make deals with each other, more products and services become available while the cost of which goes down. Benefits are derived from specialization of products and services, which outweighs the economic and social costs by achieving higher efficiency. Cooperation pays higher dividends, while defective strategies reduce social wealth. In other words, this model captures the micro level behavior that can better explain macro level phenomena.

After confirming that agent-based model more effectively captures the relationship between economic, political and demographic factors than traditional econometric models, I conduct simulation for a few societies to understand the growth path under different levels of development. In this process, I adjust parameters for population density, technology level, political capacity and instability, as well as the distribution on income, fertility, and education for the population. Cases presented below include China 1960–1980, Japan 1970–1990, and Afghanistan 1980–2000.

To explore more details of individual agents interaction, I also show below the network in the society at the beginning (tick 1, top left), one third of the time span simulated (tick 80, top right), two thirds of the simulated period (tick 160, bottom left), and final stage (tick 240, bottom right) on the right part of Fig. 2. Size of the agents indicates their wealth level, and color shows education level, with high in blue and low in red. The high population density is well presented in the graph, even from tick 1. However, at the beginning of the simulation, there are not many interactions among agents, because the level of instability is relatively high so individuals do not have the incentive to conduct socio economic transaction games, so only a few links show up. As time goes, the network density increases. Although individuals cannot reach others who are physically far away from them, high population density ensures the quantity of interactions. As instability weakens and individuals' income gap decreases, there are more and more people involved in the socio economic transaction games, as can be seen in the bottom two graphs. The size of individual agents also slightly increase in general, as a result of increased wealth due to cooperative strategies. This perfectly reflects the reality that Chinese people start to switch focus from political conflict to economic development during the period from 1960 to 1980, especially after the country opened up in 1978. Individual emergent behavior at micro level feeds back to the macro level, impacting the society's growth path.

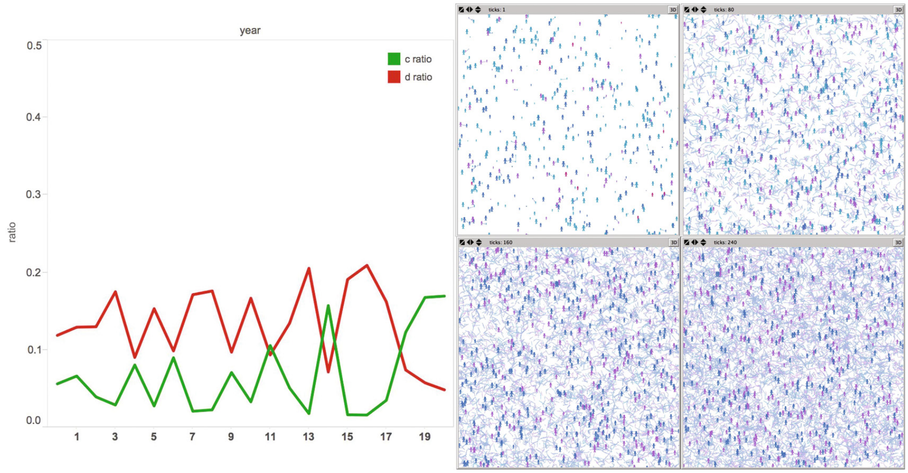

Fig. 2. Cooperation vs. defection and network formation in China's growth path.

After looking at the details of the slowly growing society, the next case I want to focus is a well-developed society, Japan, from 1970 to 1990. There is income convergence, accompanied with human capital dynamics. Due to the development of higher education and increased enrollment of women, the level of human capital increases, though at minimal level as it almost already reached the "celling" of this indicator. With more female receiving higher education and participating in workforce, people tend to marry at an older age, thus time left for giving birth to children shrinks. The slow but steady economic development also increases the opportunity cost of raising children, further reducing fertility rate across the entire period. Government capacity was relatively stable, due to the stable development of other factors. There was only a small increase, due to more control over physical resources. Then I also explore the micro level agent interactions shown in Fig. 3. The left side shows two interesting patterns that are very different from what can be seen in the previous case. Firstly, the percentage of agents interacting with each other is large. Due to high level of technology development, individuals are able to reach out to others who are far from them with telephone, cellphone, Internet and so on. The incentive of playing transaction game with each other is also high because of high level of social stability. It is consistent with the literature [13] that stable environment provides people with more incentive to invest, thus increases the potential of economic development. Across the entire simulated timespan, there are more than half of the agents interacting with each other and playing the transaction game and among them, more than half choose cooperative strategies, as the second important pattern. The proportion of individual agents playing cooperation is relatively stable over time, fluctuating between 30 % and 40 %. However the proportion of individual agents choosing to defect keeps declining over time, from 30 % to less than 5 %. The reduction of defective strategy matches with the aggregated income growth dynamics in Japan. This match also confirms the theory that more cooperative strategy and less defection leads to economic development and this is again revealed in the simulation.

From the right side of Fig. 3, one can see the population density is not as high as China's, however the networks are still dense. Starting from the very beginning, there are more interactions among agents in this society than the previous mainly because individuals are able to reach further due to advanced technology and social stability. As time goes, the density of network increases, though still not as much as China's. It is not only because the population density here is lower, but also because it is actually more difficult for individuals to match with each other once the feasible set strategy and less defective strategy accompanied with, slightly higher individual's level of education as compared to tick 1, which helps enhance the economy of the society. This pattern also coincides with real world Japan from 1970 to 1990. Although just one particular simulation, what is critical is that co-evolutionary behavior results in path dependence of economic and education change as well as being a key determinant for development outcomes. Moreover, changes towards cooperation leads to increasing wealth over time (Fig. 4).

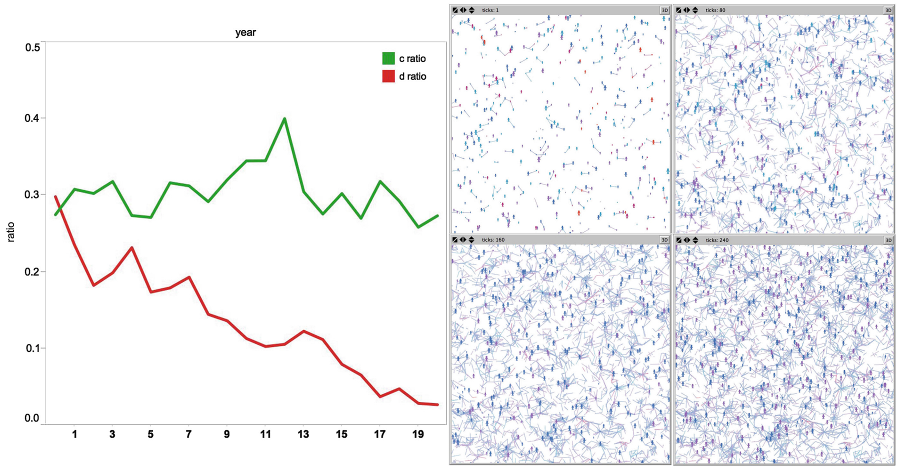

Fig. 3. Cooperation vs. defection and network formation in Japan's growth path.

Finally I run the model to simulate an underdeveloped society, Afghanistan, from 1980 to 2000. High level of political instability greatly hinders economic development, and keeps fertility rate at a very high level. Individuals choose to have more children because the cost of raising children is relatively low and the chances the children survive are also low. With a large number of young people but very little resources in the society, the level of human capital is very limited. Although increasing at a steady

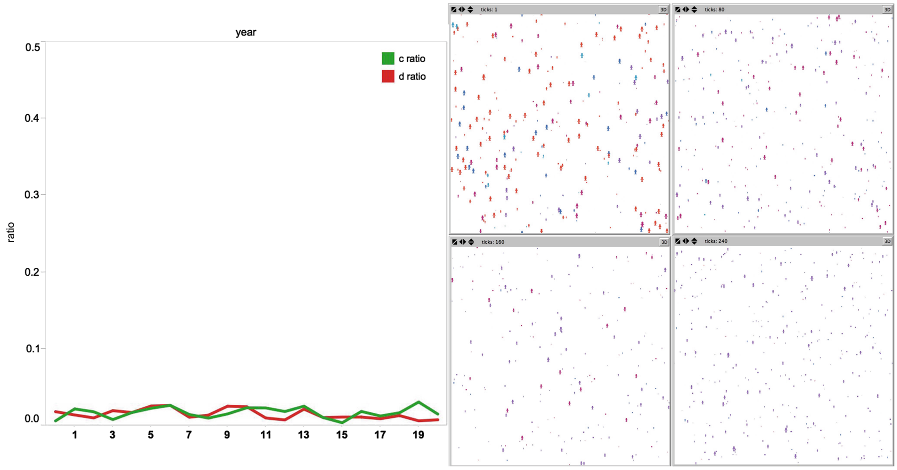

Fig. 4. Cooperation vs. defection and network formation in Afghanistan's growth path.

rate, it takes time for the society to accumulate a certain level of human capital that can enhance economic growth. Low level of economic development and human capital also constraints political capacity. The government can only extract very limited tax resources and human resources, which in turn limits its ability to facilitate education or economic growth. Turning to micro level, one can see both the red line and the green line stay at the bottom of the graph, indicating at each iteration, there are only very few individuals who are involved in the socio-economic transaction game. The main reasons are, firstly, high political instability limits individual's incentive to interact with each other; and secondly, low level of technology constraints individual's ability to reach each other. The majority of people in that society can only use telephone or mail to contact each other, which allows much less communications and transactions than what Internet and cellphone can facilitate. The other interesting pattern is the levels of cooperation and defection are very similar over time. The relatively high level of defection is also another reason why economy does not grow. This defective pattern coincides with the trend of economic stagnation and low level of political capacity that we see in the previous panel of graphs.

I also look at the network dynamics of Afghanistan between 1980 and 2000. Initially, I see low developed society with high income inequality and polarization on the education continuum. Compared to the society of China and Japan, Afghanistan a much higher proportion of undereducated population. There are almost no interactions between individuals because of three reasons: first, the society is highly instable, which reduces people's incentive to conduct socio-economic transaction games. Second, the level of technology in that society is so low that individuals have very limited capacity to reach others; so give that relatively low population density, very few interactions can be expected. Finally, there is high income inequality among individual agents, and people at different social status do not interact as often as people with smaller income difference. Therefore, with almost no interaction and no value created, agents quickly decrease in individual wealth as the instability level remains high and people undereducated. The society goes through a growth trajectory of poverty trap through tick 80, tick 160, until tick 240. At the end of the simulation, one can easily see individual wealth drops dramatically compared to the beginning of the simulation, though the level of education slightly increases.

5 Conclusion

Combining system dynamics, agent-based modeling and evolutionary game theory in a complex adaptive system, I formalize a simulation framework of the Politics of Fertility and Economic Development (POFED) to understand the relationship between politics, economic and demographic change at both macro and micro levels. The results first confirm the micro level behavior significantly impacts macro level development trajectory. The more people interact with each other, the more value can be potentially created. Besides, what matters most is individual agent's strategic choice when they play socio-economics transaction games. Cooperation pays higher social dividends on average. Individual's mutual cooperative behavior creates trust among each other, which enhances both political stability and economic growth. On the other hand, defection reduces social wealth, in addition to its negative impact to the instability in the society, which comes from second order effect. There is also feedback from macro level variables to individual agents, who update their attributes and change the pace and tempo of socio-economic transactions, which reinforce macro level development. In other words, this approach that combines both levels captures the micro level behavior that can better explain macro level phenomena.

This simulation model creates a baseline for current policy efforts, showing when poverty or growth is likely to occur. Policy implications can be inferred from three simulation cases. For developing societies like China, besides stabilizing the macro environment with increasing technology, it is essential to maintain high level of interactions among individuals, while promoting cooperative strategy and eliminating defective strategy to create more value. For well-developed societies like Japan, with stable environment and high level of technology, it is critical to maintain low level of defective strategy, while increasing the number of interactions that use cooperative strategy. For underdeveloped societies like Afghanistan, with high level of instability and low level of human capital, the effective policy of getting out of poverty trap is to increase the number of interactions among individuals while ensuring cooperative strategy and eliminating defective strategy.

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