Jay Forrester's disruptive models of economic behavior

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Abstract

A revolution in economics was probably never a conscious goal of Forrester's work. Yet, his writings might have laid the foundation for it by visualizing the decision processes in firms, markets, countries and global economic institutions, as it exists in an operational setting instead of being defined by the abstract postulates of mainstream economics. This operational perspective allows his models to be tied to policies that influence everyday decisions to avoid problematic futures. When viewed in the context of the working of the market, economic development, management of common property resources and control of growth and recession, which are important application areas of economics, Forrester's writings provide deep insights that not only tie well to reality, but can also be used for creating effective policies for managing firms, regions and countries. Drawing from my simultaneous pursuit of Economics and System Dynamics, both in my graduate work at MIT and in later research, and a careful study of Forrester's work, I discuss in this paper Forrester's alternative models that address a wide range of economics policy agendas, which set the stage for a disruptive change in the practice of economics.

Key words: System dynamics, economics, microeconomics, economic development, environmental economics, macroeconomics, economic cycles, long wave, disruptive science

Introduction

This paper grew out many years of thinking and working on the interface of economics and system dynamics that culminated into my presentation on Forrester's general theory of economic behavior at the 31st International conference of the System Dynamics Society[1]. The presentation was followed by a fireside chat with Professor Forrester on his modeling work and writings, which further helped to articulate my interpretations of his work.[2] At the outset, Forrester seems to have redefined how economic behavior should be modeled – as actions of real life managers instead of abstract pursuits of imaginary rational agents – as early as his publication of Industrial Dynamics. This perspective is maintained through Urban Dynamics, World Dynamics, and the yet to be published National Modeling Project. Forrester's work thus presents an alternative approach to dealing with economic agendas that in fact sets the stage for a disruptive change in mainstream practice of economics. Indeed, Forrester supported that proposition in his fireside chat by hoping for a revolution in the mainstream economic theory, which has become mathematically elegant but is too abstract to be effectively tied to reality or policy.[3]

Forrester's models are based on extensive discourses with the stakeholders in organizations dealing with specific illusive problems. They were built on practice rather than on theoretical premises and thus conform to Mill's position on practice preceding science (Mill 1848). They were also coded in a form that attempted to replicate the structure on ground. And they could be experimented with. As their structure differs greatly from the neoclassical economic theory currently posited as mainstream economics, they lay the foundation of an alternative economics practice that is holistic and intimately tied to how ordinary people working in economic roles make their decisions. They indeed have the potential to create a disruptive change in the way economics is studied and practiced at present time, which I'll attempt to demonstrate in this paper.

The starting point for Forrester's models is invariably stocks and flows which in his view is an intuitive representation of the system structure. You would not find causal loop diagrams in Industrial Dynamics, Urban Dynamics and World Dynamics. Feedback loops formed in his models when delineating decision structure are the basis of his explanations of system behavior. In fact, Forrester clearly stated in his 2013 Fireside chat:

"I prefer to model by identifying the stocks that I want to work with. I did not start with causal loop diagrams or some of the things that are very popular. Start with the stocks."

Feedback loops, which he calls the building blocks of systems (Forrester 1968), are formed when the logic of flows (policies) is represented as functions of stocks. They are often implicit in his descriptions of the model behavior instead of appearing explicitly as causal loop diagrams, which can lead to many anomalies when created at the level of aggregation of the stock and flow structure of a model (Richardson 1986). Although I am of the view that an aggregate feedback map helps greatly to conceptualize the relationships between major segments of a system, following Forrester's preference for representing models as stock and flow structures, all models in this paper are presented in that form while causal relationships are implicit in my narrative.

The emergence of Forrester's disruptive models

Forrester's work in most part ignored the literature on economics and focused on realistically representing the actual decision-making structure in organizations for addressing specific policy agendas. His models, however, address key economic issues like the behavior of a firm, economic development, environmental policy and economic cycles. He based these models on the experience of the real actors he worked with that he called "managers" and not on the premises of mainstream economics. He has often remarked that the absence of references to literature in his writings sometimes enraged his academic colleagues while his models always had a great appeal for managers and practitioners. They also represented a shift from the mathematical models of mainstream economics in which extremely knowledgeable agents personifying producers, households and consumers pursue abstract objectives. These knowledgeable agents and their objective are often difficult to connect to the behavior of the real actors on ground, who work with limited information to balance their everyday acts (Simon 1972, Morecroft 1985).

Forrester's models can interestingly be tied to some of the *classical* economics theories, which according to Baumol (1959) described magnificent dynamics of the free market system. This link to theory is however not deliberate and arises probably because those early theories came also from direct observation of how economic actors went about their everyday business. This is evident from the copious descriptions of human behavior included in the writings of classical economists (Smith 1776, Mill 1848). This important premise of theory building was swept under the rug when the neoclassical models were formalized as the mainstream economic theory. As the markets evolved from the situations these models were based on, they became removed from reality. In response, the reality has often been labeled as "imperfect", while the models that failed to describe reality have been held as Holy Grail.

Forrester's models interestingly seem to fall into widely used partitions of economics. Thus, Industrial Dynamics (Forrester 1961), which defined the basic premises of System Dynamics, albeit in an industrial setting, posits an alternative theory of firm that arose from his work with several major production organizations of the country. Urban Dynamics (Forester 1969) is an alternative economic development model that arose out of his work with Boston's former mayor John Collins and his colleagues. Both these writings are thus firmly grounded in practice. World Dynamics (Forrester 1971) is an alternative environmental economics model that grew out of Forrester's discourses with the Club of Rome – a diverse group of politicians and thinkers whose concern for future arose out of observation of the out of control economic growth rather than their knowledge of environmental economic theory of the time that trusted markets to mitigate any impending limits (Nordhaus 1979).

Finally, even though many mainstream economists served on doctoral committees of the researchers associated with the National Modeling project, that project was sponsored by industry not NSF. And Forrester insisted on maintaining the practice focus in the National Model by extending the constructs of Industrial Dynamics to explain macroeconomic behavior instead of drawing from established economic theory of the time. Thus, the National Model evolved as an alternative macroeconomics framework based on everyday decisions of actors rather than being built on textbook macroeconomics (Saeed 2013). Surely, all of Forrester's work was firmly grounded in practice in the tradition of classical economics thinkers, which is why it can be tied to classical economics models that were also grounded in practice. I'll discuss in the following sections how Forester's models deviate from the mainstream, how they tie into the classical thought, and how his work lays the foundation for disrupting the most important of the social sciences of our times – economics.

Industrial Dynamics as an alternative theory of firm

The neoclassical theory of firm sometimes referred to as microeconomics of product makers is based on a reinterpretation of the supply and demand schedules that have remained the staple of microeconomics texts for over half a century. It personifies the many role players in a firm as a single very perceptive and knowledgeable individual, smart a god, who consciously tries to balance the firm's marginal cost (MC) and marginal revenue (MR) schedules as illustrated in Figure 1. She exactly knows these schedules and is of course guided by the invisible hand in her effort. The result of this effort is the production of an optimal quantity Q* at an optimal price P*. The marginal cost and revenue schedules may vary a bit depending on whether a firm operates in a competitive or noncompetitive market (McConnell and Bruce 2008, Varian 2003). Oscillations may occur in this system due to perception delays.

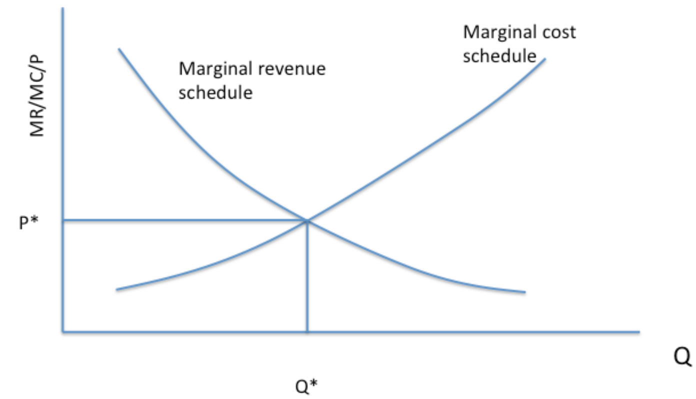

Figure 1: Neoclassical model of Firm behavior in a competitive environment

This graphical model and its variants are often also expressed as sets of differential equations, although these equations also shed little light on how the decision process they represent generates its outcomes.

Forrester initiated his alternative perspective on economics by redefining how the production system on ground should be represented – not as abstract graphs and differential equations but mimicking the operational structure on ground. Figure 2 replicated from Industrial Dynamics, chapter 2 illustrates his starting point for modeling the production process, which mimics a supply chain consisting of multiple firms subsumed also into the widely used beer game.

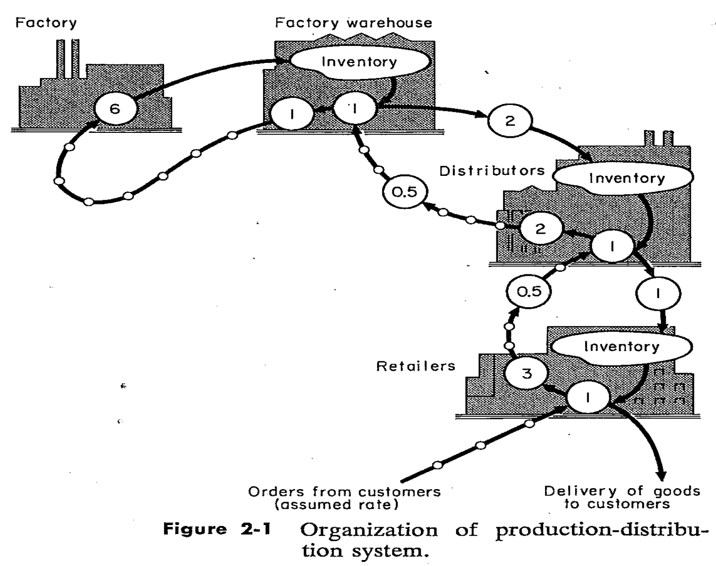

Figure 2: Production process modeled as a supply chain of firms in Industrial Dynamics [Source: Forrester (1961), p-22]

In each firm, the decisions to produce, add or lay off capacity (workers, machines), order raw materials and parts are made by down to earth managers who do not know their marginal costs and revenue schedules, but who are trying to balance down to earth firm operations like maintaining reasonable levels of inventory, workforce and physical plant to produce quantities needed for clearing the backlog created by incoming orders. He also felt that price is an outcome in this system, not a driver (Forrester 2013). Indeed, prices are determined in today's markets by long-term contracts and depend on a multiplicity of production considerations like delivery delay, quality, inventory levels and backlog, which factor into creating the needed adjustments way before prices can be acted upon. They are posted by the producers rather than arising out of a hypothetical bidding process in a market where very focused producers and consumers negotiate on basis of perfect information.

Forrester also did not attribute the supply instabilities to market, but explained them as changes arising out of the feedback loops created by the management actions within a firm. In fact, he literally pulled out a generic oscillatory structure shown in Figure 2 from the mechanics domain and notwithstanding the engineering texts, which predominantly used quintessential block diagrams and the mathematical solutions of the second order differential equation it creates to describe it (Mandra, et al 2013), he represented it in terms of stocks and flows to intuitively explain instability in the production process.

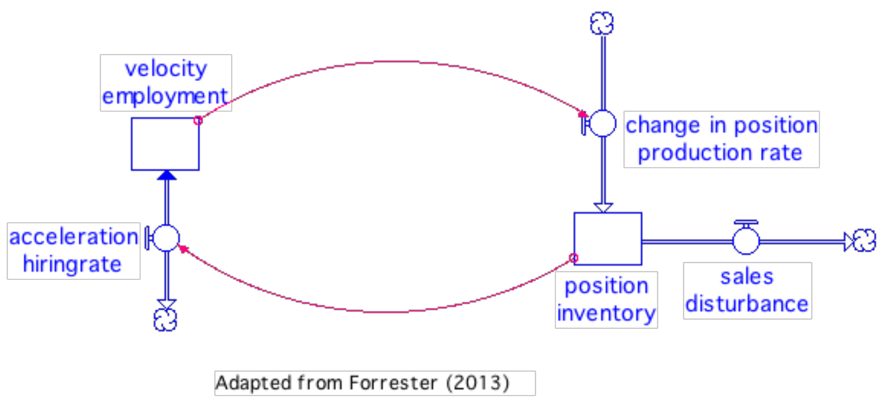

Figure 2: Negative feedback loop in a mass spring system as an analogue for explaining instability in supply in the production system

Forrester insists on creating an analogue of the stocks and flows and integration over time in our models as they actually exist in systems. "As with other parts of the industrial system, a market model will consist of stocks and flows," he points out (Industrial Dynamics, p-313). He has often stated that differential equations are an un-natural representation of a dynamic system, as differentiation process does not exist in human experience. In fact, all systems integrate over time. Hence, he created an integration representation in terms of stocks and flows both in diagraming and equations that intuitively correspond to what happens over time in reality, which has become the language of system dynamics.

In Forrester's Industrial Dynamics model, production is not driven by marginality concepts, nor do prices balance demand and supply as is commonly posited in microeconomics texts. Inventories, backlogs, and delivery delays are the primary short-term balancing forces. Price is an outcome – a performance index of sorts which depends on a multiplicity of considerations discerned by managers in a firm. Figure 3 constructed from his postulates in Forrester (2013) gives a stock and flow map translating his perspective on the way a firm operates in a market.

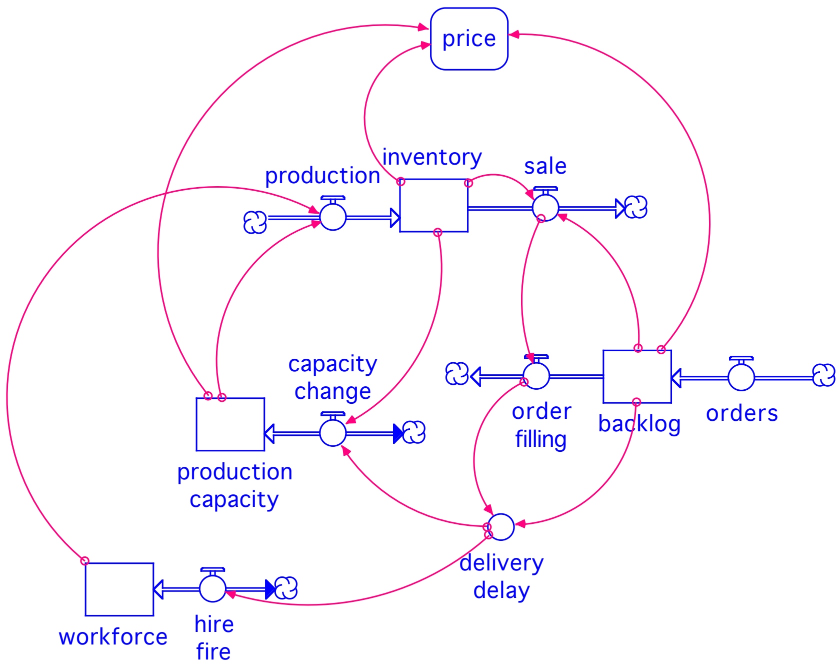

Figure 3 Production systems, managerial actions and price.

Managers working in a quasi-rational environment adjust production capacity, inventory and workforce. Feedback loops created by managerial role-play drive this adjustment. Multiple coupled and compensating feedback loops make the adjustment process parameter insensitive. The managers do not know and do not have to know their supply and demand schedules. They can have a wide range of personalities and personal preferences creating a variety of parameter sets driving the feedback system they work in. Yet, the outcome of this adjustment process will not change much due to the many compensating feedbacks that ameliorate changes in adjustment rates created by each.

Forrester's alternative view of the market is indeed in direct conflict with the neoclassical model, which assumes conscious pursuits of abstract goals of balancing marginal costs and benefits by firms. It also posits that production and sales are not driven by price; they depend on a multiplicity of factors. Furthermore, it recognizes that prices are affected in the short run by operational variables such as production capacity, backlog and inventory that simultaneously affect managerial and customer actions. It even deviates in representing the market operations by using stock, flows and integration process instead of differential equations. And it explains behavior as an outcome of feedback loops rather than a creation of an invisible hand.

Forrester also downplays the importance of numerical data and measurements that are important in the practice of mainstream economics, since a multiplicity of feedback loops creates insensitivity to tastes and preferences (Forrester 1980). He thus makes a refreshing departure from the abstract view of the market included in economics texts and creates a vehicle for designing policies in terms of every day decision riles through experimentation with models that actually mimics the operations on ground. His alternative view of the market is focused on operations carried out by real people and not by imaginary super-intelligent agents. This is a refreshing departure from the mainstream that calls for completely rethinking microeconomics.

Urban Dynamics as an alternative economic development model

The contemporary views on economic development predominantly see underdevelopment as a gap between the developing and the developed countries. These models emphasize development policies that should endeavor to overcome this gap through facilitating economic growth (Van den Berg, 2001). The key growth models used for designing growth policies are variants of the Harrod-Domar and the Solow models, although Lewis's model of structural transformation is often subsumed in defining the various stages in the growth process (Lewis, 1958). All three models exclude any constraints created by workforce or natural resource endowments. There additionally exist several revisionist perspectives that add poverty alleviation, social development and affirmative action policies to the growth agendas (Todaro and Smith, 2006, Perkins et al, 2001). In all cases the implicit assumption in the contemporary models of economic development has been that the developing economies are nascent economic systems on their way to become mature economies. The policy problem is seen to be to realize their growth potential as fast as possible by allocating resources to activities with the highest yield, speeding up structural transformation from traditional to modern sub-economies and managing other dysfunctions like income distribution, governance problems, social conflict, corruption, and maintenance of personal freedoms encountered on way to maturity.

Joseph Schumpeter's work appears as an exception to the general thinking on economic growth prevalent in his time (Schumpeter 1962). He was perhaps the first economist to recognize that resurgence in a stagnant mature economy is driven by what he called creative destruction. He suggested that this renewal was an endogenously driven cyclical process, but he did not get into devising a policy framework to facilitate resurgence, nor did he see stagnation as a complex homeostasis achieved under capacity constraints whose composition could be influenced without causing growth to improve the general welfare through pro-active creative destruction, which Forrester seems to have proposed in his Urban Dynamics model. It seems to me that Forrester's Urban Dynamics coincidentally represents a natural progression of Schumpeter's concept of creative destruction applied to economic development in a mature economy, which is relevant both to the developed and the developing countries, since growth in both is constrained by physical and institutional limits arising from an unhealthy composition of activities.

Figure 4 shows the structure of a simple model of Schumpeter's creative destruction process I have attempted to construct from his descriptive framework and from Higgins (1968)'s effort to represent classical growth theories in the language of mathematics. The details of an earlier version of this model are available in Saeed (2008). While Marx's model of destruction of capitalism through exploitation of the proletariat was based on a class system that locked capitalists and proletariat in separate compartments (Marx 1906), Schumpeter saw the possibility of social mobility between classes arising from entrepreneurship that would rejuvenate a declining capitalist economy.

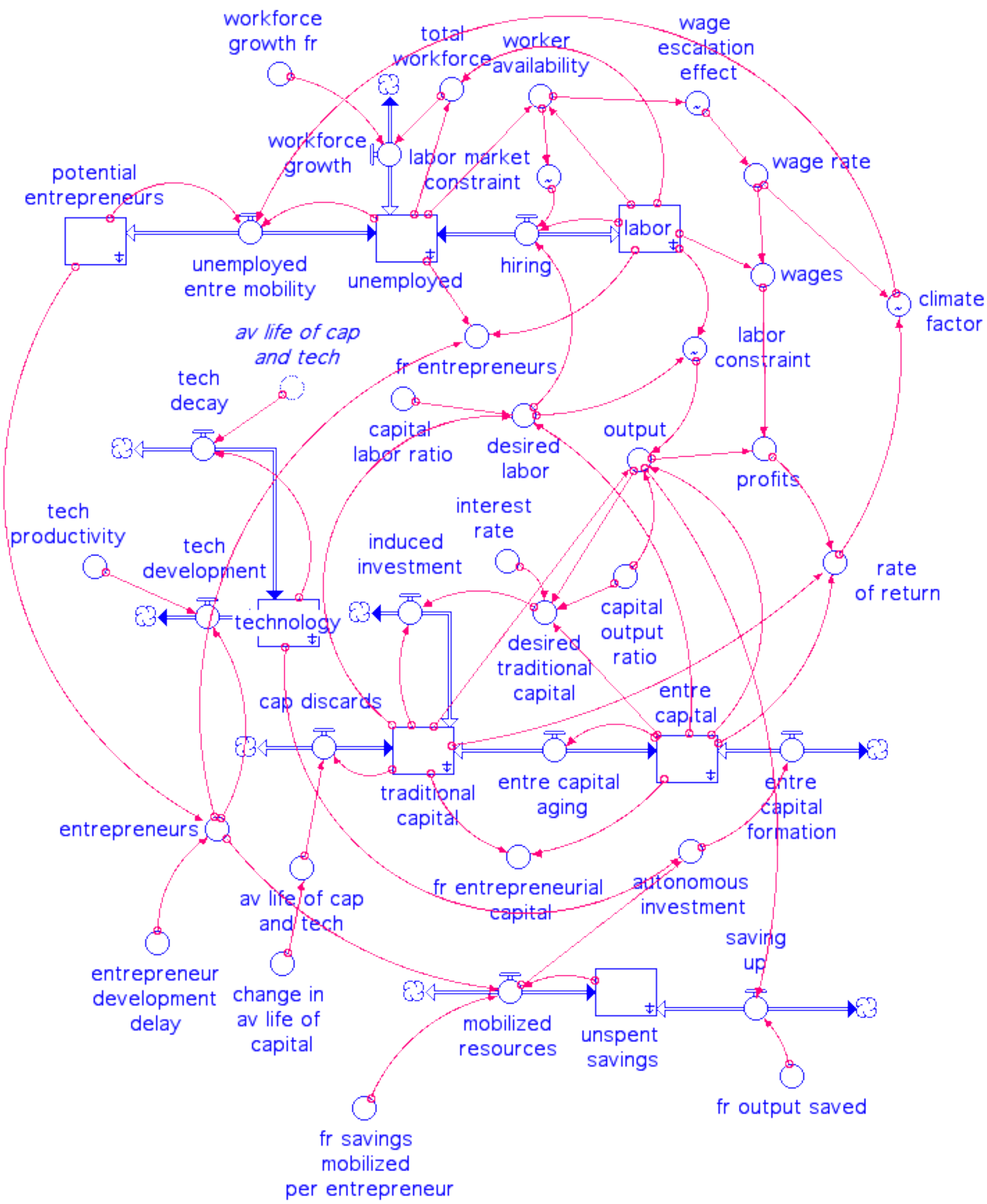

Figure 4 Schumpeter's concept of creative destruction: A model for understanding renewal in aging economies

Entrepreneurship could exist across all social classes. New entrepreneurs could emerge from the ruins of a fallen capitalist system. They could create a resurgence of capitalism from an environment in which cheap labor and the possibility of profiting from it would allow them to mobilize idle capital resources and create new and marketable goods and services from them (Schumpeter 1962).

Social mobility allows both employed labor and unemployed workers to become the potential entrepreneurs who after a delay become working entrepreneurs - new capitalists mobilizing financial resources and developing new technologies for autonomous investments that resurge the economy. In equilibrium, there exist balancing flows between unemployed and potential entrepreneurs meaning some potential entrepreneurs fail and return to the unemployed pool while some of the unemployed consider entrepreneurial roles. A similar exchange between the potential entrepreneurs and labor implies that some of the labor attempt entrepreneurial roles. And some of those considering such roles fail and return to wage work.

Figure 4 also shows the investment structure and the role of technology implicit in Schumpeter's descriptive model. Schumpeter distinguished between two types of investment that he called *induced* and *autonomous*. Induced investment arose from the discrepancy between supply and demand and autonomous investment from resources and technology created by the entrepreneurs. He also introduced a concept of "*saving up*" which is different from saving in the neoclassical growth models. Saving up constituted the part of output that is withheld from investment and consumption. Saving up possibly extended across social classes and fueled entrepreneurial activity leading to autonomous investment, hence it is computed as a fraction of the output modified by interest rate, which is taken as constant for simplification.

I made a small amendment to Schumpeter's concept of entrepreneurs creating resources; I had to call it mobilizing resources accumulated through saving up, mainly to designate a source of these resources in a formal model. I have therefore accumulated the difference between the saving up and the mobilized resources in a stock of unspent savings that supplies the venture capital for the entrepreneurs. This also allows the model to have a hypothetical equilibrium in which the autonomous investment is zero and saving up balances replacement investment.

Entrepreneurs also create new technologies and the blend of mobilized resources and new technologies lead to autonomous investments. Technology is represented in the model as a stock that is increased by technological development created by the entrepreneurs and drained by obsolescence. Output is produced by capital and labor, but desired labor depends on capital and capital labor ratio. Wage rate is determined by labor market conditions and profit is output less the wage bill. The average rate of return is given by dividing profit by the stock of capital and, together with wage rate, it yields a climate factor that may encourage or discourage entrepreneurship. It should be noted that while capital can be created through investment in this model, the workforce is fixed and creates a capacity constraint.

This system is provided a parameter set for initial equilibrium. Any disturbance in this system, including interventions to create growth will lead to oscillations and a new homeostasis. The disturbance can be introduced by injecting into or taking away agents/units from any stock or changing a parameter that unbalances flows connected to any stock. The oscillations arising from a variety of disturbances will be comparable, but the new equilibriums reached will vary. Growth as well as oscillation will occur in this system when the technological productivity of the entrepreneurs is stepped up thus fueling autonomous investment.

Figure 5 shows behavior of my simple model of Schumpeter's view of creative destruction. Growth of course creates an overshot due to the delays in the system, which is followed by oscillation that Schumpeter explained as cycles of creative destruction. A rise in technological productivity upgrades technology, increasing autonomous investment and raising output and profits, which initially draws more entrepreneurs into the system.

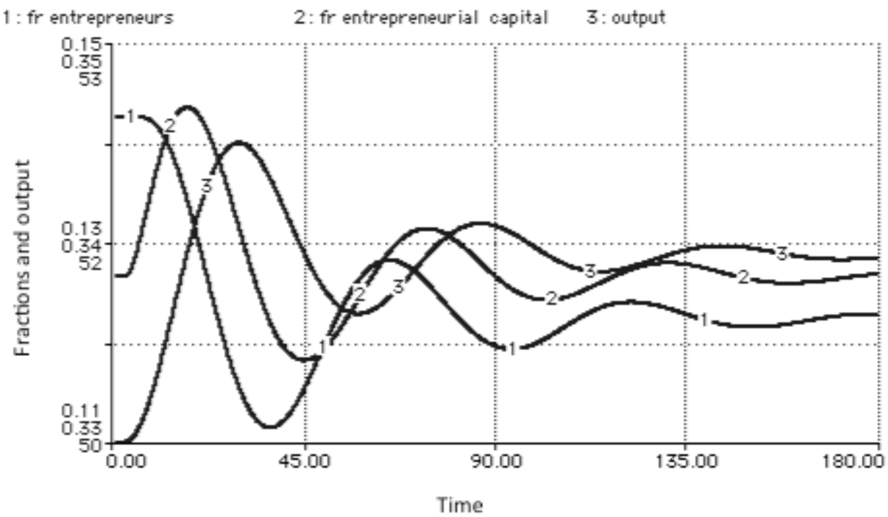

Figure 5: Growth, oscillation and the move towards new homeostasis with fewer entrepreneurs and lower entrepreneurial capital fraction in my model of Schumpeter's concept of creative destruction.

Growth however also raises wage rate thus deteriorating entrepreneurial climate and prompting some of the entrepreneurs to exit to join the labor force or the ranks of the unemployed. This process continues until the wage bill also squeezes profits, hence more potential entrepreneurs exit and autonomous investment further declines. This leads to labor attritions and a decay of the wage rate that improves climate factor creating conditions appropriate for another growth cycle.

An important thing to note additionally is that these cycles under the workforce capacity constraint lead to a new homeostasis in which there is a larger proportion of unemployed and a smaller proportion of entrepreneurs compared to the initial conditions. Clearly, growth effort in the face of capacity constraints has led to a higher output along with an inferior social mix of vocations in which more people are wage-employed or without jobs and there are fewer entrepreneurial innovators.

Forrester saw similar conditions pervasive in the US cities in the 1970 and his Urban Dynamics model creates a more or less similar low welfare homeostasis, which he proposed could be broken out of with a proactive policy of demolishing old infrastructure. The stock and flow structure of Forrester's Urban Dynamics model is outlined in Figure 6. The main difference between the two models is that while Urban Dynamics mimics an open economy with flexible population and capital flows, our model of Schumpeter represents a closed and fixed economy. There are also some other superficial differences: Forrester's Managers/Professionals are Schumpeter's entrepreneurs. The flow from underemployed to Managers/Professionals can occur through clouds in an open economy while it is portrayed as a direct link in Schumpeter's model. Forrester's economy is open with respect to financial resources; hence an internal stock of accumulated savings is not needed. Schumpeter's Entrepreneurs create autonomous investment into entrepreneurial capital while Forrester's Managers/Professionals construct new enterprises.

Schumpeter's induced investment arises from market dynamics and feeds traditional capital, while Forrester ignores such investment and assumes all new investment is entrepreneurial. Forrester also disaggregates production capital from services capital, which in an urban context is modeled as an aging chain for housing.

The two models achieve somewhat similar new equilibrium distributions of workforce and capital when growth is externally introduced in them. In this distribution, there is a reduction in the proportion of entrepreneurs/managers. Also, while the fixed population in Schumpeter's model limits growth, it is constrained by fixed land or physical resources in Forrester's model.

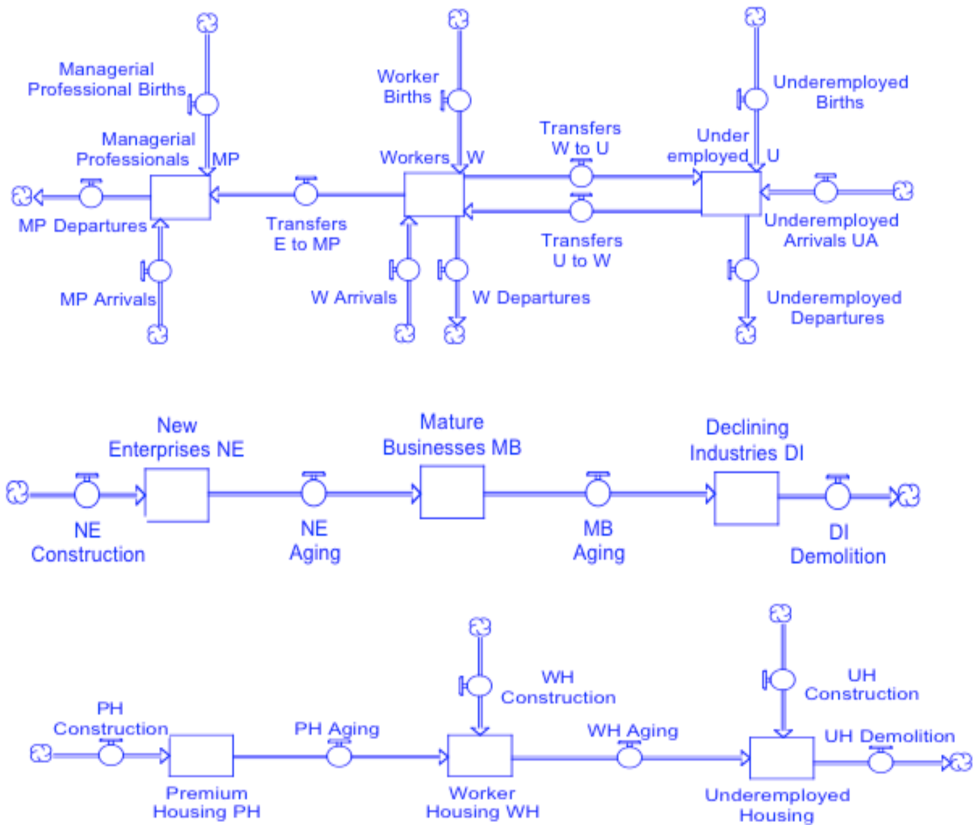

Figure 6: Worker mobility and infrastructure aging chains that created the starting point for Urban Dynamics model

I should also point out that while Schumpeter's work described the cyclical dynamics in this system that show the path to recovery from a stagnation created by obsolescence, Forrester was concerned about intervening to recover from such stagnation and took notice of the composition of workers and infrastructure when this system came to a homeostasis. Thus, while Schumpeter saw new entrepreneurial investment destroying old and obsolete infrastructure through a competitive advantage, Forrester proposed a proactive policy of removing old infrastructure, which is an important lesson for economic development. Further detail of similarities and differences between the two models can be seen in Saeed (2011).

Since Forrester's model assumes that workforce can change through migration while capital changes only through investment and the natural decay processes, it seems to mimic the modern open economies better than our model of Schumpeter's closed and fixed model. Forrester also assumes higher rates of mobility for the managers/professionals and labor than for the underemployed, which is consistent with the concept of poverty traps in the developing countries (Azariadis 1996). Towards the end equilibrium, the economy of Forrester's metropolis is characterized by stagnating businesses, a lack of entrepreneurial activity, high unemployment and dilapidated housing - conditions pervasive in the developing country economies when economic development effort began as well as in mature urban areas in the industrialized countries over mid-twentieth century.

Forrester's Urban Dynamics thus seems to represent a mature economic system mimicking the stagnating economies of both large cities and developing countries that have set into a low-welfare homeostasis due to environmental and institutional constraints. Forrester's experiments with his model also clearly suggested that the stagnation in mature economic systems can be transformed into a high welfare homeostasis through a policy set that speeds up the discard rate of old industry and service infrastructure while encouraging formation of new entrepreneurial businesses. Thus, Forrester's slum clearance policy seems to be a proactive form of creative destruction Schumpeter saw driving revival of a stagnating economy. He implemented this policy in his model by rapidly retiring old infrastructure, which translates into decreasing the life of traditional capital in our model of Schumpeter's creative destruction, whose implications are shown in Figure 7. The rapid retirement policy is implemented after the system comes to settle with lower fractions of entrepreneurial capital and workforce.

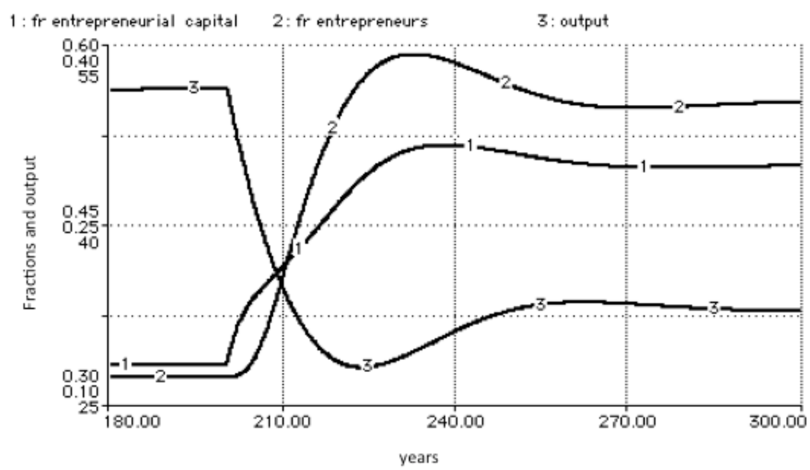

Figure 7 Implementing rapid retirement of capital in Schumpeter's model

Reducing the average life of capital in the new homeostasis will reduce output but at the same time create room for entrepreneurial activity. Thus, it also increases the proportion of entrepreneurs as the system moves to a new equilibrium. This implies that an accelerated removal of obsolete infrastructure in a resource-constrained economy will free up resources for the formation of innovative new enterprises and achieve a homeostasis with a better composition of businesses even though it may initially reduce output. And, implementing Forrester's proposed policy to mitigate economic stagnation in Schumpeter's model yields results similar to Forrester's.

There are notable differences also in the welfare indexes implicit in Schumpeter/Forrester models and the aggregates we see in economic development literature. Schumpeter/Forrester place all emphasis on the composition of households and businesses in making an assessment of a progressive environment. The traditional welfare indexes are fixated on absolute aggregate values. In fact, output is not even measured in Urban Dynamics. And it declines a bit in our model of Schumpeter when composition of households and businesses changes for better. In both cases, an economy with more entrepreneurial households and more entrepreneurial capital indicates a better environment. Thus, economic development might be better served by policies focused on changing the composition of the economic institutions than those fostering growth.

If the relevance of Schumpeter's concept of creative destruction and Forrester's Urban Dynamics model to the developing countries is accepted, economic development must be redefined to move away from the criteria of maximizing output growth, productivity and efficiency. It should instead attempt to seek transformation from a low welfare composition of workforce and infrastructure and that is creating stagnation to a high welfare composition that delivers a progressive environment. This transformation cannot occur without clearing the obsolete infrastructure and institutions, which should be an important part of the development strategy. Urban Dynamics thus clearly presents a realistic and workable model for economic development with its disruptive message that developing countries do not have infant but aging economies and that composition of the households and economic activities, not the aggregate measures of consumption and production indicate health of an economy.

World Dynamics as alternative environmental economics framework

Figure 8 illustrates the microeconomic foundation of the mainstream environmental economics texts. It personifies the firm faced with environmental repercussions of its decisions as a wise individual who is now environmentally conscious and cognizant of the firm's marginal damage and marginal control cost schedules. Guided again by the invisible hand, this time he balances marginal damage costs and marginal control costs to produce an optimal quantity Q* at an optimal cost C* (Tietenberg 2003, Field and Field 2009), which by the way may have no relationship with what might be a sustainable quantity.

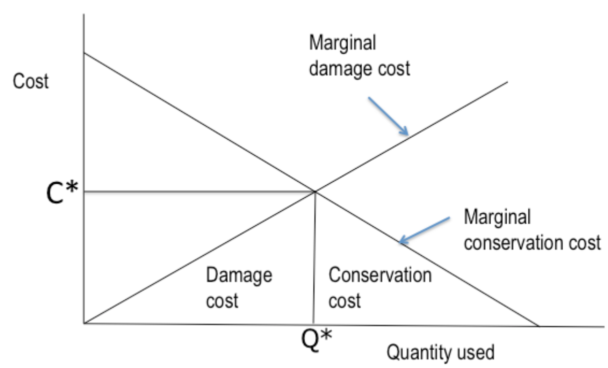

Figure 8 **Microeconomic foundations of environmental analyses in environmental economics texts**

In reality, to be able to investigate policies for sustainability, it is essential to be cognizant of the tipping points environmental constraints will create while growing in a finite world, that Forrester addressed in his World Dynamics model. I'll demonstrate how World Dynamics extends classical growth concepts by first attempting to model them and then adding additional concepts posited by World Dynamics (Saeed 2008).

If we ignore Galileo's little known definition of marginality implicit in his water and diamonds paradox (Galilee/JPE 2002), Adam Smith's Wealth of Nations (Smith 1776) is indeed the first detailed exposition on economics, although Mill (1848) more lucidly describes the economic growth process. Adam Smith did not clearly discuss the limits to growth but a demographic constraint is implicit in his model since labor is assumed to be freely available due to autonomous population growth, while capital and technology are endogenously created through investment of profits. Also, land which is a proxy for renewable resources, can be freely substituted by capital in Smith's framework (Higgins 1968, pp 56-63), hence it can be aggregated with capital. David Ricardo (1817) later designated land as a separate production factor and also endogenized population growth in the laws he posited on rents and wages, which I'll discuss later. Figure 9 represents the stock and flow structure of the production factors and the output in the growth process described by Adam Smith and then modified by Ricardo.

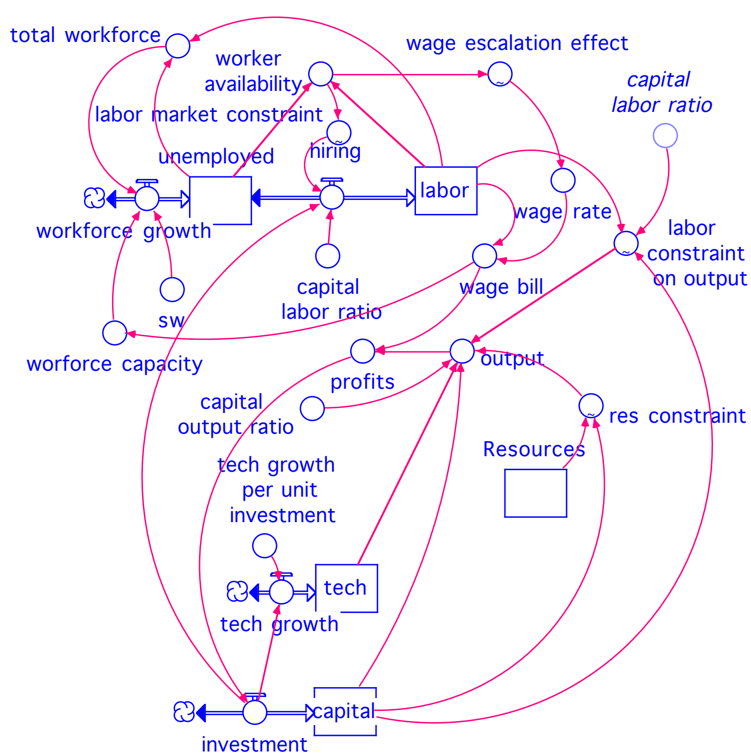

Figure 9: A model of Classical growth concepts of Adam Smith, Mill, Malthus and Ricardo. [Abstracted from Saeed (2008)]

At the outset, output is created by capital, labor and technology. A labor constraint on output appears when capital-labor ratio is suboptimal. Capital increases through investment, which is driven by profits determined by the difference between output and wage bill. Technological growth is also driven by investment meaning that new capital formation will upgrade technology. Labor can be hired form a pool of unemployed that is fed by population growth, while wage depends on the tightness of the labor market. Growth is created by investment of profits, however growth could also create a tight labor market, which would squeeze profits and bring investment to a halt. Adam Smith, therefore, considered workforce growth to be necessary to keep wages down and profits up. He even divided the countries into stationary and progressive categories based on their wage bill. In a free market, this wage bill would grow only when workforce increased (Spengler 1976).

As shown in graph 1 of the simulation of Figure 10, which is run without activating workforce growth and resource constraints, our model of Adam Smith's growth concepts equilibrates at full employment, exhibiting a manifestation of what Mill (1848) termed a stationery state.

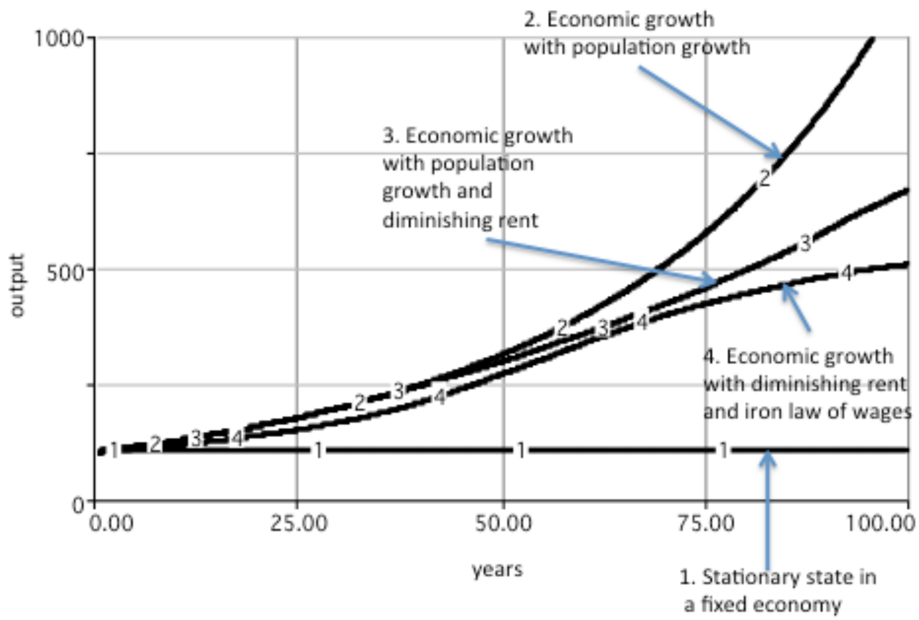

Figure 10 Behavior of the model with various classical assumptions

A sustained growth in this system is possible only when a growth in the total workforce can maintain a pool of unemployed that also keeps wage rate from escalating. Indeed, sustained growth is obtained when the model of Figure 9 is simulated with a 2% workforce growth rate. This is shown in the simulation 2 of Figure 10.

David Ricardo (1817) posited additional constraints to growth in this system. He outlined the principles of distribution between the various economic classes, landlords, capitalists and workers, which later became important building blocks of the model of growth and decline of capitalism that Marx (1906) conceived. More specifically, Ricardo brought in the constraints to growth by stating his law of diminishing returns to land cultivation and the so-called iron law of wages (McCulloch 1881).[4] Ricardo's definition of land rent in fact equated it to land productivity. To quote Ricardo, *Rent is that portion of the produce of the earth which is paid to the landlord for the use of the original and indestructible powers of the soil. It is often however confounded with the interest and profit of capital….* (Ricardo 1817, ch. 2).

This means land must be disaggregated from capital in the production schedule, however for simplification, profits and rents can still be aggregated as the two are residuals after meeting wage bill and running expenses. According to Ricrado:

Whenever, then, the usual and ordinary rate of the profits of agricultural stock, and all the outgoings belonging to the cultivation of land, are together equal to the value of the whole produce, there can be no rent. And when the whole produce is only equal in value to the outgoings necessary to cultivation, there can neither be rent nor profit… (Ricardo 1815).

Separating land (termed resources in our model) from capital and activating the constraint driven by the resources-capital ratio to the output in the model of Figure 9 creates diminishing marginal returns to resources as conceived by Ricardo. Such a constraint would slow down the rate of growth of output, but would not bring it to a halt as long as the sum of marginal increases in output from additional investment into capital and the technological growth it creates outweigh the decrease in the marginal productivity of resources. This means the relationship between investment and technological growth would be critical to maintaining growth in the face of diminishing land productivity.

The resource constraint corresponding to Ricardo's principle of diminishing returns is activated in the third graph in Figure 10 while profits and rents are still aggregated. The stock of resources remains constant in line with Ricardo's specification of "indestructible powers of the soil" - meaning that resources are fully renewable and thus do not deplete. As expected, growth rate is slower than in graph 2, while output tends towards a new plateau when technological growth rate cannot offset the diminishing resources productivity. However, as population continues to grow, the unemployed pool will continue to rise, which is anomalous since it would not be possible to feed an army of the unemployed so created. This anomaly is removed by adding the structure of Ricardo's iron law of wages to the model.

Ricardo's iron law of wages links population growth to the wage bill and predicts that population would grow until wage rate equilibrates at a subsistence level (Ricardo 1817, ch 5). The wage bill divided by subsistence wage, therefore, returns the demographic capacity to supply labor. When this law is implemented in the face of fixed land creating diminishing marginal returns to land, each additional unit of output would require more extensive use of capital and labor. And, as labor growth rate declines in response to a wage bill constrained by a diminishing wage rate and the population comes to a balance, the production reaches a plateau where the wage bill drives the profits to zero while the marginal product of labor nears subsistence wage.

The last graph in Figure 10 shows the behavior of the model with both Ricardo's laws activated creating S-shaped growth profile. The wage rate rises at first and profits decline as the economy grows faster than the labor supply thus creating tightness in the labor market, but as marginal output declines while workforce continues to grow, a rising unemployment rate suppresses wage rate and it comes to a balance near the specified subsistence level. The profit (which subsumes land rents) grows after the initial dip caused by an increased wage bill, but it eventually declines to zero as the value of produce is all used up in paying the wage bill.

Forrester's elaboration of the classical concepts of limits

Thomas Malthus, a professor at East India Company College in his attempt to map world's resources and markets published ideas similar to Ricardo's almost simultaneously as Ricardo. He surmised that population growth by itself is not enough to bring economic advances. He felt that population growth is an *end product* in the economic growth process, rather than a means and posited that an increase in population cannot take place without a proportionate or nearly proportionate increase of wealth. Malthus later became concerned with what he described as population explosion and the scarcity of resources resulting from it, and expressed more or less similar ideas about procreation as Ricardo. The feedback relationship between population growth and economic growth is however more explicitly addressed by Ricardo through his iron law of wages and the principle of diminishing marginal rent to land as represented in Figure 9 than by Malthus in his Essay on Population (Malthus 1798) and in his Principles of Political Economy (Malthus 1921).

It is also not clear whether Malthus considered resources in the framework of fixed land, which does not get depleted or nonrenewable resources, which get depleted. Hypothetically, if a resource depletion process is activated in the Smith/Ricardo model as shown in Figure 11, an overshoot and decline behavior outlined in Forrester's World Dynamics is obtained as shown in graph 1 of Figure 12.

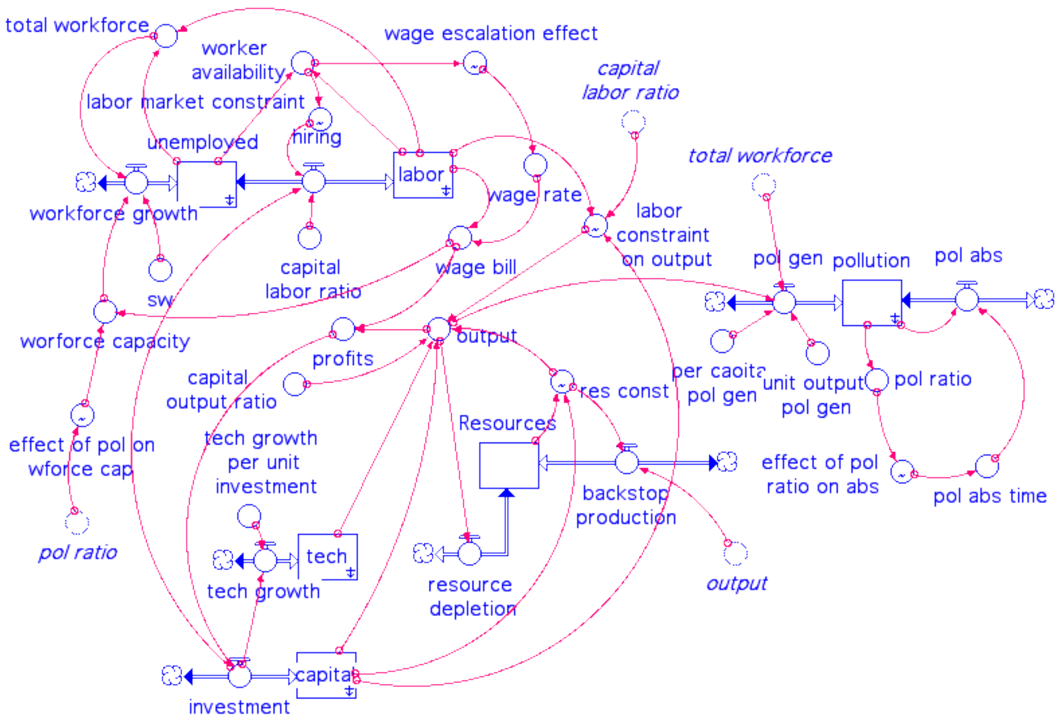

Figure 11 **Forrester's elaboration of constraints and Nordhaus's backstop production added to Smith/Ricardo/Malthus model**

Forrester has sometimes been accused of only replicating the Ricardian/Malthusian model, but he clearly has dealt with nonrenewable resources while the earlier thinkers seemed to be dealing with non-depleting land or renewable resources. However, as neoclassical economists were firmly entrenched in the concept of prices driving backstop production of resources, Forrester's model and the Limits study arising from it (Meadows et. al. 1974) created quite a controversy (Nordhaus 1973, Boyd 1972). When price-driven backstop production of resources is activated, in the model of Figure 11, growth can indeed be restored as shown in the third simulation of Figure 12. This controversy ignored one other important fact that Forrester outlined in his model - an endogenously generated environmental limitation. Rising output could poison our environment that would stifle the growth of workforce. When this additional structure is activated in the model of Figure 11, an overshoot and decline behavior shown in the remaining graph of Figure 12 appears even when material resources are still plentiful.

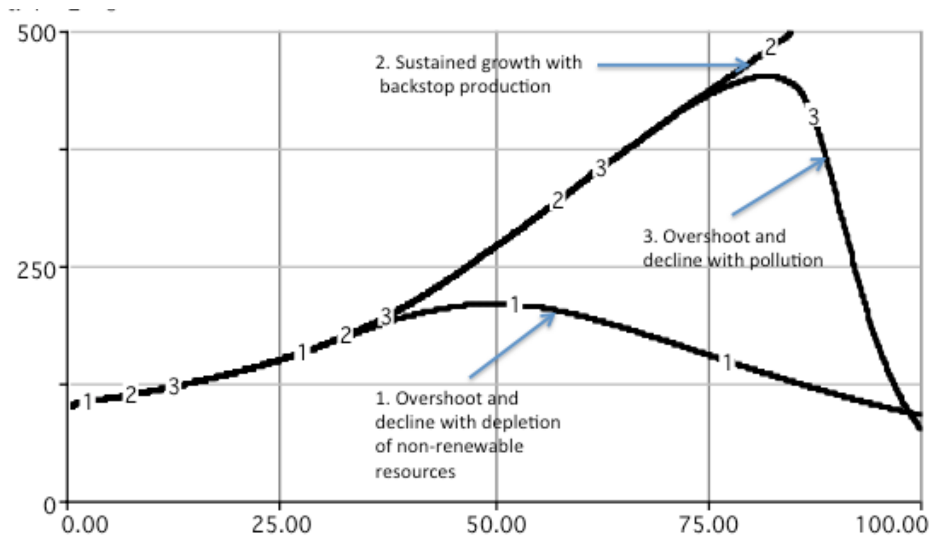

Figure 12 World dynamics like behavior obtained by extending the classical concepts to subsume depletion, backstop resource production and pollution.

Forrester's world dynamics thus rejects the prevailing microeconomic foundations of environmental economics and reconstructs its framework by extending the classical growth concepts. His model was however built from the informed concerns of the members of Club of Rome who sponsored the Limits to Growth Project not from classical economics and the two are tied together through their common foundation of the reality on ground. It, however, raises serious questions about the relevance of the microeconomics foundation of environmental economics. Unfortunately, environmental economics texts have not moved on from this arbitrary foundation, which the discipline adopted in its infancy. This baby needs to be thrown out with its murky bath water and Forrester's alternative model highlighting growth and its external and internal constraints adopted if we are to address the complex environmental problems of today.

National model as alternative macroeconomic theory

Most texts on macroeconomics start with an exposition of historical time series representing GDP, GDP growth rates, prices and unemployment rates. Then discuss the composition of national accounts and culminate into describing multiplier and acceleration processes, business cycle, the velocity of money, and government interventions in terms of expenditure, fiscal instruments and monetary controls, without ever connecting the fragments of theory to the historical trends the texts begin with (Sameulson and Nordhaus 2009, Barro 1997).

The term economic cycle has sometime been used interchangeably with business cycle, but the former refers to a wide range of periodic ups and downs superimposed on growth history, while the later usually implies a 5-7 year cyclical trends observed in market economies. Business cycle has traditionally been attributed to investment dynamics (Samuelson 1939), although as shown by Low (1980), capital formation lead times and capital output ratios existing in reality would in fact generate cycles of much longer periodicity. The real business cycle theory advanced by Lucas (1981) attempted to explain deviations from normal business cycle periodicity by attributing them to the rational responses of the economic actors to external events that might not appear to directly affect the periodicity.

Forrester could have attempted to combine the abstract fragments of macro- and micro-economic theories into a model and relax their limiting assumptions in his attempt to explain the historical trends. Indeed some of his students, including myself, went that route (N. Forrester 1982, Saeed 1980). Forrester, however, opted to extend his model of production process described in his Industrial Dynamics to explain macro-behavior. In this way, he once again set aside an abstract, albeit mainstream, theory and decided to build his model from the working of the production system containing realistic every day managerial decisions. The behavior of his model in fact succinctly explained the complex historical time pattern combining cycles of multiple periodicities given at the start of the macroeconomic texts. It identified three distinct cycles in the historical data, and expounded on the periodicity of each.

Historical records show that trends of multiple periodicities other than the short-term business cycle are quite pervasive in industrialized countries with free market economies that cannot be explained easily by external events or the chains of responses to them. Nobel Laureate economist Simon Kuznets discovered an 18-25 year cycle that is named after him while Nicholas Kondratieff observed a 50-70 years cycle, which now bears his name. Few theories exist to explain such long cycles. Growth trends experienced over the course of such cycles are often attributed to good economic management and good governance, while unfortunate events are blamed for declines (Forrester 1977, van Duijn 1977).

Some of the findings of the Forrester's National modeling project are documented in Mass (1975), Graham and Senge (1980) and a number of internal memoranda and Ph.D. theses listed in system dynamics literature archive that are available from the System Dynamics Society. Of particular interest among these memoranda are D-3573 by Graham (1984), D-2517-2 by Low and Mass (1980), D-3577 by Sterman (1984) and D-3712-1 also by Sterman (1985). Additionally, doctoral dissertations by Mass (1974), Low (1977), Runge (1976), Richmond (1979), Senge (1978) and Sterman (1981) address various aspects of the National Model. The findings of this extensive research led to unique causal explanations of endogenously generated short- and long- term economic cycles. According to these explanations, short term Business Cycles of 5-7 year periodicity are attributed to workforce adjustment policies, while Kuznets cycles of 18-25 periodicity are posited to arise from capital investment dynamics, and the Long Wave or the Kondratieff Cycle of 50-70 year periodicity from over-expansion of the capital goods production sector and the subsequent prevalence of underutilized infrastructure.

The National Model subsumed complex structure that could generate behavior simultaneously representing multiple modes creating by different segments of its structure. I am, however, of the view that complex behavior should be decomposed into its simpler components and simple models constructed to understand each component in our theory building effort (Saeed 1992). I will, therefore, outline three simple models I have built in my attempt to interpret separate slices of Forrester's behavioral theory underlying these patterns. These are based on the constructs found in the available public documents on the National Model. As I did not work on the National Model project, they should be seen as my interpretations of the public documents rather than the abstractions of Forrester's model.

A hypothetical steady state is a point of reference in the models I present rather than the disequilibrium under study. This steady state represents a dynamic equilibrium created by an internally consistent set of parameters for the homeostasis that is sought by the system but never achieved. This equilibrium is disturbed by changing a single parameter to invoke the search for a homeostasis that results in the disequilibrium pattern of interest, which is entirely endogenously generated and must be explained entirely in terms of the structure of the respective model.

A simple model of labor hiring process leading to Business Cycle

Since the 5-7 year business cycles could arise realistically only out of the relatively short lead times for hiring and firing workers in response to production needs created by unforeseen changes in aggregate demand, business cycle in the National Model was attributed to managerial responses to changes in demand that translated into production planning, inventory management and in particular workforce management.

The stock and flow structure of the production planning, inventory management and workforce management sectors is shown separately for clarity in Figure 13. Aggregate demand is computed as average desired production, which represents expected value of desired production arising from average shipments and the inventory and backlog discrepancies. Note that the term aggregate demand is not used in the model since it is not clearly identifiable, whereas average desired production is the identifiable entity that the producers are aware of. The inventory goal is in turn a function of average shipments and backlog goal a function of average production. This assumes that production should not only fulfill perceived stream of demand, it should also maintain an appropriate level of inventory that is able to cover unanticipated shocks. Additionally, there must exist an appropriate backlog of orders, which is an integration of incoming orders representing instantaneous demand and shipments representing instantaneous supply, so production resources are fully employed for a foreseeable future. Any changes in the three components of desired production will alter the aggregate demand as seen by the producers, even with fixed prices.

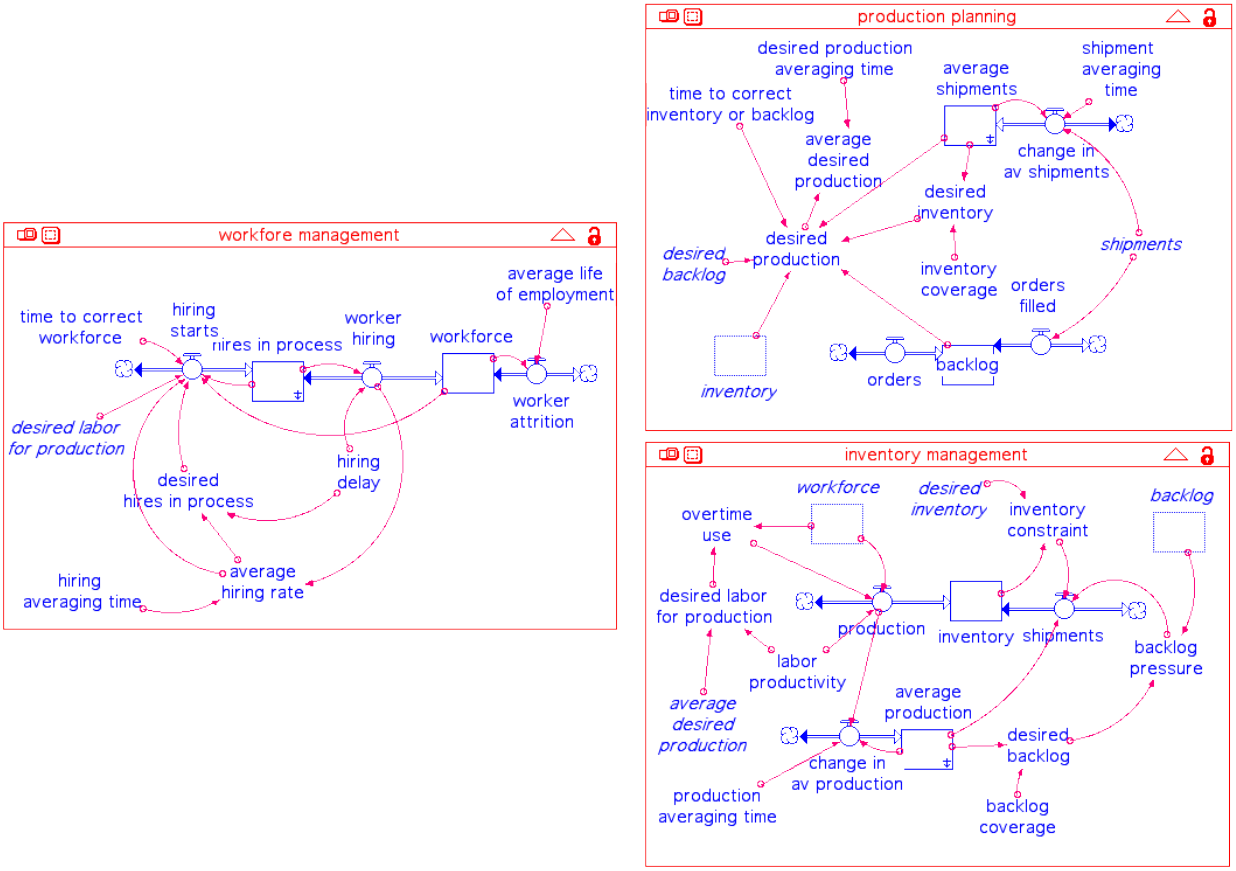

Figure 13: A simple model combining production planning, inventory management and workforce management

While inventory is an integration of production and shipments, production depends on workforce, overtime and labor productivity if we assume that the availability of capital as a production factor is completely elastic. Shipments on the other hand depend on how much is produced and the backlog of orders, since both are required for the sale to occur.

Hiring is driven in the first instance by the past hiring tradition that essentially balances attrition in equilibrium. It is further modulated by the discrepancy between exiting workforce and desired workforce merited by the desired production volume as well as by the discrepancy between the in-process pool and the needed in-process pool. This system is initialized in equilibrium, which is disturbed by an exogenous step change in demand. The resulting behavior completely represents endogenous dynamics shown in Figure 14.

The time constants of the hiring subsystem are relatively short. The delays involved in hiring are of the order of 6 months - 1 year, while the average length of employment is taken as 2.5 years.[5] Thus, the periodicity of the cycle generated by the workforce adjustment process and the responses of production planning and inventory management to changes in demand is of the order of 5 years.

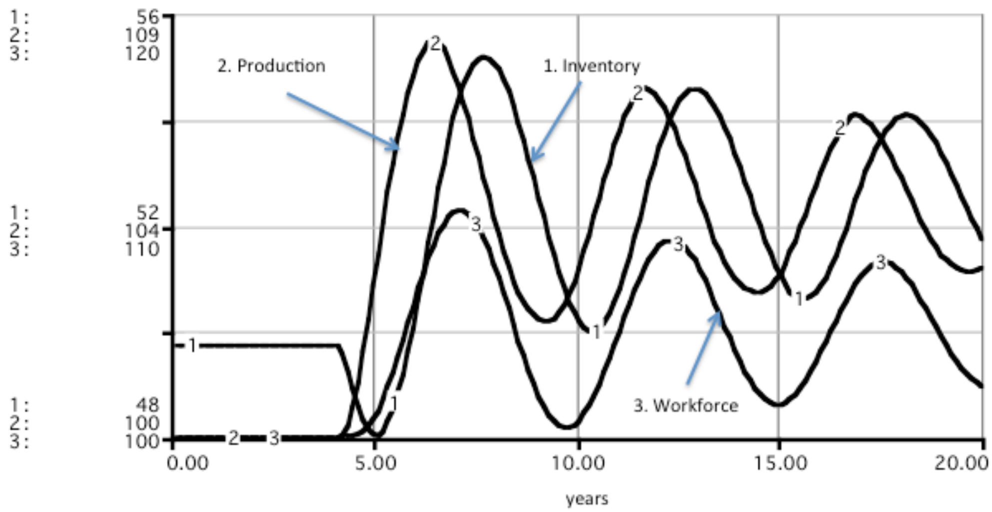

Figure 14: Business cycle periodicity generated by managerial actions involved with inventory management, production planning and workforce adjustment

A simple model of capital plant management process leading to Kuznet's cycle.

An economic cycle of periodicity ranging between 18-25 years observed in real estate sector and is sometimes held responsible for occasional deepening of the business cycle. Sometimes referred to as Kuznets cycle, it is attributed in the National Model to the interactions involved with managing investment into capital plant. Forrester postulated that this cycle arises out of mechanisms similar to those leading to the business cycle but since the capital ordering and formation lead times for durable capital are much longer (of the order of a few years) than those for adjusting workforce (of the order of several months), this cycle has a proportionately longer periodicity.

The management decisions pertaining to capital formation are shown in Figure 15. These decisions are linked to the production planning and inventory management sectors in the same way as workforce management was in Figure 13. The structure of the capital formation sector is similar to workforce management except the variables have different names and capital adjustment takes longer than labor adjustment. Also, while it is possible to lay off workers in the model of Figure 12, capital stock at the level of an economy stays in the system until it is retired through the depreciation process. Thus capital orders are adjusted through an implicit stock adjustment process based on assessment of adequacy of capital and capital on order rather than through directly considering the discrepancy between their current and desired values.

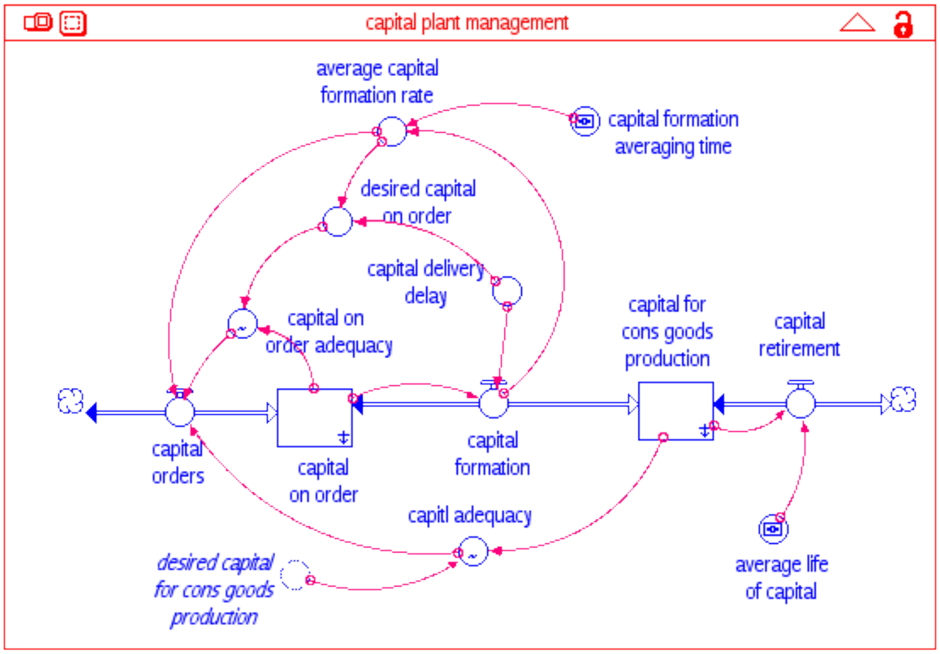

Figure 15: **The structure of capital investment decisions**

When demand is autonomously stepped up in this system, a cyclical trend of periodicity of about 25 years appears as shown in Figure 16, the exact periodicity being determined by the slopes of the adequacy functions. The delays in the expansion process lead to overexpansion of the capital and the subsequent piling up of inventories and depletion of backlog to an extended neglect of investment that creates recession much deeper and longer than in a business cycle.

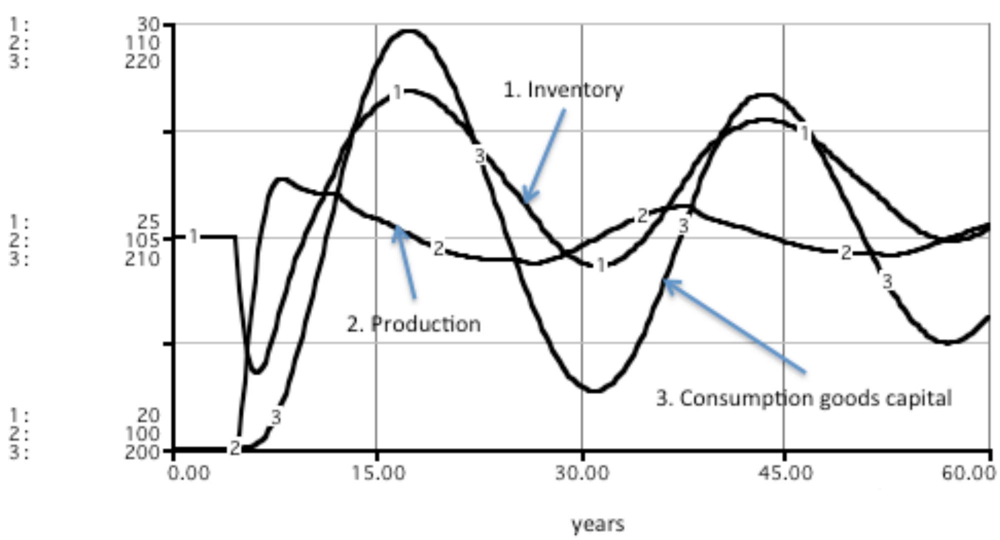

Figure 16: **A cyclical trend of about 25 year periodicity arising from interaction of capital investment decisions with Aggregate demand and supply sectors.**

A simple model of investment goods capital plant management process leading to Kondratieff cycle or long wave

A periodicity of 50-70 years observed by Nikolas Kondratieff is explained by Forrester as a function of the interaction between consumption goods and investment goods production sectors. When consumption goods production sector wants to create additional plant and equipment, it places orders for these on the investment goods production sector. When investment goods production sector has orders beyond its capacity to deliver, it must expand its own capacity before filling capital orders of the consumption goods sector. Thus it places additional orders to produce investment goods on itself that Forrester termed self-ordering.

Figure 17 shows the stock and flow structure of my simplified model of long wave. The fixed consumption goods capital sector is the same as in Figure 15 except that capital formation rate is constrained by the production of capital goods by the investment goods production sector in both consumption and investment goods sectors.

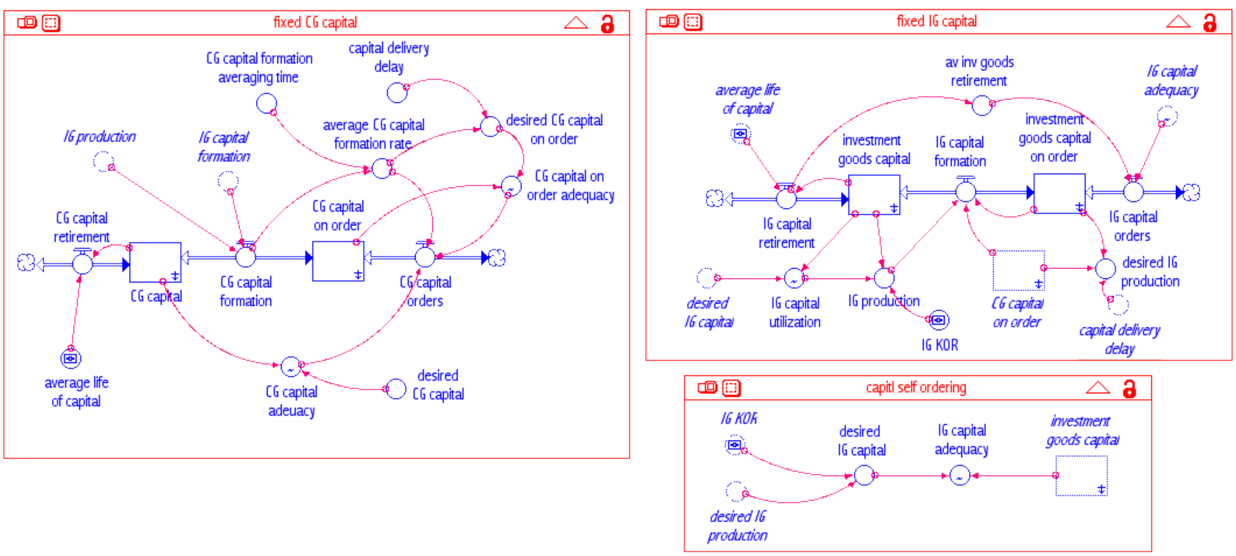

Figure 17 Creation of fixed investment goods capital and Capital self-ordering process

The structure of the fixed investment goods capital sector has a supply chain comparable to that of Figure 15 with some differences. First, the investment goods capital orders depend in equilibrium directly on its rate of retirement instead of an average of the past capital formation/hiring rates rate used in the models of respectively Kuznets and Business cycles, which are indirectly linked to the rate of capital retirement. This implies a less competitive and somewhat inward perspective that is typical of a rather specialized investment goods industry. Second, since, its specialized production is driven by orders and it often does not maintain an inventory, the investment goods on order must be seen as the investment goods sector's order backlog rather than a part of its capital supply line. Hence, it would need to produce more in response to capital on order rather than scaling down its orders as in the consumption goods sector whose capital on order is a part of its capital supply line. Last, its orders are driven both by the needs of the investment of the consumption goods sector as well as its own needs that create self-ordering. The desired capital in the investment goods sector therefore depends on desired investment goods production, which is a function of the summation of both investment goods on order for consumption goods production and those for investment goods production.

Figure 18 shows the behavior of total capital in the system (both for consumption goods production and capital goods production) in this model. Two cases are shown: Graph one assumes a capital life of 12 years, which generates a cycle with about 55 years periodicity. Graph 2 assumes a capital life of 15 years and generates a cycle with 70 years periodicity.

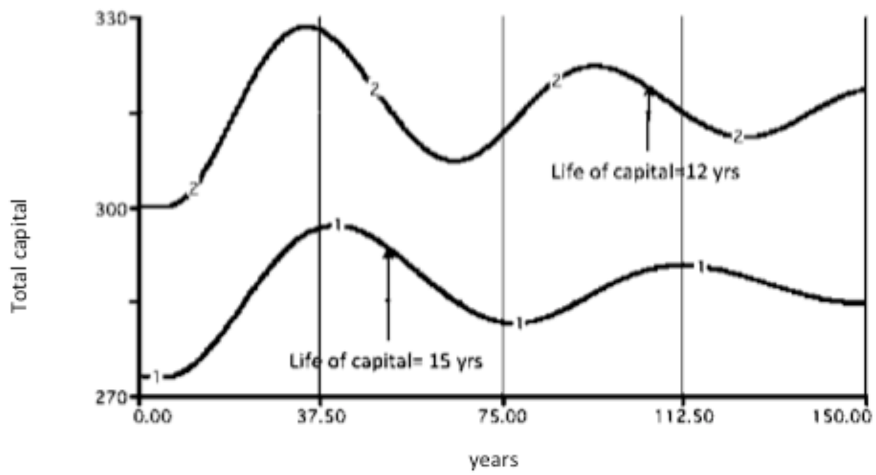

Figure 18 A cycle of 50-70 years (depending on durability of equipment) generated by overgrowth in capital stock through self-ordering process

The delays in delivery create over-ordering in the consumption goods sector. The self-ordering process of the capital goods sector, which defers deliveries to the consumption goods sector until the desired production capacity for capital goods has been achieved, further increases this over-ordering. Once the capital goods sector has achieved this capacity, its self-orders vanish even though its production capacity is enough to cater for both its self-orders and those from the consumption goods sector. Hence some of its capacity must lie idle. This also leads to speeding up clearance of the backlog of orders from the consumption goods sector, which in turn scales down its orders, which leads to further reduction of capacity utilization in the capital goods production sector. This spirals into creating a sustained down turn. The delivery lead times in this system are greatly affected by the durability of the capital since both replacement capital ordering and self-ordering are affected by the durability. It should be noted that this model excludes endogenous growth and decline processes that subsume the impact of worker lay offs from reduced capacity utilization on household income and demand.

Forrester's models of economic cycles thus provide a unique explanation of historically recorded macro-economic behavior in terms of the actions of managers working in their every day roles, without going into the abstract equilibrium growth concepts and variations on them that they have been attributed to in mainstream macroeconomics. It represents a true extension of microstructure to macro behavior that is necessary for designing any interventions for the management of a national economy. These models call for a complete rethink of the models macroeconomics, which have never been able to explain history and provide little help in managing an economy.

Conclusion

Through his development of system dynamics models for industry, urban management, global limits and national economic management Jay Forrester seems to have created a theory of economic behavior that is tied to how people go about making every day decisions in a bounded rational world. It therefore, perpetuates an alternative economic perspective that is poised to disrupt mainstream theory.

An alternative theory of firm is subsumed in his Industrial Dynamics Model, which replicates how managers act in a production system. An alternative economic development framework is subsumed in his Urban Dynamics model that dispenses with the developing-developed dichotomy by viewing the poor conditions in any economy as a manifestation of the composition of its households and infrastructure, aging infrastructure and underemployed household fraction alluding to low welfare homeostasis. It thus deviates from the usual economic development perspective that views developing countries as infant economies that need to be nurtured to grow rapidly. An alternative environmental economics perspective appears in World model that is not based on the mico-economic foundations proposed in environmental economics texts but on classical economic growth framework. Finally, his National model focuses on real and identifiable managerial interactions discussed in his alternative theory of firm subsumed in Industrial Dynamics to explain the periodicity of the economic cycles of various periodicities in terms of real time constants existing in the system.

Forrester's general theory is based on every day practice not on abstract concepts. It allows use of models for experimentation with every day decision rules for meeting goals of a firm, a city, a nation or global economy. Forrester's experiments do not create forecasts, but replicate past patterns and give outcomes of policy change. They can lead to finding operational interventions for improving the future. Thus, it can actually connect to practice, which should be the objective of economic science that its mainstream abstract theories fail to deliver.

Forrester rejects the concept of a rational economic agent who has perfect information and can consciously pursue abstract goals. He replaces abstract decision rules with actual decision-making process and creates models that can replicate observed economic patterns and yield policy design for change. He also does not hesitate to set aside traditional concepts in the contexts of specific problems like environment and development that economics addresses. His work indeed lays the foundation for a revolution in the field of economics.

The practice of economics has since subsumed many revisionist ideas including institutional and behavioral factors (Hodgeson 2004, Wilkinson and Klaes 2012), which have the potential to create an evolutionary change in the field. These innovations incrementally modify the existing foundation of the mainstream theory by subsuming learning, belief-related factors, rationality bounds and irrational psychological criteria into the actions of a rational agent rather than replacing him with ordinary role-players like managers. They also remain on the sidelines instead of becoming a part of mainstream economics; hence their use in economic management is limited. In a fireside chat held on July 24, 2013, Forrester wished to be remembered for having completely replaced mainstream economic theory with realistic models, which would indeed be a revolutionary change that has yet to happen.

Notes

1. A record of the presentation is available at: https://my.wpi.edu/webapps/cmsmain/webui/_xy-1036942_1?action=ittach

2. A video of this fireside chat is available at: http://echo360.wpi.edu/ess/echo/presentation/c5039a33-690e-440d-b77c-f023267c5429/media.m4v

3. See transcript of fireside chat with Forrester at: http://clexchange.org/ftp/newsletter/CLEx22.3.pdf#page=2

4. A little known attempt to model a slice of the ideas expressed by Adam Smith and David Ricardo, based on an interpretation by Heilbroner (1980), appears in a software guide published by High Performance Systems[1] to demonstrate how system dynamics modeling can capture and communicate the richness of the classical thought (High Performance Systems 1997). This example, however, seems to view the short run work-leisure trade off in the labor supply process as a long-term population growth process. Thus it rather explains relatively short-term work-leisure choice dynamics and not long-term limits that the classical theories attempted to address.

5. In the United Stated, where labor mobility is high, the median length of employment is 3-5 years. See, US bureau of labor statistics website 2012: http://www.bls.gov/news.release/tenure.t06.htm

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