CAN SYSTEM DYNAMICS FLOWS REACH AN ECONOMIC EQUILIBRIUM?[1]

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When I began studying economics 40 years ago, economists were enthusiastic about converting their theoretical models into empirical versions which could be estimated econometrically and used to make projections. Some even believed that this would convert economics into a "hard" science, like physics, where precise estimates and rigorous models would lead to better management of economies and sustainable growth. I was excited about possible applications to promoting economic development in poor countries. Projection models would certainly help define the best growth strategies and show governments how to invest and generate growth. The economic recoveries in Europe and Japan, the independence of most former colonies, and sound expansion of US in the 1950s and 1960s contributed to our optimism and belief that we could achieve success in spreading development through out the world in our lifetimes. Unfortunately, event have proven us wrong.

When studying economics at MIT, I ran into system dynamics in its early stages, and even did some RA work for Professors Forrester. Like most economists, I was pretty skeptical of the system dynamics approach in the area of economics. It did not seem to be founded on solid behavioral theory and rigorous mathematical relations. It was not grounded on strong empirical evidence. And it was hard to see how it could represent complex economies. The later publication of Limits to Growth and its projections seemed to confirm much of the skepticism of economists. Trends were simply extrapolated exponentially until a crisis was reached. There was no mechanism in that study for reactions to scarcity, substitution of alternative materials, or technological innovations, though I understand that later work has addressed these issues. These projections have not yet been born out and most economists are quite skeptical of their validity.

As time has past, I have come to recognize the many limitations to the projections and accuracy of economic models, even as they have become far more complex and readily calculable. The underlying theory does not seem to be sufficiently robust to explain what has happened or to lead to the rapid development we all expected to take place. Economics did not become the next physics, and attempts to make it mathematically rigorous sacrificed much of its practical applicability – theory diverged from reality. The movement to theoretical rigor was particularly hard on development economics. One had to assume perfect markets for models to function properly. While some developed countries could arguably be close enough to having perfect markets to apply these theories, developing countries are characterized by innumerable market imperfections. What theory predicted rarely happened in practice. Practitioners in the

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field of development economics had to adapt as best they could – sometimes with conventional models and sometimes with convenient rules of thumb based on practical experience.

Over time, I have become somewhat more familiar with system dynamics and have come to appreciate its strengths and values. It has demonstrated considerable capacity to be applied more broadly to economic development issues. Rather than starting from a theoretical base, it begins from observation of relations among variables and links them together in realistic ways, especially when it moved beyond Industrial Operations to broader economic issues. Here I must admit that I have not studied system dynamics in an academic environment. What I have learned comes from applied experience using system dynamics models applied to developing countries. This has been primarily with the Millennium Institute and its Threshold21 Model. So you are still getting an economist's view, and I apologize for an gross representations of system dynamics. I do think that the divergence between these two approaches should be overcome. Neither system has all the answers for economic analysis, but both have substantial contributions to make, and we would all benefit from more work that draws on the relative strengths of each approach. In particular, I see a lot of opportunities for productive collaboration in the realm of development economics.

This presentation will look at some of the key differences and similarities of conventional economic models and system dynamics models for analysis and strategic planning in the context of developing economies. I will attempt to illustrate how their different foundations and approaches have different strengths and weaknesses. Let me begin with economic modeling approaches, especially when applied to development issues. Then I will turn to system dynamics models. I will grossly simplify in this presentation to make it understandable. The basic points hold with more detailed analysis. Finally I will suggest ways I see that these two approaches can converge to create a more powerful and credible integrated approach. This is what we are trying to do in Threshold 21 and its applications in a growing number of developing countries.

Foundations of Economic Models: The theoretical foundation of economics provides a basis for understanding and modeling economic behavior. It is assumed that individuals and firms act to optimize their utility or profit. Markets are assumed to be freely competitive so that agents can chose what they want to buy and sell, whether in terms of consumption, labor, or inputs to production. They will organize their actions to jointly produce the maximum utility for each, which will, in principle, lead to the maximum total utility. No external or *a priori* judgments are made about the values of goods or services. These are determined by the functioning of the market. In this theory, markets all clear, unique prices for all goods are determined, and equilibrium is achieved. In fact, it is recognized that such an ideal world does not exist, but the assumed behavior does make sense. It has been verified in many empirical studies which demonstrate that the real world is a reasonable approximation of this ideal, especially if it viewed from a bit of a distance. The comparison is often made with the way that physics deals with gases: the aggregate behavior of gases follows well defined rules despite the actual random motion of individual gas molecules.

Building on this theoretical basis and related econometric studies, economic models have been constructed to explain a number of economic phenomena, to predict how certain policies or other actions will change the economy, and to demonstrate what happens under certain stresses. The simplest family of models can be characterized as accounting models. In these models, the structure is built around the kinds of theoretical formulations suggested above. The model specifications are more detailed and the structural parameters are estimated econometrically over a set of historical data, or they are derived from sets of individual equation estimates and comparisons with other countries, or some combination of the above. The equations may be linear or non-linear, and the model may focus on an entire economy or on a single sector of group of sectors (partial equilibrium models). To run the model, values of certain exogenous variables are supplied and the model is used to calculate the remaining variables using the equations in the model and rules of closure. These closure rules say that certain equations must be satisfied due to basic economic theory, so one variable is effectively a residual. These models are basically recursive. They are easy to construct and run, but it is hard to keep them from generating large residuals after a period of time because there is no internal adjustment of the parameters, the exogenously supplied future variables, or growth rates assumed for certain variables. The IMF FiPlan model and the World Bank RMSM family of models fit into this category.

More sophisticated families of models have been developed using simultaneous solution techniques which enforce market clearing across a large number of variables. These more closely represent the economic theories of market equilibrium. Computable General Equilibrium (CGE) models are the most commonly used family of these models. They have been made practical by the tremendous advances in computing power. These models are build around a Social Accounting Matrix (SAM) that records in detail flows of goods among many sectors as they are used in production and consumption. The flows of the SAM are often represented in physical terms and then converted to value terms (i.e., with relative prices) to allow summation over all goods. Each cell of the matrix contains a flow from the sector represented by the column to the sector represented by the row. Some may be blank if there is no actual flow, otherwise in the model, there is a function for that cell which determines the relation of the column to the row and generates a value.

Each column-row pair in this square matrix represents a market that must clear. The model is solved simultaneously to optimize a given objective function with adjustment being made in both relative prices and volumes of flows passing through each cell. The objective function typically maximizes total output or some measure of consumer utility. The model's solution (which is not guaranteed) also must satisfy closure rules governing aggregate market balances and external constraints imposed on the model. These models can be very complex and require large amounts of data to construct, estimate parameters and derive functions. And a specific objective function must be specified.

They can be used in either comparative-static or inter-temporal modes. In the comparative-static mode, a base solution of the model is used as a point of departure. Then changes in certain policies or relations or exogenous factors are inserted into the structure and the model solved again. The equilibrium with the changes is compared to the equilibrium without the changes to demonstrate the impacts of the assumed changes.

There is no time frame in the approach as the model has no mechanism for determining how long the markets take to clear in reaching the new equilibrium.

In the inter-temporal mode, the model is constructed to solve for a new equilibria in a sequence of time periods (usually years). This requires specifying the results of one solution period as input into the next period (e.g. savings in period t becomes investment in period t+1), projecting certain variables (e.g. population), and fixing certain terminal conditions (e.g. minimum capital stock) so that the economy would be sustainable after the projection period. Otherwise the model would optimize consumption during the years covered at the expense of investment in later years, which would only pay off after the projection period and thus have little if any value.

These models require tremendous amounts of computation power and are very sensitive to the terminal conditions and the exogenous variables. They are impressive pieces of work. Of great value is the collection of data form a variety of perhaps inconsistent sources and fitting it into a consistent framework. The most important contribution to understanding the processes in developing economies is the SAM. It helps comprehend the actual structure and mechanisms driving the economy. The process of creating the model itself contributes a great deal to improving our understanding of an economy and how it works. That may be as important as use of the results of the model.

Strengths and Weaknesses of Economic Models: These models have made valuable contributions to our thinking about development and examining the potential impacts of different policy options. Not because the models are themselves good predictors of anything, but because they are valuable tools in the hands of careful experts who understand their limitations and are properly skeptical of their results. They do represent plausible behavioral actions and reasonable constraints on the movement of different variables. Many of these constraints have real world counterparts, like limitations on foreign borrowing and budget balances, and many force planners and policy makers to take into account realistic views of the future, like generating positive output from investments. However, these models have a number of weaknesses.

While they are based on a clear theory of markets, they do not include the mechanism by which markets clear, nor a time frame. There is an implicit assumption that market-wide auctions take place outside of time, at no cost, and that all goods can be treated as commodities (no brand preferences). CGE and other models give no indication of what is taking place to achieve market clearing. It is a result of a mathematical solution algorithm, not a specific behavioral process, though of course the rules driving the solution are based on economics' behavioral theories. So these models tend to be 'black boxes.'

Initially, these models were based on the assumptions that markets were 'perfect,' because that was as far as theory had progressed. Work on development economics was prolific, but based on empirical observations that could not be shoe-horned into the neat theoretical boxes that were being used for models. So development issues fell out of favor with the mainstream. Applied development economists understood that the assumptions and conditions for theoretical purity simply did not apply in developing economies, and were only approximations in developed ones. Slowly theories expanded to include explicit recognition of what have been termed 'market imperfections' or 'market failures.' And the issues of development could be addressed in terms of a sounder theoretical basis explaining how imperfect markets work. Some of these innovations could be incorporated into the rigorous formulation of models, but most changes were difficult. Simple deterministic relations in pure market models were replaced by potential results that would be characterized as "it all depends," Models would not yield unique results and had difficulty endogenously determining which result to use as input for the next period.

This contributed to the use of accounting models where exogenous assumptions were made about 'what it all depends on.' Judgments had to be made throughout the model and the resulting projections depended as much on the externally supplied assumptions as the structure of the model itself. You had to trust the modeler more than the model.

One common observation of the evolution of developing economies is that markets are rarely or ever in equilibrium. And it is not clear that they are tending toward equilibrium with any haste. Indeed, the failure of their markets to function reasonably well is a major reason that they are underdeveloped. So it is hard to apply theories and models that assume stability and prevalence of equilibria to situations where equilibria are the exception rather than the rule. And this in itself explains a lot of the problems faced by development economists.

A final problem is that economic theory has little to say about equity, poverty, and social development issues, which are central to development. In part, this is because the basic theory accepts whatever initial distribution of wealth exists and optimizes welfare on that basis of that. When there are distribution problems resulting from policies that maximize total output, there are implicit assumptions that somehow those who benefit the most will offset the losses of those adversely affected and still come out ahead. This mechanism is outside of the economic process, and rarely accomplished. Similarly, improving standards of living or reducing poverty per se are not accounted for in the core theory unless they are reflected in market exchanges.

I admit that this is neither a complete or 'fair' list of the failings of conventional economic models, but it is an adequate characterization for this exercise. That said, I also have to state that a lot of bright and pragmatic economists have recognized these problems and created ways to adapt what is relevant from economics to developing countries and give good advice. But it is hard to do so in the context of models based on conventional economic theory. Even when complete CGE-type models are attempted, the lack of data makes doing them quite difficult to prepare and hard to integrate into policy making processes. It takes a long time to get consistent results, and the underlying processes are rarely transparent to policy makers, so they rarely play a key role in decision making. More likely, accounting models will be used which generate clear results, based on simple economic assumptions, though the actual process is often not transparent. However, since these models do assume market clearing and certain balancing constraints, it is not clear how relevant they are. I am thinking of World Bank and IMF accounting models.

Foundations of System Dynamics Models: Here I admit from the outset much less expertise. I have worked primarily with system dynamics models developed by the Millennium Institute, and have learned as I go along. I did have to overcome initial skepticism of system dynamics from my early exposure and the rampant criticism in the economics profession of applications like Limits to Growth. So I have come a ways. But I still have a lot to learn about the applications of system dynamics to economics. As I understand it, system dynamics models are not based on underlying theories of economic behavior, but rather on describing a series of interconnected events through differential (or sometimes difference) equations that track the natural progress or evolution of a system over time. In economic system dynamics models, these relations may be based on assumptions about economic agents seeking certain goals and behavior on certain rational principles, so they make sense.

Three principles seem to guide systems dynamics modeling. The first principle is precise causal relations. In industrial operations models, these can be physical or chemical reactions, or movements of items in response to orders or instructions, or transformations of inputs into outputs according to well defined processes. These rules are generally fixed over time, often based on physical laws, and the parameters ususally remain constant rather than adjusting endogenously to relative excesses or deficiencies in say the stocks or the size of the flows. The second principle is the use of stocks and flows. The model records changes in stocks as a function of inflows and outflows determined by its causal relations. The stocks are important in that they represent significant parts of reality and everything that is observed in economic activity are stocks used in various ways to create flows and eventual changes to stocks. But is not clear what impacts the size of the stocks or rates of change have in most system dynamic models. The third principle is the existence of feedback loops. Causal chains feed back on themselves after a few or many steps. This feedback can be positive or negative depending on the intervening causal relations.

Based on what I have seen and heard, system dynamics models can be highly effective in tracking and projecting physical systems. Causal relations based on physical relations can be assumed to remain constant over time, or vary in a predictable manner based on the underlying physical science. Here, there may be sound theoretical bases for the relationships used in the model. The strength of the relations and extent of the feedback can also use the underlying science. The key issues would be how many secondary and tertiary relations to include and where to set boundaries. Being inherently dynamic, these models project paths of various variables over time, usually to see when or whether certain goals would be reached or how certain stocks are affected or what the costs in terms of certain inputs would be. The net effect of the positive and negative impacts can be assessed. In many areas, including in economic and financial markets, these models have proven quite accurate in predicting results.

Critiques of System Dynamics from Economists: Most conventional economists seem very uncomfortable with system dynamics when applied to economic systems beyond narrow micro applications. Part of this may stem from general unfamiliarity with how to use system dynamics. And part is based on legitimate concerns. System dynamics models appear to be too deterministic and mechanical for economic projections. A large part of this reaction is based on the projections of the world models that show exhaustion of resources make no allowance for the fact that increasing scarcity will raise prices and lead to reduced demand, substitution of other goods, and incentives for technological change. The doomsday predictions of highly publicized systems dynamics models in Limits to Growth and Paul Ehrlich's work on population have not been realized. The economic systems responded and generally approximations of equilibria were sustained. The counter arguments of economic Julien Simon have held so far, though I do question how long they can be sustained.

These models assume that the set of driving causal relations will continue indefinitely. Compared to economic models, they seem to lack the kinds of closure and balancing rules that constrain economic systems, either inherently or through the actions of markets. Thus systems may explode or crash depending on the calibration of the model. Indeed, this may represent the evolution of some systems, like the population explosions and crashes of bacteria. But it is less credible when applied to economic systems where behavior changes and the economy adjusts and tends toward equilibrium. Economic agents do learn from past experiences. The general reaction to the first oil crisis in 1973 was to increase spending to offset the price increase in oil. This led to excessive inflation that took years to control. So when the second oil crisis arrived, politicians reacted differently and restrained spending. This was a problem for economists who based their projections on models which used the old behavior patterns. But it also raises concerns about deterministic systems that do not have market balancing factors included.

Let me emphasize the above critiques stem largely from economists who have very limited exposure to the full range of applications of system dynamics models to economic issues. I understand that many of these concerns have been addressed in much of the current system dynamics modeling work, though I am not yet familiar with a lot of that work. This is what leads me to urge that we find ways to build on the strengths of both approaches and promote more convergence.

Can These Approaches Work Together and Not Spit at Each Other? My experience in applying system dynamics models to developing economies strongly suggests that they offer a number of advantages. In fact, there seem to be a number of similarities when you get beyond the jargon. In economics, we talk about virtuous circles where positive, growth oriented equilibria are generated. And we worry about vicious circles where negative, slow or no-growth results occur. Sounds a lot to me like positive and negative feedback loops. While economics is primarily concerned with flows that generate the market clearing equilibria so central to its theory, it does have to take account of stocks. It usually restricts itself to capital stocks, and occasionally inventories, but labor force, technology, and other things are stocks that implicitly figure into economic models. Economists also believe in causal relations, but rather than giving them full sway, they mitigate them through various market clearing mechanisms and closure rules to satisfy their theoretical constraints.

Can we take advantage of these similarities to come up with a better tool for use in the real world? Theoretical economics made the choice of requiring rigid assumptions in order to attain clear proofs of its propositions. Applied economics was left without a realistic theoretical base and had to try to merge some of the theory to the reality on developing economies. CGE models have accomplished a lot starting from the basis of market clearing equilibria and using SAMs to clarify actual relations that lead to market clearing, but they have their limitations. In practice, markets in developing countries, and even developed countries, are rarely in equilibrium – all goods are not commodities, single prices don't obtain, and at any point, markets typically face excess supply or demand. In a well-functioning market, these lead to normal economic reactions – prices are raised or lowered, levels of production adjusted, and so on to move toward an equilibrium. It is hard to say how long it takes, because there are always disruptions of markets that change where the equilibrium might be. Consumer tastes may change, new products or processes or producers may enter the market, government policies may change. And market clearing efforts take place in real time and are not costless. So markets trend toward equilibria, over time, usually.

Even economists admit that in certain circumstances, dynamics may cause markets to be unstable rather than stable, but these are considered rare. We could look at the classic example is a 'hog-cycle,' where under certain conditions of the supply and demand curves, responses to market signals leads to a spiral away from equilibrium. What is interesting with this example is that it recognizes that economic decisions are made sequentially over measurable periods of time. The market doesn't clear instantly. In fact, that is the way real markets work. They do not reach simultaneous solutions outside of time. The agents make decisions about their next actions based in information available at a point in time. It is a sequential or recursive process, not a simultaneous one. In this regard, the recursive or sequential process embedded in system dynamics models resembles actual market processes better than the simultaneous solutions of economics.

If we start from this point, how would we combine more economic behavior with a system dynamics process, particularly for macro economic modeling and development economics? It should be possible to introduce economic behavioral responses into systems dynamics causal relations. Demand for goods can be a function of price, incomes, and other factors. Price can be a function of current productive capacity and existing stocks. So if stocks are low, price will rise. This will reduce demand in the current period, shift demand to other goods, and increase production in the next period, if costs of increased production do not rise too fast.

With proper buffers and lags, this will lead toward economy-wide market clearing equilibrium. Similar arrangements can be made for other markets – labor and even capital -- where growth in demand, perhaps as expressed in the price increase of a good, will shift allocation of investment and demand for labor. If the solution periods of the system dynamics model are short enough, this will do a good job of replicating the actual function of markets. The parameters of the demand functions can themselves be variable, determined in part by relative levels of income and satisfying 'limited' consumption needs. For example, the demand for food does not increase proportionately with income beyond a certain, relatively low point. So the parameters allocating demand across goods have to change as income rises.

Certain closure rules do need to be applied to the model to assure that markets clear in the sense that all production and consumption, or supply and demand, balance in a given period. This closure does not need to occur in the pure economic sense of prices adjusting instantly so that supply equals demand. It can occur through the accumulation or depletion of inventories or buffer stocks, which act as a residual to 'clear' the markets. These can be inventories for goods, unemployment for labor, excess capacity for physical capital. And the accumulation or depletion of inventories can affect production or consumption decisions in the current or future periods. Other residuals can be used to balance macro level 'markets.' Savings or net exports can balance the aggregate national accounts, and change in reserves can balance foreign accounts – closure equations. Including a SAM in a system dynamics model (as we have done in the Threshold 21 model) can be a big help in structuring and accounting for these balancing reactions and achieving market clearing, though with slightly different mechanisms in system dynamics than economic modeling.

Changes in stocks can feed back into other parts of the model to mitigate tendencies for some variables to grow unsustainably large or small. However, where tendencies persist for variables to grow too large, this may be taken as a sign that there are structural problems in the model that need to be addressed. Either the model is not properly formulated, or the economy modeled is not sustainable. Deeper structural changes may be required. Both indications are helpful to the modeler and policy maker, in different directions. In fact, these discrepancies may be more transparent in a system dynamics model than in a CGE model, where the equilibrium is enforced and some of the resulting market clearing actions may not be feasible in practice.

System dynamics models offer opportunities to include much more of the interactions in a socio-economic structure than a pure economic model. They can create linkages to health, education, and other social sectors that are impacted by economic actions. They can generate feedback from those sectors to the economy. This allows them to include equity and value choices that are hard to include in economic models. For example, increased provision of education, depending on the type, can increase the skill level of the labor force and raise productivity. Better medical care will reduce morbidity, increasing the effective labor force and its productivity, and will increase longevity, raising the dependency ratio. Environmental impacts can similarly be readily incorporated. Impacts of pollution can affect health and costs of production (e.g. higher costs for water treatment), and the effects of resource depletion can be included. I don't want to imply that economists are not aware of these relations. They are, and they have done a great deal of analysis and built sub sector models to examine these questions. That is where we would get a lot of our information about causal relations and potential parameter values. But it is very difficult to incorporate these partial models into economy-wide models subject to economic theories about market clearing etc.

At this point, I do not want to go further into the details. The work of many system dynamicists is moving in this direction, probably much more than I have presented. I doubt that I have introduced much, if anything, new to such analysis. What I hope I have done is show that many of the arguments between economics and systems dynamics are more polemic than real. Both approaches have a great deal to offer in deepening our understanding of how the real world works and how to estimate the potential impacts of policies and political decisions. And they have their failing. It should be possible to combine these approaches more productively. Economics offers valuable information about economic behavior and the inherent constraints in an economic system. Certain factors do have to balance.

CAN SYSTEM DYNAMICS FLOW REACH AN ECONOMIC EQUILIBRIUM?

System dynamics offers an approach to combine economic and broader social and environmental factors into a single, coherent framework that can be adapted to satisfy the constraints of an economic system. System dynamics models can be much more realistic and transparent in describing how an economy moves toward equilibrium. They could make it much easier to understand how an equilibrium is reached, over what time frame, and whether it can be reached in a sustainable manner. System dynamics models also allow easier determination of time paths to reach an equilibrium and the sequential impacts of different options. While it is possible to make system dynamics models optimize results, as economists like to do, they are probably more useful in showing how different types of behavior, represented by different structures, lead to different results. And the policy maker can decide which is optimum. That is a little more like the real world.

So lets take this as an opportunity to see if there is more scope to bring together the two approaches and draw on their strengths rather than simply criticizing their weaknesses. Maybe we can call it economic systems dynamics, or systems economical dynamics, or systems dynomics?