2 METHODOLOGY FOR OPERATIONAL ECONOMICS

The intuitive and verifiable calculus of system dynamics

While many eminent economists have expressed disdain about the abstract nature of contemporary economic theory and how it is removed from reality, few offer a cogent solution to this problem. Jay Forrester, a control engineer turned economics researcher, proposed replacing the abstract economic concepts with manager-based constructs. He also aspired to replace differential equations with an intuitive integration process he invented that can be implemented on a digital computer. This *chapter* attempts to understand how economic theory separated from reality, and how modeling it, using Forrester's intuitive calculus can make it verifiable and operational.

The development of economics into a non-verifiable theory

Classical thinkers of economics addressed complex behavioral relationships encompassing the roles pertaining to the various operational aspects of production and consumption. They also recognized the information links between roles formed in this process and how they affected macroeconomic behavior. They albeit viewed the role players as ordinary people motivated by self-interest that drove their decisions. And they described the dynamics of the interaction between the various roles and how that would create a good life for all and thus benefit the society (1). Copious narratives were needed to describe the dynamics as can be seen in Adam Smith's Wealth of Nations (2), Mill's Principles of Political Economy (3), and Marx's Capital (4).

The classical thinkers of course made implicit assumptions about social norms, like ownership and bargaining positions of the various actors (5) (6), but nowhere in their thought process appeared the assumptions of perfect information and rational agency which are the pivotal concepts underlying contemporary economic theory. Their description of the dynamics entailed articulating the feedback processes in the economic systems that created growth, limits, decline and instability, but their explicit representation was missing and the analogy of the invisible hand came handy for rationalizing macro-behavior arising out of the micro-structure of roles when words could not adequately describe the deductive logic (7).

The contemporary economic models are built around a hypothetical world of rational agency and perfect information. They are often described in mathematical language. Unfortunately, their logic cannot be verified in real world where managers working with limited information are the role players, not the rational agents acting upon perfect information. As I have discussed in (7), many scholars have pointed to the degeneration of economic theory into a non-verifiable model, but without pointing to how this progression happened and how the theory can be reformed.

How use of differential equations thwarted verification process?

As mathematics began to be used to explore surmised concepts, not only differential equations and graphical representations began to supplement narrative, the use of the precise but limited language of mathematics also led to making additional implicit assumptions. The role structure and its eventual outcomes could be conveniently merged for the sake of mathematical expediency, which gave birth to the concepts of rational agency and perfect information. Calculus became the ubiquitous language of economics. However, since the differentiation process and hence the structure of differential equations could not be verified in reality, verification was often sidetracked and economics developed into an abstract theory which we teach like a physics of social systems, with one caveat: It has greatly diverged from reality. This caveat is often conveniently rejected by ruling that the reality (the market) has imperfections, although the reality is a fact and a model, if it is to be valid, must attempt to conform to that fact.

How feedback became invisible hand?

The concept of feedback is central to economics. In the context of growth, it manifests in spiraling processes such as multiplier and acceleration effects built into the growth models. In the context of adjustment towards a goal, it is implicit in models explaining market clearing, oscillations as in business cycles, and dynamic equilibrium as in Mill's stationary state. It is however rarely referred to as feedback. Instead, classical writings used copious narratives to show how a market could create benefit for all through iterative actions of selfish individual actors. The feedback process was vaguely alluded to as an invisible hand – a term that caught on. When the use of mathematics called for merging the iterative individual actions and their outcomes, and the abstract concept of a rational agent emerged, the explicit recognition of the feedback that created rational outcomes from bounded rational actions was further pushed into obscurity.

The so-called positive economic theory is divided into two main silos namely the price theory (microeconomics) and the growth theory (macroeconomics). The former copiously refers to the negative feedbacks that clear the markets and maintain a balance between the supply and the demand without clearly describing them. The later alludes to the gain of the positive feedback that creates growth while still evading the term. Both silos concede to the invisible hand when narrative, graphics and mathematics get wooly.

Indeed, while the concept of feedback in social and economic systems has existed for a long time (8), its explicit representation has been lacking. Even when we use the precise language of mathematics, the solution of a differential equation is a function of parameters and time, while the existence of feedback in a system of differential equation is not intuitively recognizable but must be inferred from what is called *eigen values* – an array obtained by complex manipulation of coefficients of the system of differential equations defining the system. A system of differential equations may or may not contain any feedback loops, but we never know this unless we are able to interpret their *eigen value* matric which calls for considerable mathematical acumen. Hence, a gulf emerged between domain experts who created and understood theory and policy makers and managers who relied on common sense.

How lead times, perceptions, and expectations further mystified theory?

Contemporary economics recognizes that the information we act on is created not by an instantaneous recognition of actual conditions but by our perceptions and expectations of those conditions (9). Complex narratives and mathematical formulations have been used to represent expectation formation with a common element: they all use functions of past streams of information even when they forecast what is to come. These expectations then propel changes in demand. They also drive the expected return on investment that drive the supply decisions. Contemporary economics also recognizes the operational time lags between the decisions made on basis of expectations and the actual realization of changes in the supply due to the manufacturing, shipment, and construction delays.

The addition of perceptual and operational lags into the mathematical system however further mystified economic theory as it incorporated complex computational processes for representing them. Last, while aging chains in capital plant and equipment were recognized by Joseph Schumpeter (10), who suggested that the periodic replacement of old capital will lead to cyclical appearance of what he called creative destruction, they are rarely included in the textbook economics, possibly also because of the additional mathematical complexity they add to the model, although they underlie the multiple equilibria so pervasive in the economic systems around us.

The verifiable calculus of system dynamics and how it can operationalize economics.

Since reality integrates over time, a logic that captures this integration process can be easily discerned from reality and also compared to it. Thus, capturing the integration process as it happens over time would allow us to construct ? models. However, if we were to replace the differential calculus with a process that replicated integration over time, the computational detail of it would be very tedious and you will definitely need a digital computer to carry out the integration in the system so surmised. Digital computers of course did not exist when the elegant art of calculus was created. Now that we have computers that can perform the tedious computations, why not adopt a realistic integration format that can be verified and also intuitively understood?

In 2013, I had the privilege of conducting a public conversation with Jay Forrester, at the 31st international conference of the system dynamics society. Jay was 95 at the time of the interview. My concluding question to Forrester was about his legacy. *Ad verbatim*: *Jay, what do you think you'll be known for in about 20 years?*

I expected Jay to at least mention his key inventions like the random-access memory, the radar controllers, and the Whirlwind computer, but I was surprised by his response, also reproduced *ad verbatim* below:

That's much too short a time. I would rather talk about what I would be remembered for 50 or 80 years from now. Because the whole future, the possibilities of system dynamics are so huge that it's going to take a very long time for the main part of it to take shape.

Just for example, one thing that we should look forward to is a replacement of differential equations in the engineering and the social sciences. Differential equations have been the fundamental way of dealing with dynamics. It is terribly misleading. It causes a great deal of harm. And the reasons for this, mathematicians have had some difficulty defining a derivative. And there is a reason. There is no such thing. Nowhere in engineering, science, cultural theories, nowhere in the real world is a derivative taken. Nature only integrates. Nature only accumulates. And as soon as you approach it from that point, any child who can fill a water glass or take toys away from a playmate knows what accumulation is. So, they can move into complex systems and never discover that they're difficult.

I had two doctoral students from our department of electrical engineering and computer science. They'd had all of the math and all the theory about all the state physics. They came over. And they built a system dynamics model of one or two levels about what was going on in the electron cloud at the contact point of a transistor. They said it was the first time they had ever understood what was happening. The differential equations had completely obscured the reality of what was going on. I have had MIT students argue aggressively with me that the water flows out of the faucet because the water in the glass is rising. That's what the differential equation says. It causes a reverse sense of causality in many students. It totally obscures the dynamics in most for the others.

So, I would like to be known for having thrown out differential equations in all fields. This is not going to be over the next 50 years. And I would like to be known for having completely replaced economics, and that's not going to be in 25 years either. There are a few others, but that's enough for now. (11)

Replacing differential equations in economics with logic mimicking how integration actually happens does call for reverting also the abstract economic theory into easily understood and verifiable classical concepts explaining how economic behavior arises from every day managerial roles. This transformation can create economic policy recommendations informing management of operations instead of replacing the imperfect reality with the theoretical perfect market, which is often recommended in policies arising out of a non-verifiable abstract theory.

It should be granted that explicit representation of stocks and flows as bathtubs, faucets and drains requires oodles of repetitive numerical computations, which was tedious given the available mechanical devices like slide rules and abacuses. Professor Philips attempted to create an analogue representation of stocks and flows in his infamous machine (12), but that was cumbersome too. The abstract art of calculus together with equally abstract graphs and verbiage continued to reign for addressing feedback complexity in models of economics.

An alternative approach to calculus, the system dynamics method, was created by Jay Forrester, after he was appointed to the faculty of MIT Sloan School of Management to create a learning process for management (13). He proposed another format for writing a system of differential equations that is intuitive, verifiable and can be implemented on modern computers. Theories built using this format may not be abstract as they can be verified because the structure of decisions taken by the actors in the model corresponds to how decisions are made in real life. Also, when theories entail feedback loops, those loops can be explicitly visualized.

Several problems have been identified with mapping Forrester's stock and flow structure to feedback loops (14), but in my observation, these arise out of misunderstanding the relationship between the two that was painstakingly explained by Forrester in his early writings using hierarchical graphics that can now be generated easily by software like Stella. The feedback/stock-flow hierarchy is explained later in this chapter but let us first assure we understand how differential equations may be transformed into a verifiable format.

Transforming differential equations into verifiable format

Consider a simple ordinary differential equation representing population growth process:

$$d(P)/dt = P_t*(\text{birth fraction} - \text{death fraction}), \text{ where P is population} \qquad (1)$$

using formal calculus, we can arrive at a global solution that will give the value of population at all points in time in terms of its initial value, birth fraction, death fraction and time, as given in the following equation:

$$P_t = P_0 *e^{(\text{birth fraction} - \text{death fraction})\, t}$$

If you know what function *e* is, you could even visualize the pattern of change, but the solution tells little about how the dynamic growth process proceeds.

The differential equation in (1) can however be rewritten as:

$$[P(t) - P(t - dt)]/dt = P(t)*(\text{birth fraction} - \text{death fraction})$$

$$\text{or, } P(t) - P(t - dt) = P(t)*(\text{birth fraction} - \text{death fraction})*dt$$

$$\text{or, } P(t) = P(t - dt) + (\text{births} - \text{deaths}) * dt \qquad (2)$$

Now, while equations 1 and 2 embody exactly the same logic, the former uses variables that do not directly correspond to the system they describe. The rate of change on the left-hand side cannot be calculated without having observed population stock over some length of time. Likewise, birth and death fractions are *ex post* calculations that require knowing both population stock and its rate of change. The variables in equation (1) do not have direct equivalents in the system and hence the verification of this system is difficult. As for change over time, reality integrates and equation (2) intuitively captures this integration process, granted, the computations needed to carry it out would be dreary.

Fortunately, digital computers were already available back in the 1950s that could handle the dreary number crunching for these computations. Note also that when equations are written in the form mimicking the integration process, comparison to reality and verification of structure and parameters become easier. All variables and parameters in this representation would have real world counterparts and they could be measured independently of the model they are used in. Population, births and deaths information would be available from a town's records and could be aggregated to suit the level of aggregation of the model (15). The integration problem is reduced to the simple but repetitive calculation of flows and updating stocks after small increments of time.

Forrester's associates devised a language called SIMPLE that later transformed into a more capable version called DYNAMO with non-formal protocol (meaning equations could be written in any sequence) that put the newly available computing power to work for carrying out the repetitive calculations. The computational task performed by the computer is illustrated in Figure 1.

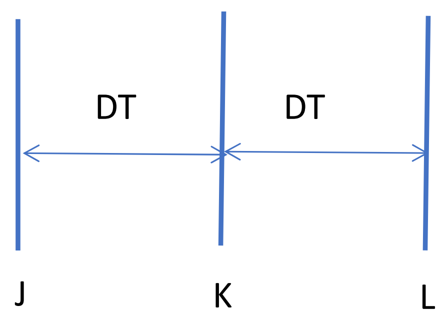


Figure 1 **Computation process for numerical simulation of stock and flow equations**

Numerical values of each variable were retained in the computer's memory registers for three time- instants: past, current and future, designated as J, K and L. Starting from the initial values of stocks at time K, flows for the period KL were calculated based on changes between instants J and K. The stocks were then updated, and the memory registers moved forward a time instant, K becoming J and L becoming K.

This memory thrifty process was ideal for the computers of the time. Remember, the first commercial IBM mainframe had a random-access memory (RAM) of only 8 KB. And the first computer built by Forrester had a RAM of only 8 bytes. More importantly, the nonformal protocol languages SIMPLE and DYNAMO extended the use of computers to a large audience outside of a very select group of computer programmers.

Graphical representation of the verifiable calculus of system dynamics

Forrester and his associates also devised several icons and connections to graphically represent the stock and flow structure. Those icons and connections have been subsumed into the modern software. Figure 2 shows the icons and the processes they represent in a typical system dynamics model constructed with widely used software like STELLA, VENSIM or POWERSIM.

A rectangle represents a stock that integrates the flows connected to it. A flow is a rate of change associated with that stock which may have multiple flows connected to it. These two types of variables are the basic components of plumbing implicit in economic theory, some part of which Professor Phillips attempted to represent with an analogue hydraulic machine. Information links from stocks to flows signify information driving the policies or rules delivering decisions. Intermediate computations transforming information in stocks into decision rules are represented by the converter symbol. A converter is an algebraic function of stocks, other converters, and constant parameters. Intermediate computations often involve using nonlinear relationships between variables. Instead of using complex mathematical functions to formulate such relationships, the software allows it to be specified as a graph between two variables, the icon for which is a special converter with a tilde added to it.

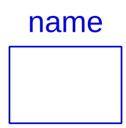
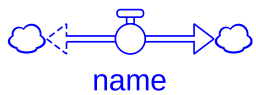
Process	Icon	Explanation
Stock		Accumulation or integration of flows linked to the icon
Flow		A rate of change or a derivative of a stock. Empty arrowhead indicates normal direction of flow. Normally connected to a stock. Cloud at one end represents unlimited source or sink
Converter		Algebraic function of stocks, other converters, and constants
Graphical function		Graphically represented function of another variable in the system
Causal link		Information relationship between two variables

Figure 2 **Diagramming tools for graphical representation of stock and flow equations**

The model equations corresponding to the icons in Figure 2 were originally written in SIMPLE and DYNAMO as shown in Figure 3.

The leftmost field specified the equation type which was separated from the equation by a blank field. The letter L (for level) designated the stock equation, and the letter R (for rate) designated the flow equation. N type equations were used to represent initial values of stocks (and sometime also of other variables). C type equations represented constants, and A (for auxiliary) represented converters. A special type of auxiliaries could be used to represent graphical relationships that were specified in two lines of code. The first line gave the names of the abscissa and the ordinate, and also the minimum and the maximum values of the abscissa and the separation between its values. The second line, designated by letter T, gave the values of the ordinate corresponding to each value of the abscissa. Finally, NOTE in the first column allowed the modeler to insert any text like variable definition, equation cluster name, units of the equation or even just a space.

L	STOCK.K = STOCK.J + DT * (IN.JK -OUT.JK)	(STOCK in Figure 2.2)
N	STOCKN = Initial value of stock	(FLOW in Figure 2.2)
R	IN.KL = f_1(STOCKS, PARAMETERS)	
R	OUT.KL = f_2(STOCKS, PARAMETERS)	
C	CONSTANT PARAMETER	(CONVERTER in Figure 2.2)
A	AUXILIARY	
A	GRAPH.K = TABHL(ABSISSA.K, ORDINATE, 0, 2,.5)	(GRAPHICAL FUNCTION in Figure 2.2)
T	ORDINATE = 0/.2/1/1.8/2	
NOTE		

Figure 3 **Equations corresponding to the graphical symbols in Figure 2**

The software now used allows construction of the stock and flow structure of the model using icons. Once a model the been constructed using this graphical representation, the software allows the modeler to specify initial values of stocks, constant parameters, algebraic functions, and graphical relationships that define each stock, flow, and converter. Nonquantifiable variables are often represented by indices that are normalized with respect to a given ambient condition. The population growth system of equation 2 could thus be mapped into this representation as shown in Figure 4:

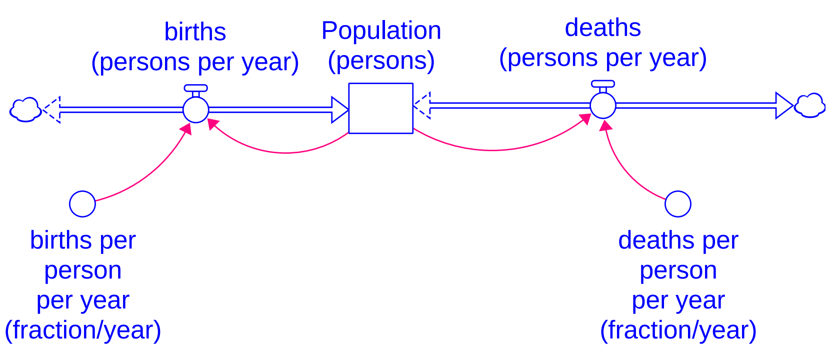


Figure 4 **Stock and flow representation of equation (2)**

Its equations generated by the software after algebraic relationships have been defined would appear as follows:

Population(t) = Population(t - dt) + (births - deaths) * dt

INIT Population = 100

INFLOWS:

births = Population*fractional_birth_rate

OUTFLOWS:

deaths = Population*Fractional_death_rate

fractional_birth_rate = 0.05

Fractional_death_rate = .02

Note the subscripts J and K are replaced by (t-dt) and t, as in standard calculus notation, and the subscript L has been dropped. Also, variable names can be elaborated, the software constructs stock equations and lists flow equation following each stock. The letters designating type in the first column has been dropped. More importantly, a strict correspondence between the stock/flow diagram and equations is assured. When the two were created separately, there often appeared discrepancies between them no matter how careful you were.

Reinstating feedback loops for invisible hand

The term system dynamics and the related concepts of feedback control originated in the engineering domain. They concerned the behavior of innate mechanism used to maintain controlled conditions like position, speed, direction, frequency, brightness, sound volume, etc. The adjustment processes in these mechanisms were driven by iterative corrective actions determined by the discrepancy from goal termed error. The use of discrepancy to drive adjustment processes created characteristic problems like steady state error, instability and sluggish adjustment. These problems were corrected by combining control processes that created coupled feedback loops driven by multiple functions of the error, typically, the proportional (P), the integral (I) and the derivative (D) functions were combined to achieve fast adjustment to goal without instability. Forrester transferred these concepts to social systems. With my own undergraduate training in electrical engineering, I was fascinated when I rediscovered the term system dynamics in a course on operations research (16) in the context of human systems. It showed me how to represent invisible relationships that drive decisions in organizations and create an experimental process to find ways to overcome problematic behavior.

It should be recognized that feedback maps and the stock/diagrams representing the computational process have different levels of aggregation. Forrester highlighted in his principles of systems that a feedback loop must involve one or more *stocks*, which also implies the level of aggregation of a feedback map can vary. Engineers devised the block diagrams of integrators to represent feedback control process in engineering systems, but these integrators lose sight of the discernable plumbing of stocks and flows (17), thus also becoming a step removed from an intuitive and verifiable representation of the system. Explaining feedback existing in systems of differential equations is even harder as stocks become implicit and the feedback process must be inferred from abstract eigenvalue metrics, i.e., if you are a math wizard . No wonder descriptions of feedback existing in constructs described by differential equations ranges between rare and hazy.

Representing feedback in a computable stock/flow model

Mapping a stock and flow map to causal feedback diagram offers many problems even in system dynamics (14), since the two representations are maps of different but related characterizations of the system structure (18). The feedback map articulates the understanding of the behavior as it arises from structure; the stock and flow structure creates a computable model whose behavior can be obtained through computer simulation. Unfortunately, the relationship between the two is often left to intuition that can lead to multiple interpretations of the behavior of a stock and flow model, which negates the requirement of uniqueness of a theory. The extended use of the two representations in isolation from one another has even led to a separation between system thinking and system dynamics. The former is limited to qualitative explanations and the later focused on computer simulation, although the two must go hand in hand (19).

The two representations must be seen as different views of the system and the relationship between the two must be clearly delineated. A stock/flow model is an intuitive representation of the integration process carried out by the computer, while the feedback map is a mental model of the aggregate *information* relationships explaining system behavior. Thus, in a computer model of the integration process, the feedback diagram must show relationships between clusters of the stock/flow structure rather than between each element of it. And the relationship between the two must be unique and easily discernable.

The relationship between a feedback map and computable stock/flow model can be illustrated by programing a one stock model using the hierarchy in Stella software. Figure 5 showes a simplified version of the population model of Figure 4.

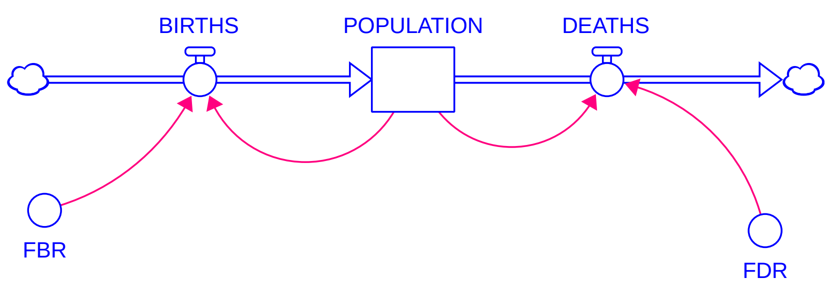


Figure 5 **Stock/flow structure of the simple population growth model.**

The inflow in Figure 5 has an information link going from population to births, but it designates a policy that computes a flow into the stock. It creates a feedback effect, but not an information path a feedback loop must represent. The feedback effect associated with the outflow is even more confusing. An information link connects the stock to the policy, but the outflow it creates does not even give the appearance of feedback in view of the direction of the outflow. Forrester talks briefly about feedback loops in Chapter 4 of Principles of Systems (18). The two relevant principle he states are summarized below:

Principle 4.2-1. Decisions always occur within feedback loops.

Every decision is made within a feedback loop. The decision controls action which alters the system levels which influence the decision. A decision can of course affect multiple feedback loops.

Principle 4.2-2. Feedback loop — the structural element of systems

The feedback loop is the basic structural element in systems. Dynamic behavior is generated by feedback. The more complex systems are assemblies of interacting feedback loops.

Principle 4.2-1 describes, how stocks affect flows creating iterative adjustments, while principle 4.2-2 ties behavior to feedback structure embodied in the information network connecting clusters of stocks and flows. Both must be kept in view for explaining behavior and its contingencies. Forrester never intended the two to be separated, but the separation arose possibly out of the software limitations to connect the two.

In my interpretation, Forrester construed feedback loop as an information relationship that is the basic building block of the system, not as a part of the computable stock and flow structure but as a relationship between clusters of structure. Let me illustrate this point by reconstructing the simple population growth model of Figure 1as a hierarchy between information relationships and computable stock/flow structure.

Let us construct population, births and deaths as three separate computation sets represented in the stock/flow diagrams if Figure 2 parts a, b and c.

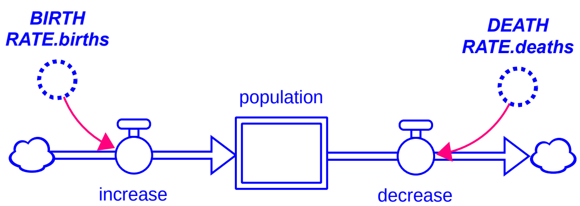


Figure 6(a): Module representing population stock and its associated flows

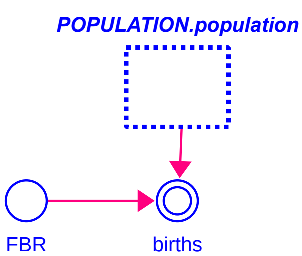


Figure 6(b): Module computing births

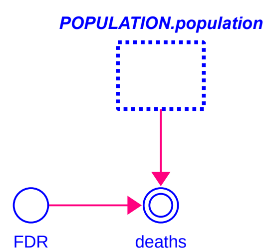


Figure 6(c): Module computing death

Figure 6 Population model reprogrammed using module/stock flow hierarchy.

Now, when the structure of the diagrams in Figure 2(a), 2(b) and 2(c) is placed in different modules, the top layer showing information relationships between modules will generate a feedback map making no distinction between computable elements of the model. It will display the feedback loops entirely created by information links as shown in Figure 3. The information feedback that exists between clusters of the computable stock/flow sub-models is shown as the relationship between the modules containing those clusters.

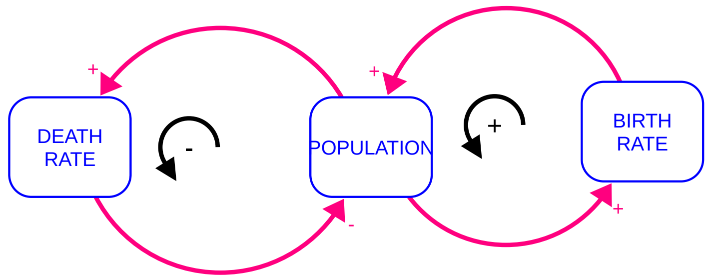


Figure 7 **Information relationships in the simple population model generated in the top layer of Stella**

Another simple example is a simple CO2 cycle model shown in Figure 8. It contains a draining process driven by a goal seeking negative feedback loop and a tipping point structure driven by a positive feedback loop containing a nonlinear relationship. The nonlinearity results in two equilibria, one of them unstable, which creates a tipping point making the efficacy of policy interventions path dependent. Yet, these feedback loops are not evident in this map and must be left to imagination. However, when the flows, the stock and the overload condition are represented by separate modules containing computable clusters of icons for each as shown in Figure 9, the information relationships between them clearly generate the coupled feedback loops shown as the module map of Figure 10 that explain the behavior of this system.

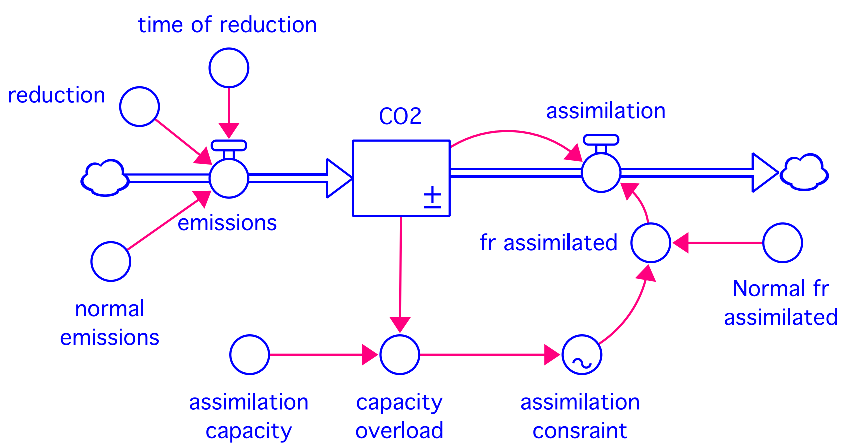


Figure 8 **Simple CO2 cycle model**

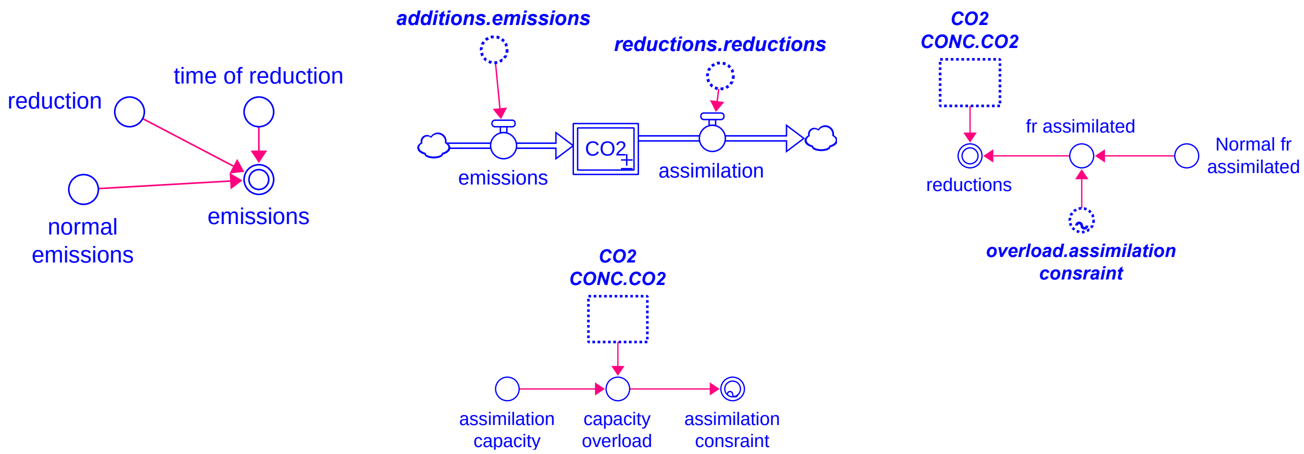


Figure 9 **Modules for inflow, stock, outflow, and overload in the simple carbon cycle model**

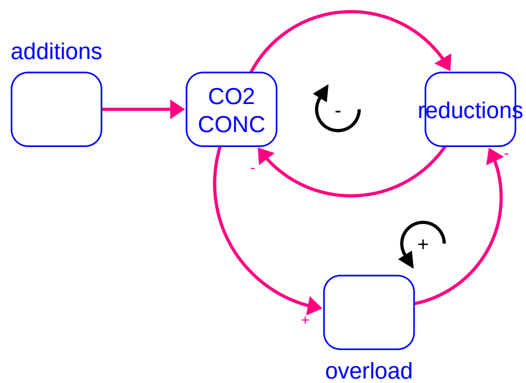


Figure 10 **Module map giving feedback relationships between computable clusters of Figure 5**

A feature in Stella allows you to place signs on the information links in the stock/flow model, which I think is anomalous since this diagram does not define feedback loops as *information relationships* that Forrester surmised. Designating polarity makes sense only in the feedback loops shown in the map layer of the software.

Forrester's pioneering use of feedback/stock-flow hierarchy

Forrester recognized the hierarchy between feedback loops and computable stock/flow structure from the inception of his modeling practice and it appeared both in his hand-drawn diagrams and the equation clusters of his models. Figure 7a shows an original diagram Forrester created to articulate the feedback structure of his market growth model (20). His feedback map represented relationship between subsystems of his model, each consisting of computable stock/flow structure. Figure 7b shows the top layer of Forrester's market growth model I programmed using the module hierarchy in Stella software. Each variable in this top layer is an aggregate representation of its underlying computable subsystem. Through this hierarchical relationship, it becomes possible to unambiguously tie the feedback map with the stock/flow structure.

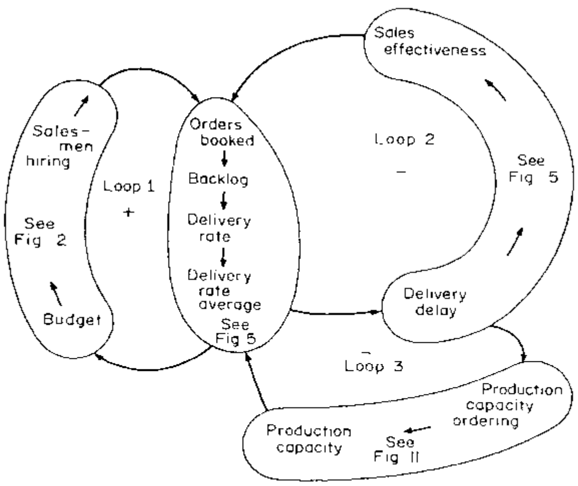


Figure 11a: Feedback loops connecting Subsystems in Forrester's market growth model.
Source: (20)

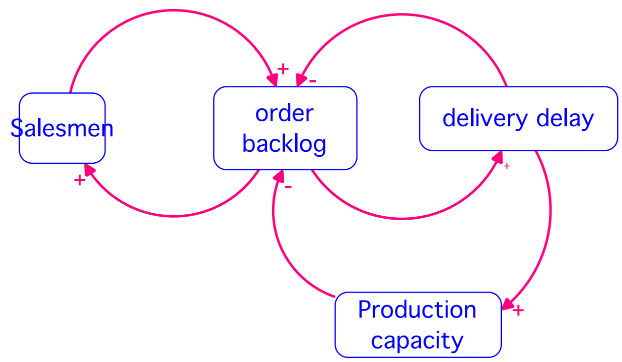


Figure 11b: Sector map created in the top layer of Forrester's model programmed in Stella software. Each module in this layer is linked with its respective stock/flow structure.

(Forrester's model reprogrammed by the author

Figure 11 Feedback map representation between model sectors in Forrester's Market Growth model

Articulating the relationship between the feedback map and the computable model was a challenge when our software presented models in flatland, but the possibility to create hierarchical views has made it possible to relate the aggregate feedback map of model sectors to detailed stock and flow structure, which is of great value for organizing the model as well as explaining its behavior.

Figure 8 shows the stocks, flows and other icons, and the information links connecting them within each aggregate variable in Forrester's feedback map shown in Figure 7. Forrester is quite clear about what each representation means and how are the two intertwine. Stocks and flows are parts of the computable model of the system, while feedback loops are formed by information relationships between the clusters of computations in this model, and they create the dynamic behavior arising out of the system. He surmised the more complex systems to be assemblies of interacting feedback loops (18). Without the benefit of having an explicit way to represent the relationship between feedback loops and the stock and flow structure, he organized his model equations into clusters that were connected by information feedback.

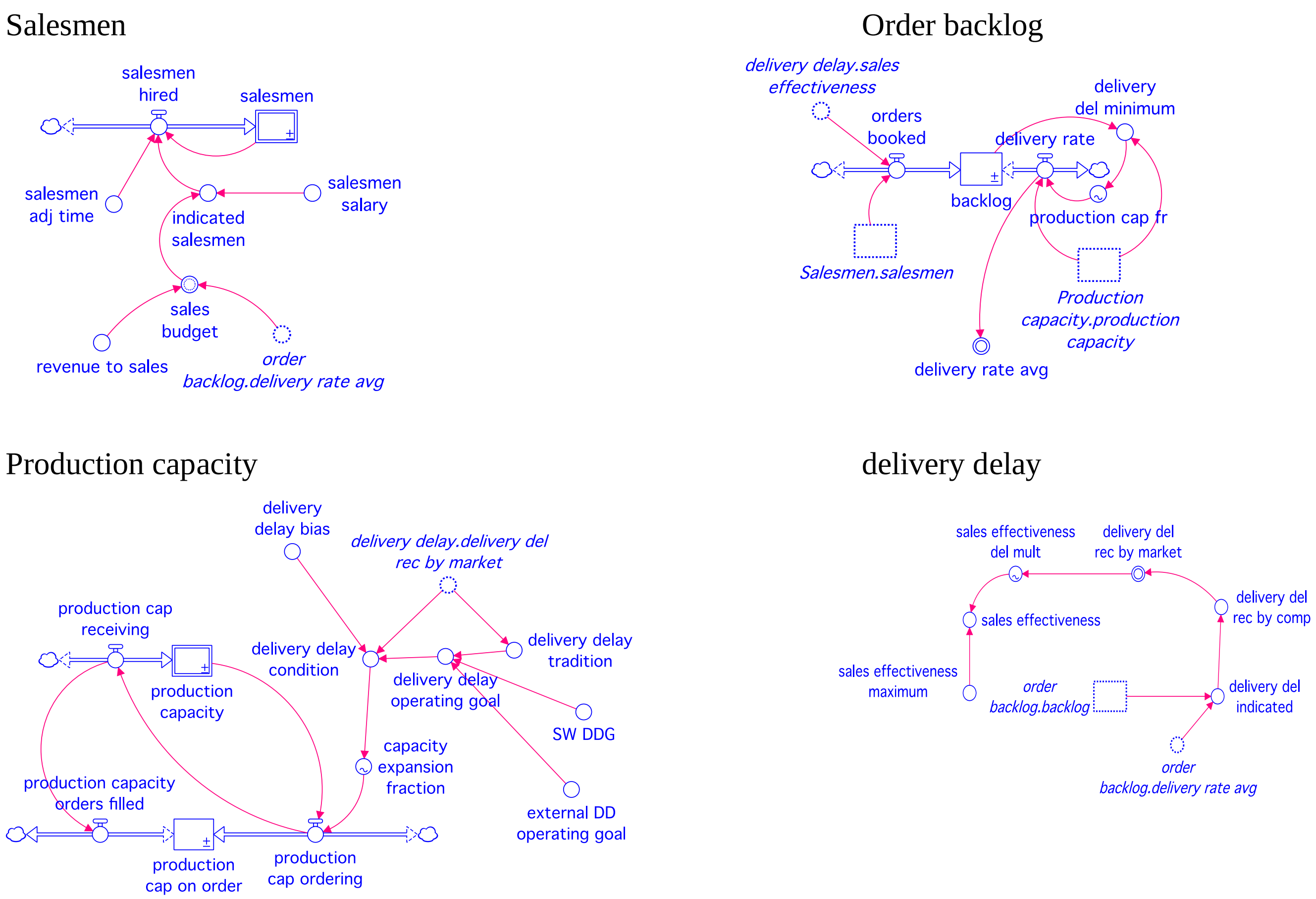


Figure 12 **Stock and flow structure underlying the feedback maps of Figure 7**

As Forrester's models grew bigger, the feedback maps representation became less explicit, perhaps due to software limitations. For example, Forrester explains the behavior of his model in his World Dynamics (21) book using narrative alluding to the feedback relationships shown in Figure 9, which is not coincidental. This map appeared when I programmed his world3 DYNAMO equation clusters into modules in Stella software.

The aggregate feedback organization, although not as explicitly stated as in his market growth model, was now implicit in the way he organized the Worls3 model equations into sectors. This organization came from his dynamic hypothesis whose variables were aggregates of his model sectors each containing computable stock/flow structure.

The stock and flow structure residing in each module constructed from Forrester's equation clusters is shown in Figure 10.

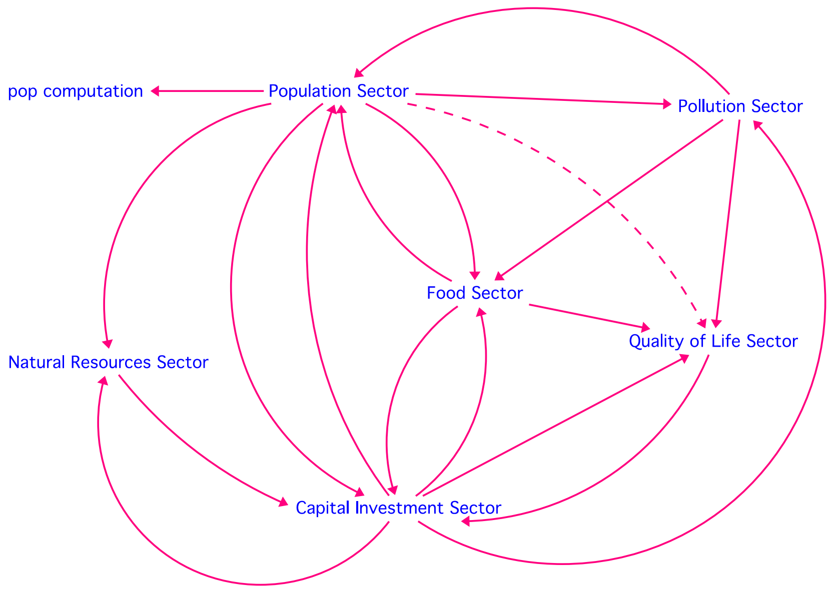


Figure 13 **Top layer feedback map of Forrester's World3 model sectors programmed into modules**

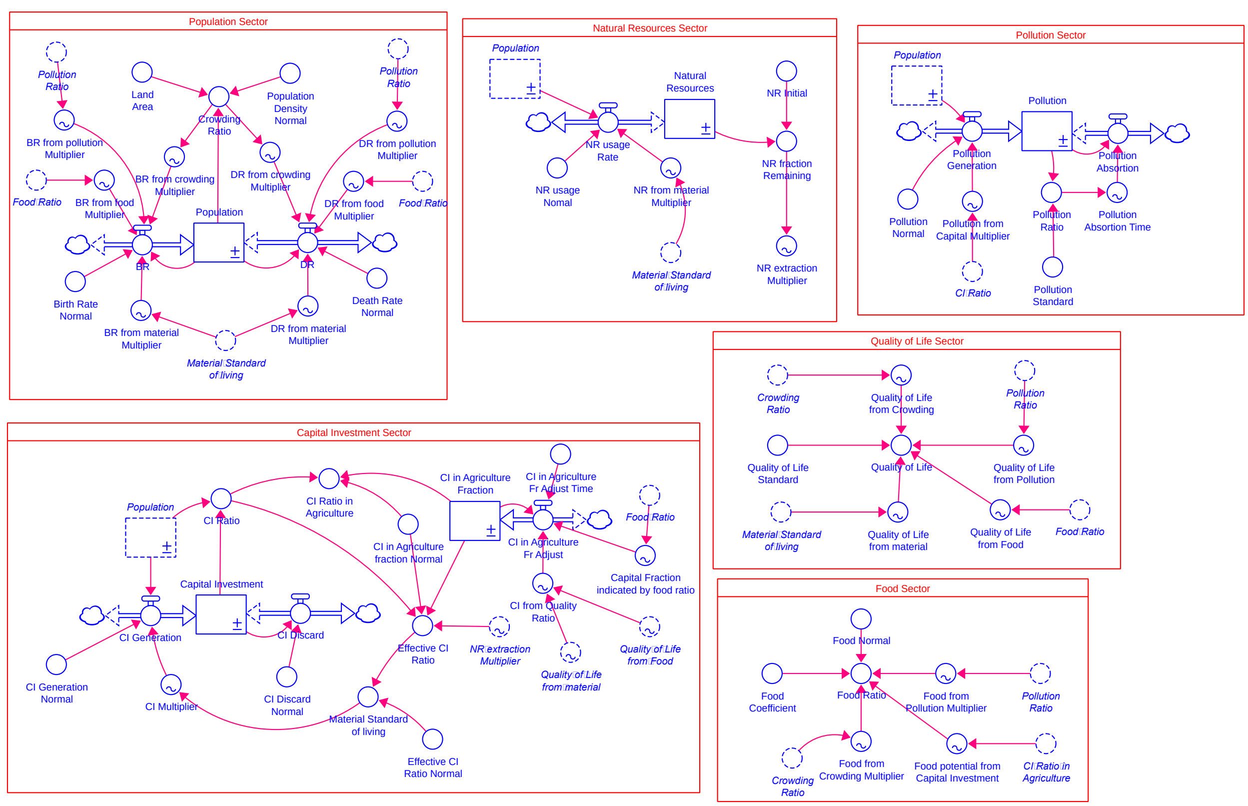


Figure 14 **Forrester's DYNAMO equation clusters of World3 representing its subsystems**

Perhaps Urban Dynamics (22) was the largest published model Forrester constructed. I am excluding the System Dynamics National Model (SDNM) as it remained unpublished. My colleague Karim Chichakly and I tried to reconstruct its equation clusters into modules and, in our first attempt, arrived at the module map shown in Figure 11, which is obviously useless as an explanatory instrument. Karim then attempted to organize the equation clusters into a two-level hierarchy of modules as Stella allows multi-level hierarchy. This reorganization created the module map shown in Figure 12 in the top layer.

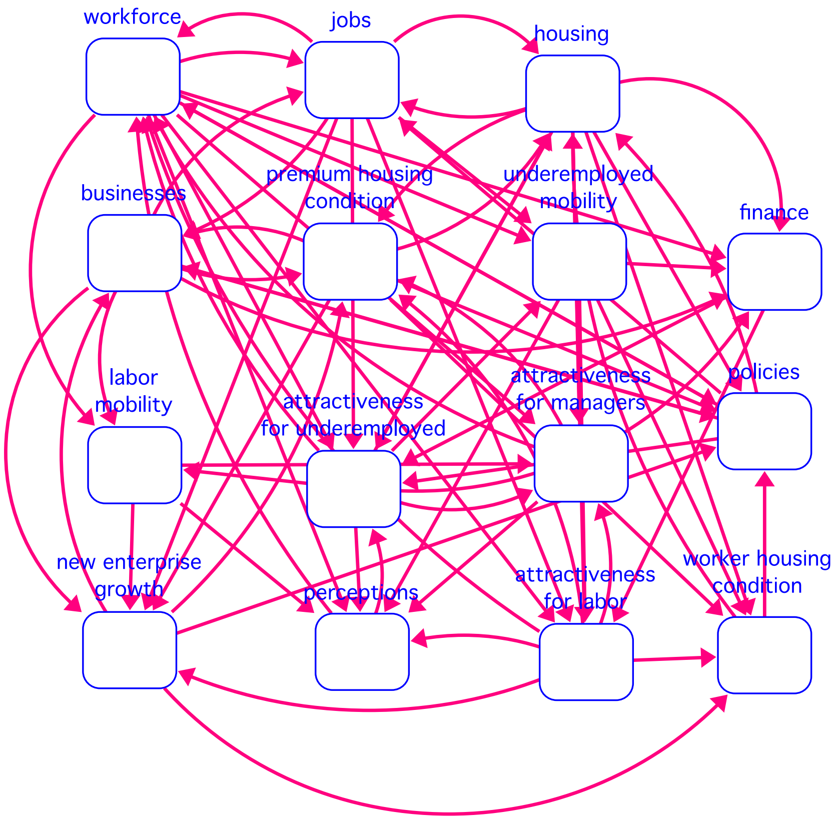


Figure 15 **Module map of Urban Dynamics equation clusters.**

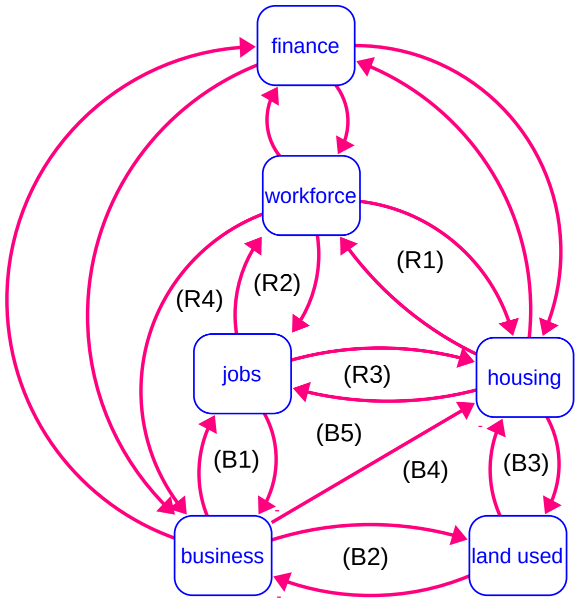


Figure 16 Urban Dynamics equation clusters programmed into two level module hierarchy

Using a multi-level hierarchy will call for creating dynamic hypotheses at the multiple levels of feedback pyramid so created, which further helps explain behavior at various levels of aggregation in a system. For example, in Urban Dynamics, Workforce comprises of the subsystems shown in Figure 12(a); Businesses in 12(b) and Housing in 12(c)

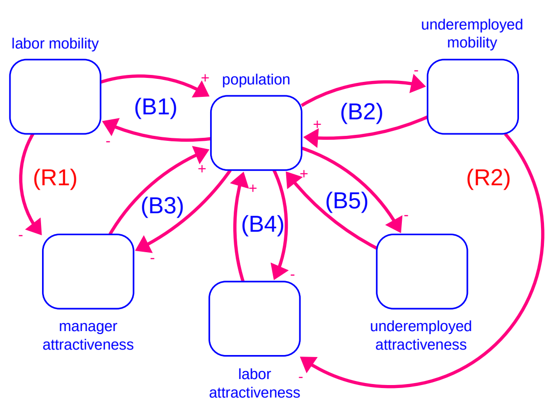


Figure 17(a): workforce subsystems

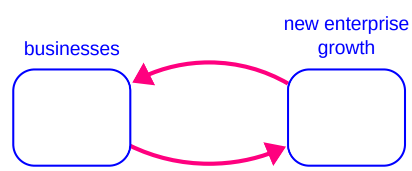


Figure 17(b): Businesses subsystems

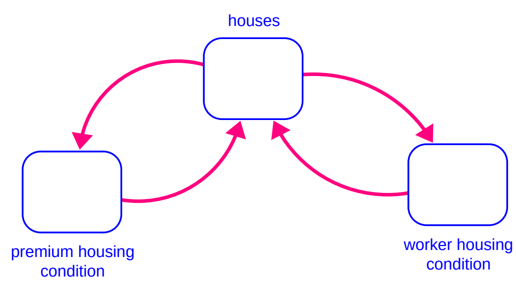


Figure 17(c): Housing subsystem

Figure 17 Module maps within modules in Forrester's Urban Dynamics model of Figure 12

Since the feedback map explains the behavior generated by the stock and flow structure in terms of the information relationships between subsystems of the model rather than between each variable, the anomalies created by exactly mapping one into the other are moot. We are better off understanding the hierarchical relationship between the two representations of the system instead of being caught up in the problem of trying to exactly map one representation to the other.

Degree of aggregation in feedback maps

The examples of relationship between the feedback map and stock flow structure in the preceding sections are vastly different with respect to the level of aggregation of the stock-flow structure represented in the feedback maps. The variety of the levels of aggregation represented in these maps implies there is no set rule defining the level of aggregation between feedback loops consisting only of qualitative information relationships and computable stock/flow structure, which is an important finding. It is sometimes recommended that the feedback map might be conceived as a relationship between stocks, but this can truncate causal information that might make a feedback map ambiguous. I am in favor of keeping this level of aggregation flexible, so a clear dynamic hypothesis can be formulated and tied to the computable model. Stella allows for a multilevel hierarchy and I encourage using it when representing complex models if they cannot be avoided even after having sliced the problem to identify a pattern of interest subsumed in the historical behavior (23).

Representing expectation formation and supply lags

Notwithstanding the complex mathematics used in economics for expectation formation, Forrester showed that perception that drives expectations, is really a moving exponential average. The weighting function of this average is determined by the order of the averaging process. He also created macros for representing perceptions that are an important part of managerial decision-making.

Supply lags appear as changes arising from managerial decisions that do not instantaneously translate into changes in the supply lines but are subject to process delays. The structure of these supply lags, though mathematically equivalent, is slightly different from perception formation. Hence, separate macros have been created for representing supply lags. Expectation formation and supply lag macros will be discussed in detail in Chapter 3 in the context of managerial decision-making.

Replacing linear policy recipes with system thinking metaphors and feedback control

Policy, especially in the public domain, has invariably been driven by two inputs: a) observations and measurements that describe the problem as a snapshot, and b) linear policy recipes striving to overcome what is discerned in the snapshot. Observations and measurements are also widely fed into complex forecasting instruments generating non-verifiable futures that still inform linear policy recipes. Forecasting is driven by simple or complex functions of past trends and in all almost all cases, its use amounts to using what is called derivative control in engineering without an anchor, which can be very destabilizing (24, 25).

Forrester has often stated his belief that a small number of pervasive generic structures can describe the majority of real-life situations (26) The ubiquitous structures he developed include Advertising (27), Market Growth (20), Industrial Dynamics (28), Urban Dynamics (22), and World Dynamics (21). The former two describe aspects of corporate growth that many organizations wrestle with. The latter four, together with his unfinished National Model represent a restructured theory of economic behavior that can be applied to managing firms, markets, regions and economies (29), (7). Such generalizable models of policy paradigms at a metaphorical level, drawing from situations in everyday life as well as distant history, that should serve as pointers to the latent structures needed to be targeted by policy, which I'll later attempt to catalogue in this book.

As for policy implementation, there is a need to draw from engineering practice that extensively utilizes ex post error to achieve fast and smooth adjustment to a desired condition using feedback control. The classical control process is often denoted as PID (for proportional, integral and derivative) control and a combination of these functions (often determined experimentally can reliably achieve the desired path of adjustment to a goal. Such a regimen can also be used to drive economic and business decisions to achieve desired performance and should replace authority driven policy implementation process. Indeed, such a control process was proposed by Phillips (12) and has become the center piece of a maverick thread in economics sometimes called economic dynamics. However, since the practitioners of economic dynamics often attempt to calculate optimal weights of the various components of control, it can be applied to only very abstract models that may be far removed from reality. Use of PID control in a macroeconomic system using system dynamics modeling will be discussed at length in Chapter --- .

Aging chains (conserved systems) and multiple equilibria

Most macroeconomic models assume equilibrium that perpetuates over-growth and cycles although there have been movements for including disequilibrium over the course of growth. Equilibrium is also often seen to signify perfect allocation since Mill discussed his stationery state. That is of course a lot of bologna, since there is pervasive experience of societies existing in stagnation with widespread poverty (6), banditry and illicit production, (30), decayed infrastructure and rampant underemployment (31).

The structure of such dysfunctional equilibria was demonstrated by Forrester in his Urban Dynamics model by using connected stocks for infrastructure and employment shown in Figure 22.

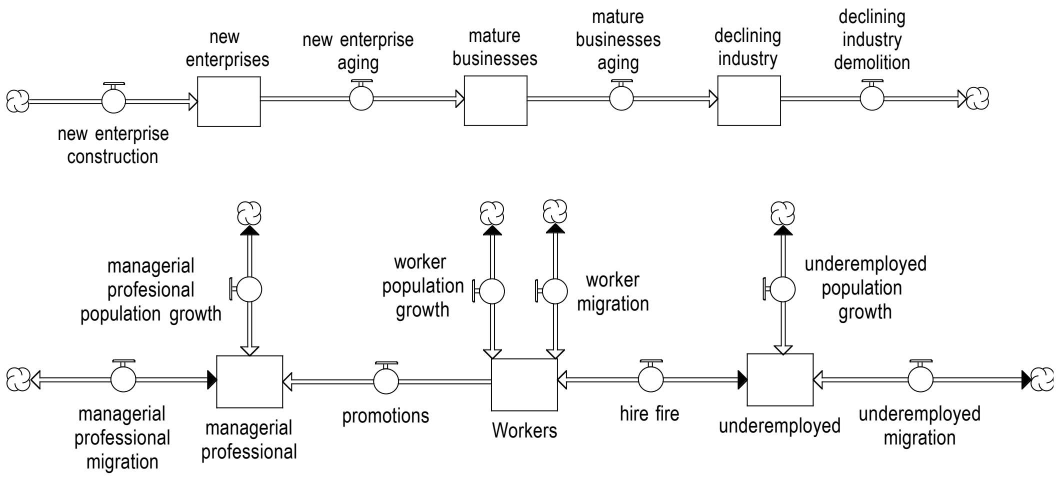


Figure 22 **Connected stocks forming aging chains in Forrester's Urban Dynamics Model**

These connected stocks disaggregated the variables into several categories while conserving the total quantity. They also allowed the possibility of both functional and dysfunctional equilibria created by the variety of distributions between stocks that could be created by the logic of the flows connecting them, that Forrester called policies (32).

Saeed et al (30) divided the workforce between farmers, bandits and soldiers in their metaphorical model of a political economy as shown in Figure 23.

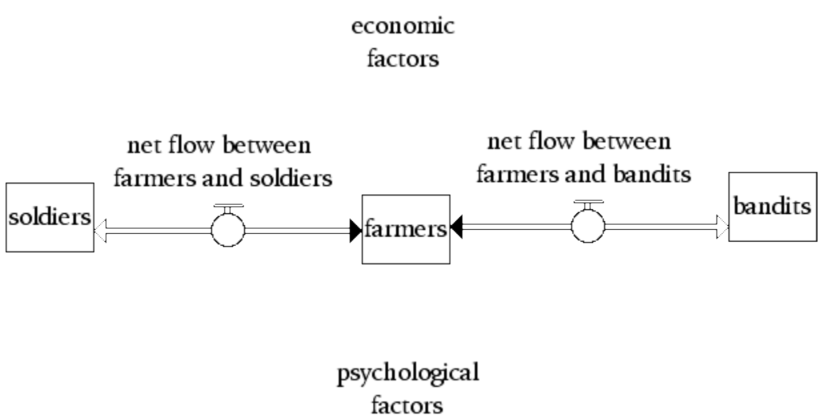


Figure 23 **Connected stocks in Saeed's model of political economy**

This distribution of workforce between these stocks can create a variety of equilibria depending on the factors affecting the mobility between them. Also, a variety of functional and dysfunctional income distribution scenarios can appear when the connected stocks of workforce, and modern and traditional production infrastructure and its ownership assume different distributions based on the policies affecting the flows connecting them (6).

Such complex aging chains would be difficult to represent using ordinary differential equations but are a breeze to formulate using the intuitive calculus of system dynamics. Their inclusion in our models can provide the much-needed policy space that will help operationalize economics.

Summary

A derivative is an *ex-post* computation of historical experience. Thus, a differential equation cannot be compared with the related system in the real world. On the other hand, since reality integrates over time, a logic that captures this integration process can be easily discerned from reality and also compared to it. However, if we were to replace the differential calculus with a process that replicated integration over time, the computational detail of it would be very tedious and you will definitely need a digital computer to carry out the integration in the system so surmised. Digital computers of course did not exist when the elegant art of calculus was created. Now that we have computers that can perform the tedious computations, why not adopt a realistic integration format that can be verified and also intuitively understood?

Forrester devised the bathtub – faucet – drain representation that we have adopted in system dynamics. This format replicates in an intuitive way how systems move over time. It can be inferred from reality and the models created in it compared to the real constructs and thus verified. Also, our explanatory tool - the feedback loops are an integral part of this representation. This takes the guessing game out of our explanations of the model behavior. Forrester's bathtubs and faucets are an intuitive way of representing calculus that is the cornerstone of system dynamics.

Although economics started as a descriptive theory, we began representing it using differential calculus and since verification of differential equations is difficult, the verification process was really dispensed with. The abstract models created with calculus gave birth to the concept of rational agency that underpins modern theory. Albeit, the world is run by managers, not rational agents. Manager, an agent in a bounded rational role is the actor in Forrester's work on economic issues. He aspired to replace rational agency-based economics with manager-based economics – a version of economics that managers can relate to, understand, and practice.

Forrester's Industrial Dynamics (28) presents a manager-based theory of firm and his unpublished National model – a model of the macroeconomic system is an extension of his model of a firm since an economy is an aggregate of firms. In these models, the decisions are made by down to earth managers who might be trying to balance everyday firm operations like maintaining reasonable levels of inventory and workforce to produce quantities needed for meeting incoming orders. Other managers try to balance production capacity with their perception of what is needed. Problems of inability to meet goals (steady-state error), overshoot, instability, and sluggishness in adjustment arise out of the interaction of the bounded rational policies the managers follow.

The representation of perceptions, expectations and supply chains is clumsy and overly complex. The possibility of multiple equilibria arising out of connected stocks as in an aging chain has been rarely attempted due to the computational complexity. All these methodological challenges can be resolved by replacing the abstract calculus used in economics by an intuitive stock and flow structure that mimics integration in reality. Consequently, verifiable theory that is built around managerial decisions can be constructed. The use of system dynamics method is therefore essential to operationalizing economics.

References

1. Baumol WJ. Economic Dynamics: An Introduction: Macmillan; 1951.
2. Smith A. An inquiry into the nature and causes of the wealth of nations By Adam Smith, ... In two volumes. London: printed for W. Strahan; and T. Cadell,; 1776. Available from: http://galenet.galegroup.com/servlet/ECCO?ae=T096668&c=1&stp=Author&ste=11&af=BN&tiPG=1&dd=0&dc=flc&docNum=CW105124089&vrsn=1.0&srchtp=a&d4=0.33&n=10&SU=0LRL+OR+0LRI&locID=camb27002.
3. Mill JS, Charles C. Little and James Brown (Firm), White and Potter. Principles of political economy : with some of their applications to social philosophy. Boston: Charles C. Little & James Brown : White and Potter, printers ... 1848.
4. Marx K, Moore S, Aveling EB, Engels F. Capital: a critical analysis of capitalist production. London,: S. Sonnenschein, Lowrey; 1887.
5. Saeed K. Development planning and policy design : a system dynamics approach. Aldershot, England ; Brookfield, Vt., USA: Avebury; 1994. xix, 254 p. p.
6. Saeed K. Dynamics of Income Distribution in a Market Economy: Possibilities for Poverty Alleviation. In: Dangerfield B, editor. System Dynamics: Theory and Applications. New York, NY: Springer US; 2020. p. 491-522.
7. Saeed K. Jay Forrester's operational approach to economics. System Dynamics Review. 2014;30(4):233-61.
8. Richardson GP. Feedback thought in social science and systems theory. Philadelphia: University of Pennsylvania Press; 1991. x, 374 p. p.
9. Muth JF. Rational Expectations and the Theory of Price Movements. Econometrica. 1961;29(3):315-35.
10. Schumpeter JA. Capitalism, socialism, and democracy. New York, London,: Harper & Brothers; 1942. x, 381 p. p.
11. Forrester J. System Dynamics: A Disruptive Science a Conversation With Jay W. Forrester, Founder of the Field. In: Saeed K, editor. 2013 International System Dynamics Conference. SSRN2013. p. 7.
12. H. RW, Cavana RY. A system dynamics translation of Phillips Machine. In: Cavana RY DB, Pavlov OV, Radzicki MJ, Wheat ID, editor. Feedback Economics. Switzerland: Springer 2021.
13. Forrester JW, Sloan School of Management. Economics, technology, and the environment. Cambridge, Mass.: Alfred P. Sloan School of Management, Massachusetts Institute of Technology; 1987. 15 leaves p.
14. Richardson GP. Problems with causal-loop diagrams. System Dynamics Review. 1986;2(2):158-70.
15. Graham AK. Parameter Estimation in System Dynamics Modeling. In: Randers J, editor. Elements of System Dynamics Method. Cambridge, MA: MIT Press; 1976.
16. Hillier F, ., liberman G. introduction to operations research: McGraw-Hill; 2015.
17. Mundra R, Kazantzis N, Saeed K, editors. Translating Between Block Diagrams and Stock & Flow Diagrams, An example-based approach using Simulink and iThin. 31st annual conference of the International System Dynamics Society; 2013; Cambridge, MA: System Dynamics Society.

18. Forrester JW. Principles of systems. Cambridge, Mass.: Productivity Press; 1971.
19. Forrester JW. System dynamics, systems thinking, and soft OR. System Dynamics Review. 1994;10(2-3):245-56.
20. Forrester J. Market Growth as Influenced by Capital Investment. Industrial Management Review. 1968;9(2).
21. Forrester JW. World dynamics. 2d ed. Cambridge, Mass.: Wright-Allen Press; 1973. xv, 144 p. p.
22. Forrester JW. Urban dynamics. Cambridge, Mass.,: M.I.T. Press; 1969. xiii, 285 p. p.
23. Saeed K. Slicing a complex problem for system dynamics modeling. System Dynamics Review. 1992;8(3):251-61.
24. Saeed K. Trend forecasting for stability in supply chains. Journal of Business Research. 2008;61(11):1113-24.
25. Saeed K. Can trend forecasting improve stability in supply chains? A response to Forrester's challenge in Appendix L of Industrial Dynamics. System Dynamics Review. 2009;25(1):63-78.
26. Forrester JW. Policies, decisions and information sources for modeling. European Journal of Operational Research. 1992;59(1):42-63.
27. Forrester JW, Advertising Research Foundation. The relationship of advertising to corporate management. New York,: Advertising Research Foundation; 1958. 27 \2113. p.
28. Forrester JW. Industrial dynamics. Cambridge, Mass.: M.I.T. Press; 1961. 464 p. p.
29. Saeed K. Urban dynamics: A systems thinking framework for economic development and planning. ISOCARP Review. 2015;11:129-32.
30. Saeed K, Pavlov OV, Skorinko J, Smith A. Farmers, bandits and soldiers: a generic system for addressing peace agendas. System Dynamics Review. 2013;29(4):237-52.
31. Saeed K. Urban dynamics: A systems thinking framework for economic development and planning. . ISOCARP Review. 2015;11:129-32.
32. Forrester JW. Principles of systems : text and workbook. 2nd preliminary ed. Cambridge: Available from Technology Store, M.I.T. Student Center; 1968. v. p.