An Agent-Based Dynamic Model of Politics, Fertility and Economic Development

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ABSTRACT

In the political economy of development, government policy choices at a single point in time can dramatically affect a country's development path by impacting fertility, economic and political decisions across generations. Combining system dynamics and agent-based modeling approaches in a complex adaptive system, a simulation framework of the Politics of Fertility and Economic Development (POFED) is formalized to understand the relationship between politics, economic, and demography change at both macro and micro levels. First, a new political capacity measurement is used; and the system dynamics model is validated with the latest data. Second, the endogenous attributes are fused with non-cooperative game theory in an agent-based framework to simulate the interactive political economic dynamics of individual intra-societal transactions. Finally, macro and micro levels are connected with policy levers of political capacity and political instability by merging system dynamics and agent-based components. This paper also explores the agent-based model's behavioral dynamics via simulation methods to identify paths towards economic development and political stability. This model demonstrates micro level human agency can act, react and interact, thus driving macro level dynamics, while macro structures provide political, social and economic environments that constrain or incentivize micro level human behavior.

Keywords: Complex Adaptive Systems, Agent-Based Model, System Dynamics, Game Theory and Development.

1. INTRODUCTION

This paper investigates countries' growth paths under different economic, political, social, and demographic conditions. Growth and development has been an important issue in the field of political economy. Among existing studies, two faces of development attract considerable attention: one is a poverty trap with persistent economic stagnation; the other is industrialization and rising incomes. It is argued that political development, measured as political stability and political capacity, is sometimes identified as a cause of economic growth and fertility decision, but sometimes as a consequence of it [8][13]. On the other hand, economic development is sometimes modeled to have an impact on human capital and political development, but sometimes as a result of fertility decision and political institution [8][12][13].

The rich 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, GDP growth, 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 for POFED. Therefore, it makes sense to investigate income level, fertility decision, and education at micro level of human agency, to better understand how individuals make critical decisions and how they behave. In addition, it will also be critical to understand how macro environment impacts individual decision, and the feedback of individual behavior that subsequently shapes and shifts macro societal trends and conditions.

2. POFED BACKGROUND

For many decades, there have been contradictory findings in studies of the political economy of growth, exploring the factors that lead to either steady growth or a poverty trap, including political factors, demographic factors, social and economic factors. Scholars argue demographic change has significant impact on economic growth, with fertility rate and human capital as the two most important attributes [12][13]. Besides demographic patterns, political factors are also playing a critical role in a country's growth path. For example, Feng et al. [11] argues political freedom is capable of producing sustainable long-run economic growth once an identified threshold is exceeded. Even a one-time change in the political environment affects economic factors over many generations, and the political condition can be captured via a few critical variables like political stability and political capacity [12][13].

Feng et al [13] presents a formal model that characterizes the two faces of development—persistent poverty, and industrialization and rising incomes, and establishes that the interaction between politics and economics determines which path a nation travels. In one of the latest POFED literature, Abdollahian et al. [1] emphasizes the dynamic interrelationships between income, fertility, political effectiveness, and social stability. For example, fertility change is impacted by income; while income depends on past income and political conditions. There is generational feedback on the creation of human capital, while political instability has a temporal feedback and depends on political capacity. Similarly, political capacity is a function of per capita income, fertility, and instability. Their work describes how the five main components work at society level, which can be empirically tested via two systems of equations, one at aggregated individual level focusing on human capital, fertility, and income, and the other at society level focusing on instability and political capacity.

3. COMPLEX ADAPTIVE SYSTEMS

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.

This paper extends previous work by Abdollahian et al.'s [1] system dynamics representation of POFED at the societal level towards integrated macro–micro scales in an agent-based framework. As macroscopic structures emerging from microscopic events lead to entrainment and modification of both, co-evolutionary processes are created over time. Quek et al. [22] also design an interactive macro–micro agent-based framework, which they call a spatial Evolutionary Multi-Agent Social Network (EMAS), on the dynamics of civil violence. A new approach is proposed 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 robust techno-social simulation [26] platform, first a system of coupled nonlinear difference equations that capture the core logic of POFED macro-social theory is instantiated. Following Abdollahian et al [2-4] approach, the following equations are empirically validated using updated real data: fertility, income, and human capital from World Bank [28], instability and political capacity from Kugler and Tammen [17].

$$b_t = \lambda_1 \bullet y_t^{\alpha 1} \quad (1)$$

$$y_{t+1} = \lambda_2 \bullet y_t^{\alpha 2} \bullet h_t^{\beta 2} \bullet s_t^{\gamma 2} \bullet x_t^{\delta 2} \quad (2)$$

$$s_{t+1} = \lambda_3 \bullet s_{t-1}^{\alpha 3} \bullet x_t^{\beta 3} \bullet \left(\frac{x_t}{x_{t-1}}\right)^{\gamma 3} \quad (3)$$

$$h_{t+1} = \lambda_4 \bullet b_t^{\alpha 4} \bullet h_t^{\beta 3} \quad (4)$$

$$x_t = \lambda_5 \bullet \left(\frac{y_t}{b_t}\right)^{\alpha 5} \bullet s_t^{\beta 5} \quad (5)$$

where b indicates fertility, y indicates income, s indicates instability, h indicates human capital, and x indicates political capacity.

Then the POFED endogenous system of agent attribute changes is fused with a generalizable, non-cooperative Prisoner's Dilemma game following Axelrod [5-7], Nowak and Sigmund [20][21] to simulate intra-societal spatial economic transactions. Understanding the interactive political effects of macro-socio dynamics and individual agency in intra-societal transactions are key elements of a complex adaptive systems approach. Finally, the model's behavioral dynamics is explored via simulation methods to identify paths and pitfalls towards economic, social, demographic and political development as well as societal cooperation across different stages of development. Strong interactions with interdependent strategies and local social co-evolution [16] help determine global-macro development outcomes in a particular society.

4. POFED IN AN AGENT-BASED FRAMEWORK

An agent-based model is proposed 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 [2-4], this 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 key elements of complexity processes, emergence, connectivity, interdependence and feedback found throughout several disciplines across all scales of 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 heterogenous evolutionary game process.

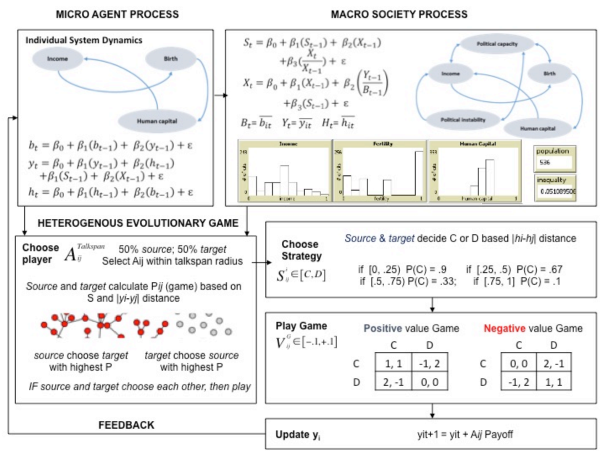

Fig. 1. POFED Agent-Based Model Architecture

The design of the micro agent process module incorporates system dynamics, which allows each individual agent to behave as a system. Traditional approaches in political science are static thus cannot capture the dynamic feedback loops that reflect real-worlds complexity, assuming time plays no role. System dynamics models can be used when behavior of the system changes over time and is statistically significant. This module maintains individual agent variable relationships and changes following the latest POFED literature [1]. 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 [7]. Agents are created by adjusting the mean and standard deviation of fertility, income, and human capital at the society level. Each individual agent carries all three variables that are randomized from the society's distribution. At the beginning of this process, agents are allowed to give birth to new agents based on their fertility attribute. Empirically validated parameter values from Three Stage Least Square estimation are used as a good first approximation. This method has been widely used by many scholars in recent work [2-4] to simulate the dynamic process at individual level. In this module, feedback is used to model individual and social phenomena. The value of system dynamic component is tied to the extent that constructs and parameters represent actual observed project states. This component helps facilitate human understanding and communication, and is more accurate to model time-based relationships between factors and simulate a system continuously over time.

Similar to micro agent process, system dynamics technique is also used 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 and fertility rate are also calibrated 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 impact the evolutionary game process. Empirically validated parameter values from Three Stage Least Square estimation are also used in this process. The updated instability attribute is brought into the evolutionary game process to affect the probability that agents interact with each other. This feedback loop is extremely helpful when studying how individual behavior changes macro environment, and how environment in turn impacts individual behavior.

Evolutionary game theory provides insights into understanding individual, repeated societal transactions in heterogeneous populations [14][24]. Social co-evolutionary systems allow each individual to either influence or be influenced by all other individuals as well as macro society [24][29][25], perhaps eventually becoming coupled and quasi-path interdependent. This work does not have well mixed populations, but explicit spatial contact networks given population density, technology diffusion and agent attributes. It can be explicitly recognized that the differential impact of heterogeneous, spatial structures matters. This captures various individual preferences and their socioeconomic attributes.

Prisoner's Dilemma is conducted in the evolutionary game process. Variable talkspan is used to control spatial proximity interactions, ranging from 1 to 20, defining the grid size radius for the local neighborhood. At talkspan of 1, agents only interact and calculate probability of playing the transaction game with direct neighbors, while at 20, agents can potentially interact up to 1200 neighbors. To model communications and technology diffusion for frequency and social tie formation [18], this module has agent i evaluate the likelihood of conducting a socio-economic transaction with agent j based on similarity of income level, stability of the environment, and physical distance. This approach reflects recent work on the importance of both dynamic strategies and updating rules based on agent attributes affecting co-evolution [16][19][3][4].

At every time step, 50% of the agents are chosen to be sources that can choose a target partner; and the remainder agents to be chosen based on symmetric preference rankings but asymmetric proximity distributions. Social Judgment Theory [9][15] describes how the positions of two agents can be conceived along a Downsian ideological continuum [11] and distance between these positions affects the likelihood of one accepting the other's position. Source agents evaluate the average y between themselves and all target agents within a given neighborhood radius. Smaller income difference increases the probability that A^{ij} will enter into a socio economic transaction and play a non-cooperative game. This is the first probability that will impact the choice of target.

The second probability that goes into the calculation come from society attribute, instability, measured as the proportion of a country's physical capital destroyed in antigovernment violence [8]. As discussed in literature [12][13][1], political instability impacts individual decision and capital accumulation. In an unstable environment, people have less incentive to conduct economic activities, so the probability of playing a socio-economic transaction game is low in such condition. When political instability is low, people are more likely to interact with each other so the probability is high. The multiplication of the two probabilities determines the probability that the source agent plays the transaction game with the target agent. After each source agent calculates its probability of playing a game with all possible target agents, it chooses the target with the highest probability to be its partner. The target agents also conduct the same process symmetrically for the success pairing.

Once two agents are paired, they choose strategies based on $|h_i-h_j|$. Siero and Doosje [23] among others show that messages close to a receiver's position has little effect, while those far from a receiver's position is likely to be rejected. So when the difference of human capital is small, there is a high probability of playing cooperate while long distance results in high probability to defect. The relative payoff for each agent is calculated based on simple non-cooperative game theory [24][20][10] where T>R>P>S, with T= 2, R=1, P = 0 and S= -1. When both agents cooperate, they both gain TT; when one plays cooperate but the other plays defect, the cooperating one loses while the defecting one gains ST; when both play defect they don't gain anything from the transaction PP.

Non-cooperative A^{ij} game is set up, whose outcomes impact agent y^i values for the next iteration. A random value between [-0.1, 0.1] is used to model different potential deal sizes, costs, benefits, or synergies of any social interactions, following Abdollahian et al. [2-4]. Socio-economic transaction games can produce either positive or negative values, which allows the model to capture behavioral outcomes from games with both upside gains or downside losses. Subsequently, A^{ij} games' V^{ij} outcomes condition agent y_{t+1}^{i} values, modeling realized costs or benefits from any particular interaction. The updated y_{t+1}^{i} = y_{t}^{i}+ A^{ij} game payoff for each agent then goes into the next iteration, in which individual endogenous process is repeated, aggregated up to society as a whole with game processes for $t+n$ iterations, where n is the last iterate. A^i 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 talkspan radius, are impacted through cascading higher orders. Agent interaction therefore captures co-evolutionary behavior in a simple yet elegant manner. Although easily done, this work specifically does not model mathematically complex, individual agent memory or learning from V^{ij} outcomes [5][6][24][3] for simplicity. However, memory and history still matters. The sum of all prior individual system dynamics behavior and evolutionary through iterations, does contribute to each individual and societal current states.

As an initial effort at a scale-integrated framework, the design of three modules allows the study to focus on the coupling of structure and agency first, before enriching subcomponent process detail. Thus agents simultaneously co-evolve as strategy pair outcomes at t to increase y at t+1, thus driving both positive and negative h, b and y feedback process through $t+n$ iterations. These shape A^i attributes, which allows adaptation to a changing environment with aggregated y_i, b_i, and h_i values. Feedback into subsequent A^{ij} game selection networks and strategy choice yields a complex adaptive system representation across multiple scales.

5. RESULTS

The agent-based model is implemented in NetLogo [27]. The entities that interact are all individual agents. The baseline initial population is 500 to represent a sample of any given society. State variables 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 daily basis, the model approximates one time step as one month given data calibration [3][4] for a simulated time span of 20 years, which is appropriate for a cycle in the study of political economy. This design allows studying the dynamics of politics, economics, and demography of a society with reasonable frequency and length of time.

In order to make generalizable model inferences, a quasi-global sensitivity analysis is conducted on both input and initial condition parameters, for over 17,000 runs across 240 time steps. With income as the dependent variable, the result is shown in Table 1. Cooperation is measured as the number of agents who choose to corporate in the socio-economic transaction game, and defection is the number of agents choosing to defect. The number of transaction games and the number of agents in each time step are also tracked and presented as Game and Population below. The last variable Time is the number of iterations in each run, distinguishing each step in each society's development process.

Table 1. Sensitivity Test Result

	(0) Income	(1) Income	(2) Income	(3) Income
Fertility rate	0.0470***	0.1223***	0.1331***	0.0324***
	(0.0032)	(0.0024)	(0.0024)	(0.0031)
Human capital	-0.0460***	-0.0067	0.0044	-0.0915***
	(0.0072)	(0.0054)	(0.0054)	(0.0071)
Instability	-0.0304*	-0.2269***	-0.2491***	-0.0026
	(0.0126)	(0.0095)	(0.0094)	(0.0124)
Political capacity	0.0121	0.0036	-0.0057	0.0292**
	(0.0111)	(0.0084)	(0.0083)	(0.0109)
Cooperation		2.3920***	2.1699***	
		(0.0079)	(0.0089)	
Defection			-0.3522***	
			(0.0067)	
Game				0.7777***
				(0.0121)
Population	-0.0896***			-0.4343***
	(0.0053)			(0.0075)
Talkspan	0.2792***	0.1071***	0.2275***	-0.0087
	(0.0017)	(0.0014)	(0.0027)	(0.0048)
Time	-0.0165***	-0.0411***	-0.0408***	-0.0153***
	(0.0010)	(0.0008)	(0.0008)	(0.0010)
_cons	0.3430***	0.3306***	0.3280***	0.5365***
	(0.0083)	(0.0059)	(0.0058)	(0.0087)
N	121035	121035	121035	121035
Adjusted R^2	0.2002	0.5432	0.5533	0.2265

Standard errors in parentheses *** p<0.001", ** p<0.01, * p<0.05

The first column presents the baseline model from POFED theory with only macro level variables. One can see that about 20% variance of aggregated income is explained by aggregated fertility rate, human capital, political instability, political capacity, population, time, and technology, which is presented as "talkspan". This model serves for comparison purpose with the other three models with individual level variables.

Model (1) first confirms POFED theory that negative value of instability significantly speeds economic development with substantive effect (β = -0.2269), as people are able to create more value in a stable environment. As to the impact of evolutionary games, one can see the number of agents with cooperative strategy has a significant positive impact (β = 2.3920) in increasing societal economic value, and the impact is much stronger than that of instability. Talkspan spatial proximity is also positive and significant (β = 0.1071), confirming priors that increasing technology and compressing potential social space also accelerate development processes. Increasing individual agents' ability to reach other like-minded agents spurs cooperation dramatically based on first order local interactions. This impact is even greater than that of cooperation, suggesting technology development provides the sufficient condition for individuals to interact and create economic value. Time is slightly negative (β = -0.0411), indicating that economic prosperity is not self-reinforcing. Model fit (R^2=0.5432) is acceptable given the highly complex and non-linear dynamics and pooled nature of sensitivity analysis data. Compared to baseline model, adding individual choice of cooperative strategy doubles the explanatory power. In other words, this model captures the micro level behavior that can better explain macro level phenomena.

After confirming the positive impact of cooperative strategy, model (2) explores the impact of agents choosing to defect at the same time. In the process of economic development, defective behavior has strong and negative impact (β = -0.3522), contrary to the positive impact of number of agents playing cooperation (β = 2.1699). This suggests that cooperation does pay higher social dividends on average. Besides, defective strategy has stronger impact, in comparison to that of instability (β = -0.2491) and talkspan (β = 0.2275). Model fit (R^2=0.5533) increases marginally than model (1), though both cooperative strategy and defective strategy significantly impact individual wealth and society wealth, adding more explanatory power to macro level dynamics.

The last columns focus on the number of interactions among individual agents and how that impacts the level of income. Unsurprisingly, the number of societal economic transactions positively influences wealth (β = 0.7777). In the process of individuals communicating and making deals with each other, more products and services become available while the cost of which goes down. This logic at the societal level is well discussed and empirically tested in globalization literature: in the process of increased interconnections among countries, benefits are derived from specialization of products and services, which outweighs the economic and social costs by achieving higher efficiency. Compared to the baseline model, this model contributes to explanatory power at a limited level, performing worse than the other two models, suggesting only counting for the number of interactions is not enough, what is more important is the type of strategy individuals choose when they interact with each other.

6. CONCLUSIONS

Combining system dynamics, agent-based modeling and game theory in a complex adaptive system, this simulation framework of the Politics of Fertility and Economic Development (POFED) explores the relationship between politics, economic and demography change at both macro and micro levels. The results first confirm the findings of the POFED theory at macro level. The extension of micro level agency and feedback loop provides more explanatory power to economic development. The number of individual interactions is critical to development, as more value can potentially be created. However, besides the quantity of individual interactions, 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, which enhances political stability and economic growth. On the other hand, defective strategy reduces social wealth, in addition to its negative impact on the level of trust in the society. Consistent with the findings from the macro POFED model, the model with micro inputs also shows increasing technology and compressing potential social space speed development processes. Macro level variables also feed back to individual agents updating their attributes and change the pace and tempo of socio-economic transactions, which reinforce national development and economic growth. In terms of model fit, adding individual choice of strategies increases model fit by doubling that of the baseline model in which only macro inputs are taken into account. In other words, this approach that combines both levels captures the micro level behavior that can better explain macro level phenomena.

This innovative approach creates a baseline for current policy efforts, showing when and how instability or sustainable growth is likely to occur. Policy can then be tested compared to baseline outcomes, under normal and crisis scenarios, to assist in robust policy development. The strength of agent-based model is its ability to model interactions between individual agents and the environment, as well as emergent behavior and complexity of the entire system. The key benefit is understanding how macro structural environments change and constrain or incent individual micro-level behaviors, and how micro interactions shape macro structures.

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