Chapter 4
Economics and Markets

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Economic matters are often entangled with interventions. Aid agencies need to understand where they can have the highest leverage, and where aid may cause harmful economic distortions. Humanitarian interventions in crises will be more effective if the economic and social root causes of the crisis are addressed as well. The root causes of insurgencies often include economic issues, particularly economic discrimination. Planners for military operations in a country need to know the economic side effects of military activities, including the effects of withdrawal. Government agencies trying to bring developed-nation investors into a developing country must understand, along with the potential investors, what the economic prospects of the economy are, and how safe an investment is (or is not). Economic modeling and analysis can assist in each of these cases.

It is easy to wish for a general-purpose economic model that not only correctly forecasts future economic behavior but also accurately predicts the impact of any given action. However, there is no economic model built yet that encompasses the entire range of potential issues and impacts for *any* country, let alone the many countries an analyst might need to understand. A model *of* a country will seldom be an adequate model *for* a given very specific purpose and use.

Moreover, uniformly good forecasts are neither possible nor usually required. What is actually required often is an analysis indicating which plan of action is more desirable, irrespective of precise conditions, which implies that choosing a model (or to purpose-build one) very much depends on the exact use to which it will be put, as opposed to a general topic area (e.g., "exchange rates").

This chapter excludes consideration of the related topics around a country's domestic economic policies, which would speak to a different audience and involve a different profile of the economic issues dealt with. The topic of models for monetary and fiscal policy is narrower and deeper than the topics considered here. Monetary and fiscal policy models almost always need to be fully quantitative, well-verified versus time series, and at least medium sized. They also simplify

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away many of the givens that are missing or partially functioning in developing economies, such as a nationwide financial system. So monetary and fiscal policies are generally taken as givens in what follows, and the models are not evaluated on the basis of their ability to say what happens when such policies change.

There are many more possible combinations of model purpose (decisions to be influenced), economic issues that impact outcomes, and geographies than there are extant models, and in turn many more extant economic models are available than is practical to catalog. Therefore, this chapter focuses on principles for determining a match among a user's purposes, the economic setting being analyzed, and a given existing model or proposed model creation or modification.

This chapter does not provide step-by-step instructions for building or using economic models but rather is more of a navigation guide, allowing an analyst to slice through the different combinations of purpose, economic behaviors, and geographies to:

Locate data that characterize the relevant economic situation, and

Identify which types of economic analysis or modeling are most appropriate to the purpose, geography, and modeling resource constraints.

For analysts whose background and resources foreclose the active use of a quantitative model, a later section gives a case study of using diagrammatic modeling and scoring to tease apart a complex resource allocation problem with a satisfactory degree of confidence.

For analysts whose background and resources allow them to choose building or modifying a quantitative model, this chapter describes an economic model with the focus on design choices appropriate to a model purpose and validation tests available to a model builder. The same discussion also illustrates by example why "general purpose" models are hardly ever directly suitable for specific uses in international economic situations.

A critical organizing concept in what follows, especially in the context of scoping an analysis, is the idea of a behavior mode. The concept itself originates from feedback systems mathematics. In a complex system, such as the interlinked markets that make up an economy, the system is capable of a variety of somewhat distinct behaviors, a few of which will dominate the behavior at any one time. For example, developed economies tend to show a somewhat irregular cycle (the "business cycle"), with intervals of expansion alternating with intervals of contraction, with peaks typically 3–7 years apart. Sterman (2000, Part V, "Instability and oscillation") provides an extensive analytical framework for such cyclical phenomena.

Behavior modes can be thought of as analogs of medical definitions of diseases or syndromes: patterns of behavior that arise from a distinctive set of causes, which may or may not occur in isolation. Behavior modes are associated with behavior of specific quantities, here called "indicator variables," just as a physician will decide whether a patient has a flu infection by looking for elevated temperature, headache, body ache, and nausea. Similarly, much of the initial scoping involved in economic analysis is arriving at sensible hypotheses for which behavior modes are occurring or are likely to occur.

Before proceeding to the standard behavior modes of macroeconomics, working with developing economies may require some understanding of another set of behaviors that arise and persist due to systemic causes but are not part of the standard economic corpus. For convenience, these can be called "near-economic" behavior modes, and we begin the cataloging of behavior modes and indicator variables with them.

1 "Near-Economic" Behavior Modes

Table 1 lists several behavior modes that represent departures from the developed country norms or ideals: corruption, discrimination, insurgency, and economic controls. These become important to the reader when they materially impact the economy in question.

Each of these behavior modes is maintained by a self-sustaining interaction among multiple stakeholders. For example, a corrupt political leader may take payoffs, whose proceeds are sufficient to bribe prosecutors and judges to suppress law enforcement and permit election-rigging, which maintains political power, which includes the ability to appoint, e.g., judges. Graham (2009a) further discusses such self-sustaining behaviors; Bueno de Mesquita et al. (2002, 2004) provide solid empirical support. One consequence of the self-sustaining nature of such behavior modes is that they

Table 1 Near-economic behavior modes

Behavior mode	Description
Corruption in political processes	Rigged elections, widespread patronage, political control of media
Corruption in law enforcement	Judiciary and enforcement controlled to permit, e.g., drug trade
Corruption in economic processes	Routine confiscation or near-confiscation of private property, extensive bribes needed for construction or business operation
Discrimination in law enforcement	Routine and egregious violation of civil rights of ethnic or racial groups
Economic and social discrimination	Explicit or implicit limitations on education and hiring with respect to race or ethnic group, sometimes by an economic elite, sometimes by the majority ethnic group
Insurgency	Attempts to resist or control government by violent means. "Groups with gripes" are often a consequence of behavior modes above.
Protectionism	Prohibitions or tariffs on imported goods and services. Legal limits on the ability of domestic companies or persons to make investments outside the country. Also limits on foreign investment in domestic corporations, and/or limits on repatriation of domestic profits from foreign-owned assets.

Table 2 Sources for indicators of near-economic behaviors

Organization	Web address
United Nations Universal Human Rights Index	http://www.universalhumanrightsindex.org/
World Bank Governance Indicators	http://info.worldbank.org/governance/wgi/sc_country.asp
Internet Center for Corruption Research	http://www.icgg.org/corruption.html
Transparency International	http://www.transparency.org/
Freedom House	http://www.freedomhouse.org
Human Rights Watch	http://www.hrw.org/
Amnesty International	http://www.hrw.org/
Gallup Political Stability Index	http://www.voice-of-the-people.net/ContentFiles/files/VoP2005/VOP2005_Democracy%20FINAL.pdf

generally persist. Anticorruption crusades seldom succeed, and if they succeed, they succeed slowly – not over months and years but over years and decades.

The "good news" in the very persistence of near-economic behavior modes is that indicator variables are reasonably trustworthy about future prospects. There are several organizations that produce indexes of corruption, economic freedom, and political freedom, as shown in Table 2:

In addition, as described in the Resources section of this chapter, there are broader research surveys available that emphasize the economic climate as well as significant amounts of international data.

2 Economic Behavior Modes

Tables 3–6 describe standard textbook economic behavior modes.[1] For each, the table gives a brief description, a reference for further reading, and economic variables to look at to determine where a given economy lies on the spectrum from "that behavior is happening right now" through "it isn't happening now but it could" to "it's unlikely to happen." They, along with the near-economic behavior modes, allow a modeler to say what is going on economically in the region of interest.

For clarity, the table information is divided into three types of behavior modes. Table 3 describes "business as usual" behavior modes, which go on all the time, in developing and developed economies alike. Table 4 describes some departures from business as usual that create moderate economic vulnerabilities. Tables 5 and 6 describe severe economic crises and the conditions under which countries are vulnerable to them. The taxonomy is more for convenience than for reflecting any fundamental distinctions.

In brief, then, a modeler or modelers will start from general surveys of a country's Political, Military, Economic, Social, Infrastructure and Information (PMESII) situation. From there, gathering data about each economic behavior mode should

[1]Chart of economic behavior modes adapted from Graham et al. (2008a, b), © PA Consulting Group, Inc. Used with permission.

Table 3 Economic behavior modes that are "business as usual" in developing and developed economies

Behavior mode	Description	Indicator variables	Commonly modeled with
Secular industrialization	Long-term (i.e., over decades and centuries) accumulation of physical and financial capital, and technological know-how leads to increasing use of capital plant and equipment broadly across the economy	Long-term trend in real production per capita (adjusted for inflation, and minus income due to natural resource extraction)	Usually, modeled as a function purely of passage of time in productivity equations. See (Solow 1956, 1957) for this classic treatment, and (Romer 1990) for an analytical model of technology investment, technological progress and increased productivity
Demographic transition	Often hand-in-hand with later stages of industrialization, accumulation of physical capital (matched by financial savings), which allows retirement supported by savings, rather than support from many children	Decreasing average family size, increasing household wealth and income per capita (financial and nonfinancial) approaching low end of developed country levels	Implicit in parameters of quantitative models, in population growth and savings targets. See (Caldwell 1976; Caldwell et al. 2006)
Business cycles	"Course correction" by corporations to manage inventories through production and employment, which tends to overshoot. Normal random disturbances turn this into approximately cyclical behavior with 3–7 year period	Timeline of GDP growth Explicit business cycle leading and concurrent indicators, particularly employment and inventory investment relative to long-term trend (see ECRI in references)	Stochastic models (Eckstein 1983; Fair 2004), system dynamics models (Mass 1975; Forrester 1982; Forrester 1989). For business cycle statistics in the US see (NBER 2009) and internationally (ECRI 2009)
Trade balancing through exchange rates	When, e.g., the US imports more than it exports (a negative balance of trade), it gives out more dollars than it takes in other country's currencies, so the value of the dollar should fall. That makes imports more expensive and should reduce them, and likewise exports, which reduce the imbalance, should be increased (may be "stuck open" by currency exchange mercantilism, below)	Stability of exchange rate relative to weighted basket of currencies Gross imports and exports and their difference (net exports) as fractions of GDP	Analytical models (Gandolfo 2002, Ch. 15) Stochastic models (which may leave exchange rates or export demand exogenous (i.e., future values assumed rather than determined by model dynamics), as in (Fair 2004)

Table 4 Economic behavior modes that create moderate vulnerabilities or persistent undesirable conditions

Behavior mode	Description	Indicator variables	Commonly modeled with
Currency exchange mercantilism	A country (e.g., China) keeps exchange value of its currency low by buying, e.g., dollars and accumulating them, making their exports cheap in international markets. So they export more than they import, and continue to accumulate dollars	Growing foreign currency and debt holding of government and central bank relative to GDP, relative to other countries	Analytical models such as (Gandolfo 2002, Ch. 15) could be adapted. See (Curry 2000, Ch. 8) and (Burgess et al. 2009, Sections 1.2 and 3.1) for more detailed descriptive analysis
Natural resource export dependence	Natural resource extraction paying for imports, with relatively few goods and services being produced for domestic consumption or export (natural resource exports may disguise what would otherwise be a failed market economy. Such economies are very vulnerable to world commodity price fluctuations, hence very volatile)	Exports of specific commodities relative to GDP (e.g., oil, iron ore)	Macroeconomic statistical models with endogenous importing/exporting and foreign exchange rates
Import dependence and stagflation	If a country depends on importing a critical commodity (food or oil) whose price increases, consumers buy at the higher price, leaving less money for other goods. The domestic economy starts to decline. The government attempts to maintain consumption by making money easily available, which creates inflation simultaneous with the economic stagnation	Imports of a specific commodity (e.g., oil, coal, food, iron ore, and steel) relative to domestic consumption	Stochastic models (Eckstein 1983; Fair 2004), analytical models
Capital flight	When domestic investment opportunities offer only poor returns, business investment and personal savings leave the country. With little capital investment, the economy does not grow and the incentives for capital flight persist	As fractions of GDP: Domestic capital investment Net capital account balance Investment owned outside the country	If at all, implicit in parameters describing capital investment in macroeconomic statistical models (Eckstein 1983; Fair 2004; University of Maryland 2009)

Table 5 Economic behavior modes of crisis originating from domestic financial issues

Behavior mode	Description	Indicator variables	Commonly modeled with
Debt deflation spiral	Rising asset prices (stocks, housing) secure large debts relative to income. If any event stops the rise, households and businesses use money to reduce debt rather than consuming or investing. So the economy shrinks, and asset prices fall further. Defaults reduce the value of assets held by financial institutions, which further reduces lending and consumer purchasing (usually, follows a period of asset price inflation, and will persist over multiple business cycles) Debt deflation spirals are usually thought to explain the worldwide Great Depression of the 1930s, Japan's Lost Decade of the 1990s, and to some extent the recession of 2007–2009	Consumer Price Index (CPI) decline Housing price index (adjusted for CPI) decline Mortgage foreclosure rate (%/year), whole population, increases sharply Bond default rate (%/year), whole market shows sharp increase Household debt relative to income Medium-term stock market decline (adjusted for CPI)	Analytical models summarized in (von Peter 2005). For extensive discussion as "balance sheet recessions" see (Koo 2008). For system dynamics modeling in terms of 50-year cycles (a.k.a. "Kondratiev cycles"), see, e.g., (Graham and Senge 1980; Graham 1982; Sterman 1986)
Deficit-lead hyper-inflation	The usual trigger for high inflation is government spending far more than its revenues, and borrowing is not possible. So the government creates more money, and prices start to rise. Once inflation is built in, the government has little choice but to support the economy and continue inflating the money supply. Often accompanied by the inability to acquire foreign currencies (through foreign trade) to repay foreign debt, followed by default	Consumer Price Index or GDP deflator Government deficit and debt as fraction of GDP External debt (i.e., debts to foreign governments or financial institutions) relative to national currency reserves (i.e., "do they have enough money to pay off their debts?") Payments of external debts relative to trade surplus (i.e., "are they taking in enough foreign currency to make payments on foreign debts?")	Analytical models

Table 6 Economic behavior modes of crisis created through foreign currency exchange

Behavior mode	Description	Indicator variables	Commonly modeled with
Currency crisis/ investment boom and bust	A period of rising foreign investment brings foreign currency into the economy, which stimulates spending, importing, and borrowing, including borrowing from foreign sources. The currency exchange rate rises, increasing the value of investments. However, if any event (business cycle downturn, oil price increase, whatever) reduces the investment flow, spending suddenly drops, currency exchange rate falls, foreign debts become too large to repay, and the economy declines sharply	Foreign Direct Investment (FDI) sharply declining External debt (debt to foreigners, in foreign currency) relative to FDI plus currency earnings from exports increases sharply Dollar price (or market basket-weighted price) of that foreign currency declines sharply	Analytical models, e.g., (Krugman 1999), also (Gandolfo 2002, Ch. 16). For very accessible description, see (Krugman 2009)
Currency exchange defense	For many reasons, the value of a country's currency may decline. A country's government can decide to attempt to maintain their currency's value at a high level (usually for reasons of national pride, or keeping imports cheap and available). Maintaining a high value requires them to buy their own currency back in foreign exchange markets, and pay for it out of their reserves of foreign currencies, which are limited. Financial markets have a way of betting that a currency value will fall (short selling) which actually tends to make the currency value fall further. The country runs out of foreign currency, and the currency falls anyway	Exchange rates Announced government policy of defending the value of its currency	Analytical models (Gandolfo 2002, Ch. 16). For very accessible description, see (Krugman 2009)

give a picture of the economic situation that is both broadly scoped and concise. That is the background for modeling decisions: whether creating or borrowing a model at all is justifiable, and if so, what economic behaviors a model will need to deal with.

3 Overview of Modeling Approaches

Tables 7–9 summarize the major varieties of analysis and modeling approaches used or advocated for economic issues. The names of the methods in some cases are not quite what their practitioners would call them; the names were chosen to be meaningful to nonpractitioners.

Strengths and weaknesses of different modeling approaches are sometimes a topic of disputes among practitioners of different methods. In part, the disputes originate from pure misinformation about "foreign" methodologies; for example, inferring characteristics of a whole class of methods from academic teaching examples. An expert will know the power and flexibility of his or her own method but will not easily see the power or flexibility in other methodologies, especially if judging only from published academic work.

In part, the disputes are due to the (often correct) perception that many weaknesses of an approach can be overcome by experts. Expert statisticians have techniques to deal with missing data. System dynamics experts can often build and use models quickly, and so on. That said, the experts' bags of tricks are unhelpful for nonexperts and very unhelpful for analysts trying to determine the extent to which a model built by someone else for a different purpose can in fact be useful for the analyst's purpose.

Perhaps the most contentious disputes arise when an expert in one field has tightly-held assumptions about what modeling is for, what form it is to be delivered in, and what types of validation tests are acceptable to the final audience. Modeling for a different purpose, delivered in unfamiliar ways and using unfamiliar validation tests (and missing the familiar ones) is palpably substandard, at least in perception. Academics develop compact theories that explain things in a teachable way. They rightly prefer results that are objective, reproducible, and publishable in a refereed journal. So there is a strong incentive toward small models, and hence working on problems amenable to analysis via small regression models and analytical models. Modeling practices and preferences and indeed curricula have built up around these methodologies.

Academic model-building often has several disconnects with the needs and purposes of corporate and government decision-making. Many areas of concern are simply not well-studied academically and often lack even elementary data. Academic studies are often limited to cross-sectional comparisons of different countries, with the predictable result that the results are often inconclusive. First-time explorations of problems that include data-poor areas should be conducted differently than well-studied problems. Logically, modeling that pioneers such issues lean toward use of

Table 7 Summary of analytic methodologies for assessing economic effects

Methodology	Description	Typical application	Strengths	Weaknesses
Cross-sectional and historical indicators	Collect concise statistics measuring a behavior from many countries to identify the most troubled (or likely to be troubled) country	Assessing political risks in developing countries; assessing financial risk of, e.g., currency crisis (Gallup Corporation 2009)	Straightforward and easily communicable. Typically, data are widely available from commercial and government organizations	Indicative rather than definitive; usually, does not explicitly account for special circumstances nor quantify the uncertainties involved
Quantitative Systems thinking	With Subject Matter Experts (SMEs), diagram the (usually interlocking) drivers of the behavior of interest, and then use SMEs to score causes and effects to rate alternative actions. Use sensitivity testing to assess robustness of recommendations	Resource allocation in data-challenged situations, e.g., law enforcement, counterinsurgency, complex or very new markets, regulatory issues (Mayo et al. 2001; Lyneis 1999; J8/WAD 2007)	Makes full use of SME first-hand operational knowledge, supported by statistical evidence. Process is transparent	Judgments on strength and timing of cause and effect are subjective (even though often repeatable and surprisingly accurate as measured by later quantitative modeling) Quantitative validation testing against time series is not possible
Analytical	Few enough symbolic equations (usually without numerical values) that their behavior and implications can be derived with algebra, calculus, or graphs	Publish a journal article testing an hypothesis about a given economic behavior (Krugman 1999; Solow 1956; Romer 1990)	Conclusions derived rigorously and explicitly from equations or graphs. Explanation of behavior is compact	Multiple simplifying assumptions can prevent analysis of more than one behavior of interest, which may make the scope of analysis smaller than that would be useful for a decision-making situation Derivations often require fluency in calculus to follow

Single-equation regression	Explains movements of one variable in terms of a few drivers, with parameters derived by statistical methods	Present an hypothesis about an economic cause and effect in an academic publication (Modigliani and Brumberg 1954)	Confirms or disconfirms hypotheses with objective, repeatable statistical tests. Widely taught in college courses as "econometrics" or "statistical regression" (as opposed to the more theoretical probability and statistics)	For analysis in support of a decision, variables in a regression equation may be too aggregate to be relevant for assessing the impact of a specific action, and too restricted in scope to be trusted in influencing a decision Without significant expertise and diligence, flaws in data can create apparently good but incorrect results (Sterman 1988)

Table 8 Summary of analytic methodologies for assessing economic effects

Methodology	Description	Typical application	Strengths	Weaknesses
General equilibrium	One of the two major variants of macroeconomic statistical models (i.e., uses many equations to describe an economy, and uses statistical methods to derive parameters for the equations). Uses data on prices and quantities to estimate supply and demand functions, and then compute equilibrium. Analysis is comparing different equilibria resulting from different government policies or external events	Understand the effect of regulatory change, or (in detailed models) understand the economy-wide impact of large sectoral changes (e.g., collapse of the car industry) (Kubler 2008; University of Maryland 2009)	When the primary analytical deliverable is a changed end state (e.g., competition in an industry under a different regulatory scheme), comparing two equilibria shows the consequences of policy changes very clearly (assuming that transitioning from one state to another is benign and secondary for the analysis) Excluding dynamics allows greater focus on detail (e.g., by industry) and scope (with multiple countries)	Limited to markets where high-quality data on price and quantity are available, usually "real" (non-financial) economy Says little about the path from one equilibrium to another, which excludes many dynamic behaviors of interest, e.g., business cycles, foreign exchange currency crises, the 2007–2009 debt-deflation (see Koo 2008). In such economic behavior modes, transitions between equilibria are far from smooth, and usually involve major overshoot and other transient conditions important to stakeholders

Stochastic	The other major variant of macroeconomic statistical models, likewise using many equations and statistical estimation of their parameters. Known more technically as "dynamic stochastic general equilibrium (DSGE) models". Translation: some markets are assumed to balance instantly ("general equilibrium"), the system is part driven in part by randomness ("stochastic"), and some changes happen over time ("dynamic")	Short-term economic forecasting (Eckstein 1983; Fair 2004)	During "business as usual" periods, best forecasts and known error bounds	Limited to markets where data on price, quantity, debt, interest, inventory, foreign exchange rate, etc. are available, usually "real" (nonfinancial) economy and balance of trade. Generally not capital account dynamics Quickly becomes impossible when data are unavailable Forecasts based on "business as usual" fail when they are most needed – during unusual economic behavior Model testing usually does not emphasize boundary adequacy testing, subsystem testing, extreme condition testing – all of which support the ability to forecast (see Lyneis 2000)

Table 9 Summary of analytic methodologies for assessing economic effects

Methodology	Description	Typical application	Strengths	Weaknesses
System dynamics	Use SME knowledge to formulate dynamic equations (i.e., present conditions and the equations that govern the change in those conditions over time, equivalent to differential equations), then test against observed behavior (see Section 6.5)	Economic cycles (Mass 1975; Forrester 1982), commodity cycles (Sterman 2000 Ch. 20), public policy and regulation (Graham 1976; Graham and Godfrey 2003), counterinsurgency (DARPA 2006; OUSD Policy 2007), as well as corporate strategy, large project management, and legal disputes (Stevens et al. 2005)	Can integrate economic and non-economic issues, can use SME data to compensate for scarce time series data, allows many types validation, models can analyze extreme conditions and not-yet seen behaviors Counterintuitive behavior and unintended consequences often well treated (Forrester 1971) Well suited to medium-term forecasting (Lyneis 2000)	Serious model-building and policy analysis requires considerable experience, not readily available Models are typically valid and useful for a sharply defined set of questions and issues – clients and academics can be disappointed by the inability to appropriately address the issues outside the defined scope
Game theory	For each of (usually two to five) actors, quantify their decisions, goals and constraints on action. Use mathematical theory to solve the game for viable solutions	Negotiations; auctions (e.g., wireless spectrum). Concepts are probably more widely used than the formal analysis (Dixit and Skeathmore 2004; Williams 2007)	Captures thinking and behaviors very difficult to capture with other methods, e.g., coalitions, “cheating,” multiple-move strategies (analogous to chess strategies)	Relative to methods above, practical application lags far behind mathematical sophistication and academic exploration. So software and the skills to use them are rare (game theory is mostly about the form of analysis; it can coexist with different ways of modeling the underlying descriptions of reality, e.g., there is a rich theory of dynamic games)

Agent-based (AB) simulation	Give a multitude of agents (hundreds or thousands) goals, available actions, and a decision-making algorithm, all randomly distributed. Do Monte Carlo simulations to understand behavior	Where the distribution of behaviors is the central problem: AB is the dominant method to analyze the spread of infectious disease. For social sciences, see (Billari et al. 2006)	Truly unexpected behaviors can emerge. Problems where the "tail" of a distribution is key (e.g., insurgents), Situations involving changing of a taxonomy (e.g., new definition of market segments)	Like game theory, practical application lags behind academic exploration. So software is immature by comparison to other methods, and long application experience is rare Need to detail all decisions of all actors can be considerably more work than other methodologies (Rahmandad and Sterman 2004)

diagrammatic and system dynamics modeling as more robust approaches in such circumstances, with validation techniques and standards different from those for problem domains in which considerable knowledge and modeling already exist. Similarly, many areas of government and business concern spread across many disciplines and interactions of many types of actors, and analysis of such decisions must weigh the impact in all areas. Analysis in such situations calls for models that are far from compact.

In an unachievable ideal world, everyone responsible for modeling to support government or business decisions would understand the strengths and weaknesses of a variety of methods and be comfortable working with models both small and large. However, realistically, professors have only so much time in MBA or MPA programs to teach about modeling. Learning on the job usually gives in-depth experience with a very limited spectrum of models – in part because success with one type of modeling usually causes repetition of that same type of modeling.

Limited exposure to modeling techniques has left an unfortunate gap in the use of models in corporations and governments, in which there is not only a real lack of practical knowledge about other approaches but also a lack of knowledge about how to go about choosing one approach versus another. Indirectly, the widespread paucity of knowledge or skill in matching models to purpose is why the author is so adamant about using explicit deliverables that define and validate what a model's purpose is to be.

So in approaching the potentially contentious subject of choosing a modeling method, think of Tables 7–9 as describing the "comfort zones" of applicability, where the characteristics of the method are well suited to the problem domain and a body of application experience, a user community, and perhaps good software support have developed.

Tables 7–9 can also be used as a first cut at understanding where a given model might be weak, when a given problem setting seems well outside the comfort zone of a given technique. Tables 7–9 cannot *prove* that a given approach *cannot* be used to provide useful answers to a given question, let alone whether a given approach is "better" than another in any absolute sense. But it is a guide.

4 Case Study: Resource Allocation in Law Enforcement

The following case study is offered both because it shows a methodology for tackling complex issues that is a great deal easier to use than, say, macroeconomic modeling or system dynamics simulation, and because it is also an example of the preparatory steps for more thorough quantitative modeling. This method is an extension of causal diagramming (Sterman 2000, Ch. 5; Senge 1990) that arose when the London Underground needed a very rapid assessment of different ways that it could be privatized (Mayo et al. 2001). The resulting method relied on a diagram and scoring by subject matter experts (SME). There are many similar situations in which formal quantitative equation-writing is not possible, whether due to time pressure, budget pressure, or lack of time-series data. Such situations often still allow adequate modeling, and robust, usable recommendations can be obtained.

Specifically, the setting is the situation of Transport for London (TfL), the government agency responsible for all public transport in greater London. Like most major cities, London suffered acutely from traffic congestion. Increasing the public's use of public transport, especially buses, was highly desirable, but research indicated that the public feared crime and violence around bus stops and aboard buses and disliked the length and unreliability of the ride. Controlling such crime and violence is the responsibility of the Metropolitan Police Service (MPS). However, MPS had limited resources, and more urgent issues, such as antiterrorism and street and gun crimes, inevitably took priority over transport policing.

The traveling public was about to receive a powerful incentive to ride buses rather than take private cars when the congestion charging scheme, starting February 2003, would impose a sizable cost on taking a private car into downtown London.

There was a plan to deal with the fear and unreliability deterrents to bus travel, but the plan involved many uncertainties. A pilot, then a fully-funded branch of London's MPS, would be dedicated to transport issues, the Transport Operational Command Unit (TOCU). This unit needed to be in place and doing a good job by the time the congestion charging scheme went into effect. The human, economic, and political costs of failing to improve the safety and reliability of bus transportation would be huge.

Here, the bang for the buck discussions emerged. There are dozens of major categories of activities to which the TOCU efforts might be applied, including educating the public about bus lanes, ticketing bus lane or "yellow box" (stopping in an intersection) offenses, placing cameras for remote ticketing, centralizing traffic control (which also coordinates with enforcement against vandalism), riding buses both to reduce fare evasion and to protect against on-board crime (as opposed to crime at the bus stop), and so on. These activities have both direct and indirect impacts on fear and reliability. Activities affect other facets of the transport ecology with diverse delay times, ranging from minutes to months or years. Activities interact with one another (e.g., better monitoring has no impact if there are no resources with which to act on what the monitoring shows) and so on.

How was TOCU to quickly find an effective mix of activities in time for a pilot and full-scale deployment prior to the onset of the congestion charging scheme?

TfL asked a team of modelers[2] to conduct a semiquantitative analysis of the resource-allocation problem, that is, to diagram the key interactions and interventions and use SMEs to score each potential use of resources. The modeling activity mostly comprised meetings among consultants, TfL representatives, and SMEs (TfL, MPS, and others). The meetings always focused on one of a sequence of graphical representations of the problem. The first representation, a block diagram shown in Fig. 1, is useful for discussing and defining the scope of the issues involved:

[2]The modelers were from PA Consulting Group, which also employed the author. Text and figures adapted from various materials copyright © PA Consulting Group, Inc., and are used with permission.

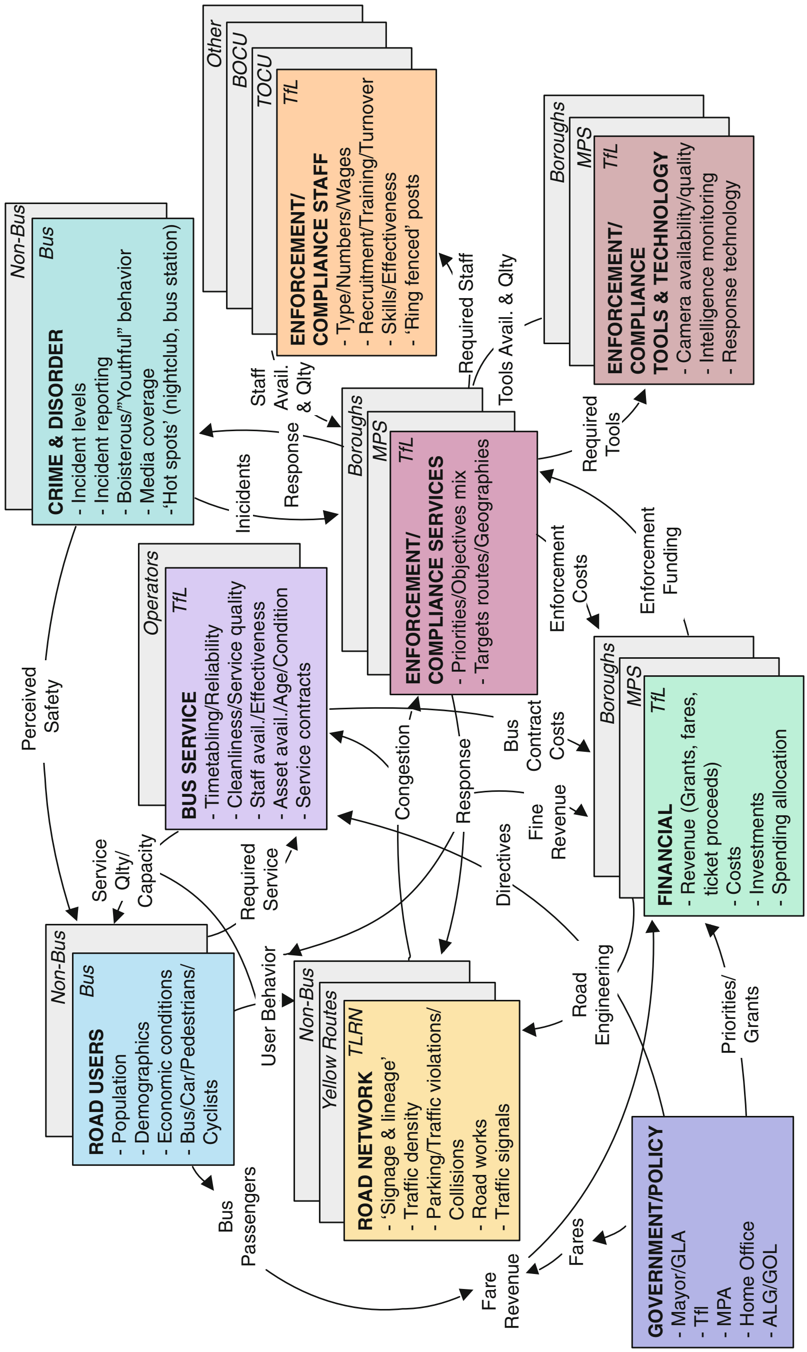


Fig. 1 Block diagram for TfL law enforcement resourcing analysis

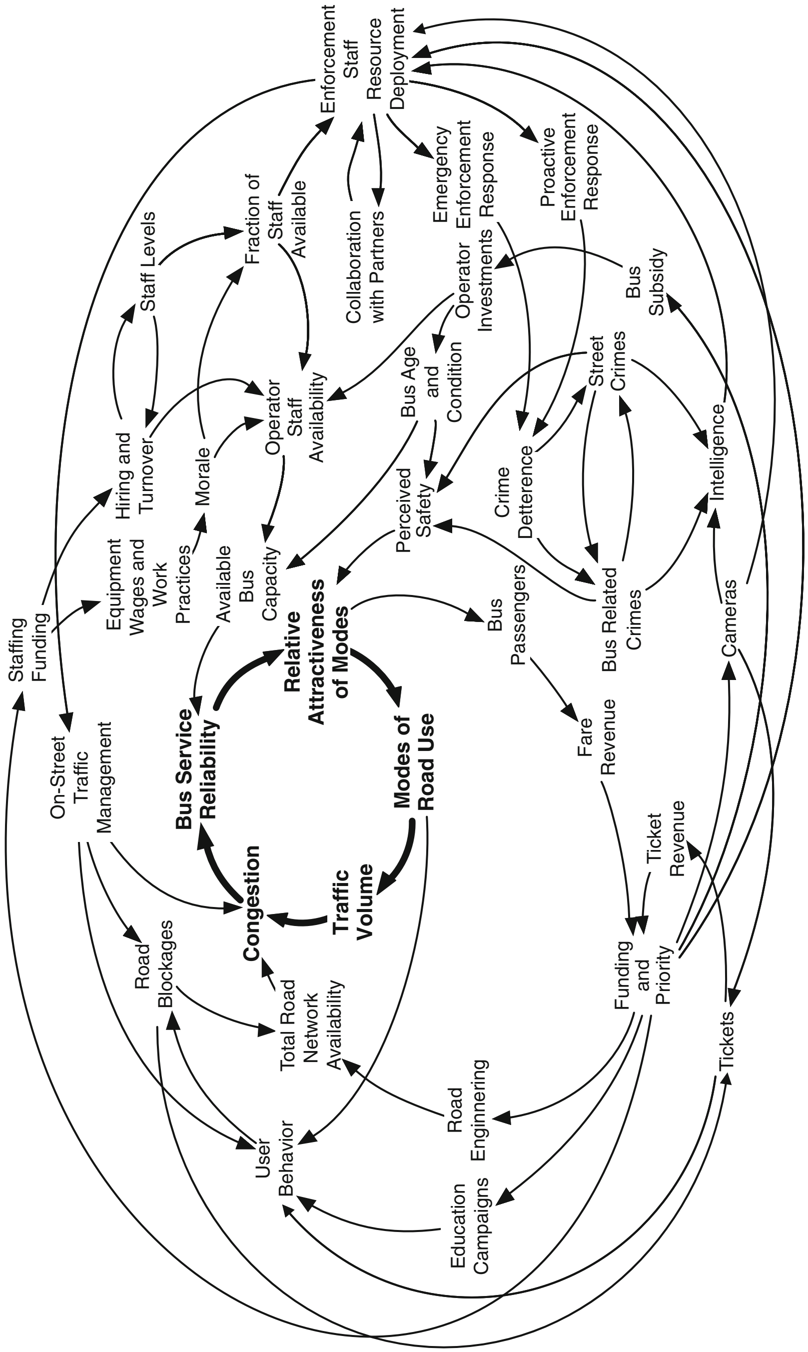


Fig. 2 Causal diagram for TfL enforcement resourcing analysis

The second representation transformed the block diagram into specific cause-and-effect relationships on a *causal diagram*, as shown in Fig. 2. In meetings (in contrast to publications like this book), such diagrams are shown to people as step-by-step buildups so that each piece of the diagram can be discussed and digested before adding more complexity.

The diagram (and its buildup) emphasizes feedback loops, which can have major impacts on the operation of the system and the effectiveness of activities. For example, balancing loops (a.k.a. negative loops) like that highlighted in the middle of the diagram tend to compensate for interventions. A larger number of bus riders leads to more buses and more traffic, which reduces reliability and deters more riders. The operation of such a loop will tend to control ridership relative to what the roadways can carry. By contrast, the other type of feedback loop, self-reinforcing loops (a.k.a. positive loops, or vicious or virtuous circles), tends to amplify the effects of interventions. So a larger number of riders would somewhat deter crimes at bus stops and on buses, which would increase safety and thus ridership.

The causal diagram must also show drivers for outcome measures of interest – what the client is trying to improve, in this case, two measures: perceived safety and bus service reliability.

The modelers sat with SMEs to score each link on the diagram: high, medium, or low strength, and short or long time to impact. (Sometimes, this step is skipped in the interest of time, especially SMEs' time. The omission leads to more uncertainty and to the need for discussions in later steps.)

In general, the next step is for SMEs to trace impacts of the actions under consideration through the various links to the outcome measures of interest. In a simple case, actions will directly change one variable on the diagram, and the SMEs can trace through the impacts on outcome measures of interest and score (High, Medium, Low, or 0–5, or some other scoring scheme). In more complex settings (which includes this case), actions can affect more than one variable on the diagram. In this case, the scoring task can be divided in two: scoring the impact of TOCU activities on the variables, then scoring the impact of variables on the outcome measures. Thus, potential TOCU activities were mapped onto the causal diagram, as shown in Fig. 3. Then, SMEs were asked to trace the path from impact points to outcome measures, looking at the strength and timing ratings of each link along the way, to score each combination of impact point and outcome measure. This scoring was done in collaboration with modelers, who knew from working with all the SMEs what the variables of the diagram were supposed to represent.

In a separate task, the cost of doing each activity at the present levels was estimated so that the cost of each activity at different levels of intensity could be known. The raw scores were first aggregated into a cost-benefit measure of single activities, which were then reviewed and analyzed for sensitivity of weightings, etc. Then, portfolios of enforcement activities at different mixes of intensity were scored and again reviewed, as summarized by Fig. 4, for an assumed increase in total budget. Notice, in that figure, that it is possible to spend more money and get worse results, a reassuringly plausible outcome.

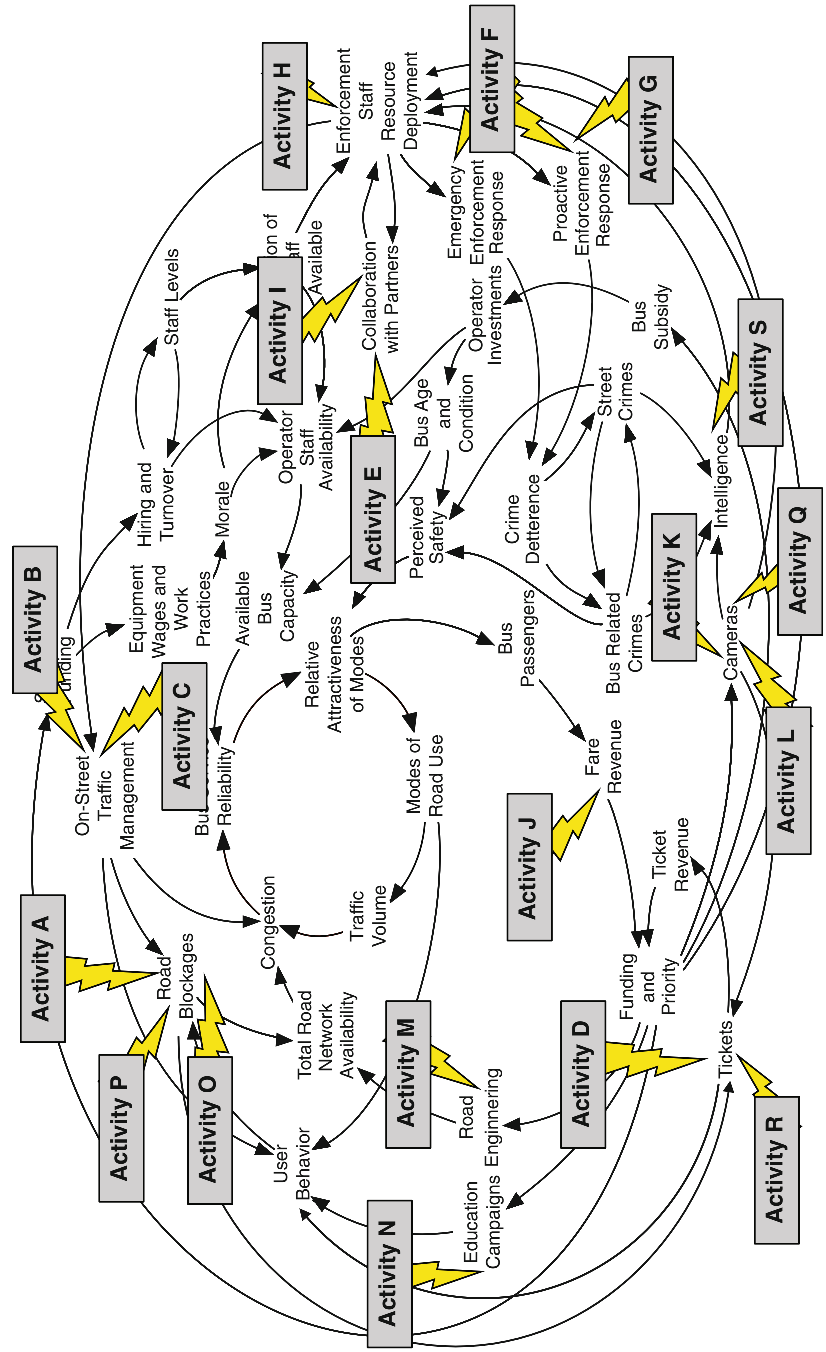


Fig. 3 TfL potential enforcement activities mapped onto the causal diagram

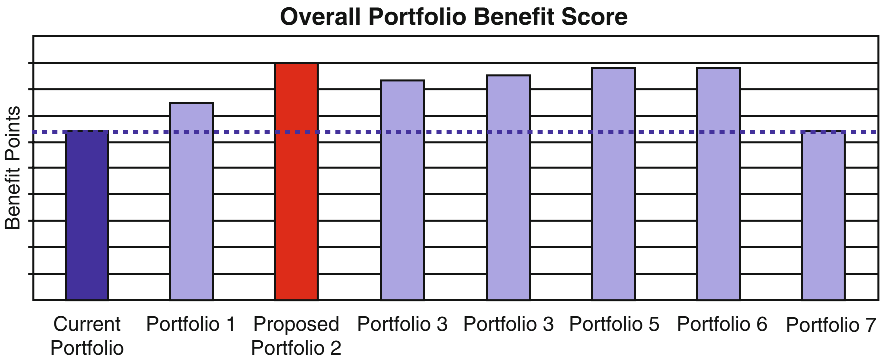


Fig. 4 Final scoring for portfolios of enforcement resourcing strategy

In addition to simplicity of discussion, another reason for looking at portfolios of activities is that some require organizational change, both of who reports to whom, and who works with other divisions. For example, changing the numbers of people working at various activities means changing the number of supervisors and possibly the number of layers of organization. In addition, TOCU staff doing enforcement on buses and on the street would need procedures and points of contact to interact with the regular police. As in corporations, such changes are impractical to execute piecemeal; they are accomplished in a single reorganization.

TOCU decided on a mix of activities and implemented them as it launched itself as a separate unit. The impact of TOCU's activities was immediate and impressive, relative to the undesirable and static situation that had persisted for many years. It increased bus reliability and reduced levels of lost mileage due to traffic problems on the routes it covered. Customer satisfaction improved significantly according to surveys. There was a 14% aggregate growth in the number of people traveling by bus in London in the 2 years following implementation. There were 1,700 arrests by the new unit in the first year for crimes, including robbery, theft, assault, and possession of drugs and weapons. And these arrests have been made in areas that were formerly very lightly patrolled if at all by the MPS. For comparison, there are somewhat over 700 bus routes (Transport for London 2009). Managers at TfL were very pleased with the analysis and the actual results.

If an analyst decides to use this approach, these are the areas to which special attention must be paid:

1. Control the level of detail and the level of abstraction of variables so that the diagram fits on one page and yet captures the essence of what goes on well enough to get the agreement of up to dozens of SMEs. SMEs are able to unleash a torrent of detailed operational knowledge. It is up to the modeler to abstract details into concepts. For example, there are doubtless dozens of different types of crime. A causal diagram, however, should have at most a handful, and perhaps just one.
2. Practice making and discussing several causal diagrams before the final one, or work with someone who has that experience. When one has a facile skill of knowing how positive and negative feedback loops operate, one can identify

important loops during conceptualization (i.e., drawing the causal diagram) and understand their impact during the scoring process.
3. Do a dry run. This prepares the modelers to deal with many of the concepts and questions that will come up during sessions with SMEs and gives the modelers time to think through a scoring system appropriate to the situation at hand: Score links or not? Separate scoring for actions and impact points or not? Experience suggests that the scoring process usually changes slightly from case to case and from problem domain to problem domain.

This case will come back later, in the discussion of model validation. It turns out that the block diagrams and causal diagrams are important and useful steps in quantitative modeling to obtain expert feedback about model purpose, scope, and detail so that such questions can get worked out before the modelers begin writing detailed equations.

That said, we turn now to a different kind of economic modeling, fully quantitative, with the discussion emphasizing the design choices that make models well matched or poorly matched to a specific purpose and use.

5 Case Study: COMPOEX Economic Model

5.1 Model Setting, Purpose, and Methodology

The Conflict Modeling, Planning and Outcomes Experimentation (COMPOEX) project has produced an eponymous planning tool (Kott and Corpac 2007). COMPOEX explicitly accounts for PMSEII effects (Political, Military, Social, Economic, Infrastructure, and Informational effects) through a number of models run together automatically, with a general and uniform facility for testing actions and analyzing results in the aggregate system. Most critically, the methodology for each model is chosen to be appropriate for its own problem domain. In effect, COMPOEX combined a "politician in a box," an "economist in a box," and so on by linking a political model with an economic model, and so on. The COMPOEX Economic Model (hereafter, Economic Model), the topic of this case, attempts to mimic an "economist in a box" by predicting the reactions of markets and actors in the region of interest to U.S. government (USG) operations.[3] Infrastructure is also represented in the Economic Model; investment in infrastructure is an important economic process.

The Economic Model must deal with issues specific to developing countries for which far fewer data are available. Many elements of infrastructure such as electricity, water, and health are sporadically available, and the availability is an important component of both the response to U.S. actions and of limitations and modulators of economic responses. Domestic government responses, particularly biases in distributing and spending among regions and activities, had to be explicitly modeled;

[3]This example is adapted from "Economic Model Capability Description Document" by PA Consulting, March 31, 2008, copyright © PA Consulting Group, Inc. 2008, used with permission.

economists look for redistribution effects, in which availability of aid may reduce the need for the domestic government to spend money. In some regions, financial markets were nonexistent. In some regions, the illicit economy (e.g., growing poppies, white slavery, and smuggling) was a key element in the economy and security planning, over and above the shadow economy of transactions for normal goods and services hidden from government taxation.

The team managing COMPOEX development approached methodology choice essentially with two lists: One list specified a set of PMESII variables of interest derived from various planning documents and prior experience. The other list was modeling teams and people and their methodologies thought relevant to the exercise. Several rounds of discussion assigned responsibility for defining each variable to a modeling team or person.

Data issues, the need for ubiquitous modification of standard economic assumptions, and the availability of system dynamics modelers made that methodology a relatively uncontroversial choice for the Economic Model.

5.2 Scope and Level of Detail

Outputs of other COMPOEX models affect the Economic Model. For example, the Corruption Model influences incentives for capital investment and the government's ability to collect taxes. The Rule of Law Model (representing police and the criminal justice system) and the Military Model take a portion of government revenues to support.

Similarly, the Economic Model affects other COMPOEX models. When the Rule of Law Model or the Military Model invest funds to purchase plant and equipment (representing buildings, vehicles, and hardware), the Economic Model tracks the accumulation and depreciation of that plant and equipment, which goes back to influence the effectiveness of law enforcement and military operations. The Economic Model tracks employment in the Rule of Law Model, the Military Model, and in the illicit activities sector inside the Economic Model, accounting for all labor in the country.

An important question is which economic sectors should be modeled separately. The needs of the other specialized models suggest separate representation of Rule of Law, Military, and illicit activities. Beyond these, planners have particular interest in actions that impact different types of infrastructure, particularly those supported by the government, or mixed public and private infrastructure (such as education and health care). Therefore, the Economic Model has separate representations for the industries that produce education, health care, transportation infrastructure, power and telecommunications, shelter, water and sanitation, and other government services. The "private sector" includes only two industries: agriculture (a major factor in most developing nations) and all other goods and services. This mix of detailed public sectors and highly aggregated private sectors is nearly the reverse of typical macroeconomic models of developed countries.

The importance of education and technological expertise in developing economies has given rise to the "human capital" school of development economics (Eatwell et al. 1987 v1, pp. 818–825; Sen 1985; UN Development Programme 2009). The Economic Model represents human development relatively simply, by separately tracking blue-collar and white-collar labor, with the mix determined over time by a combination of education, work experience, and work opportunities. The mix and experience base of labor impacts productivity and production of each type of good or service (including education).

Economic sectors interact in several ways. They all participate (along with the household sector) in a labor market, with variable wages. The government and consumers allocate spending among economic sectors. The government collects taxes from households and private sectors and makes spending decisions for the public goods. Households decide whether to spend or save, and to varying extents, businesses are able to turn to external financing, ultimately from the householders.

The financial sector and treatment of financing in this model is simpler than would be the case for an economic model whose purpose was monetary and fiscal policy. A single financial instrument aggregates debt and equity, and there are no explicit financial intermediaries so that the household holds net assets and the public and private sectors hold net liabilities. Tax revenues and an acceptable level of deficit spending govern public borrowing. This simplistic treatment is sufficient to allow the model to be the "economist in a box" and provide warning if, e.g., an action produces crowding out in the financial markets (if there *are* financial markets). While imports and exports for each industry are explicit, exchange rates are assumed constant, since for various reasons they were not at issue for the regions to which the Economic Model has been applied.

Figure 5 shows a top-level view of the Economic Model. Ovals are groups of equations (often themselves organized hierarchically into groupings that are more detailed). The heavier lines show the simple linkages of textbook economics: The Population Needs combine with available Finances to create Demand (and Importing and Exporting) of products. That demand both creates Employment and justifies investment in Physical Infrastructure. These combine to create Production. Employment creates wages that feed back into Finances. Production creates tax revenues, which also feed back into (government) finances.

The Macro Finance group is where interest rates strike the balance between household saving and industry and government need to borrow. The Macroeconomic Performance group, its name somewhat to the contrary, is where measures of macroeconomic performance such as GDP and its components are *computed* from activities performed elsewhere.

The Economic Model has around 1,300 equations, many of them repeated (with different parameters) for different geographic subareas and different economic goods and services. The simulation starts at the year 1995 and simulates forward in time steps of ¼ week. The simulation was compared to time-series data generally between 2001 and 2006 (due to poor data availability both before and after that time period). The analysis used the simulation from the beginning of 2008 to the beginning of 2011. Standalone, the 1995–2011 simulation took about 9 s on a laptop.

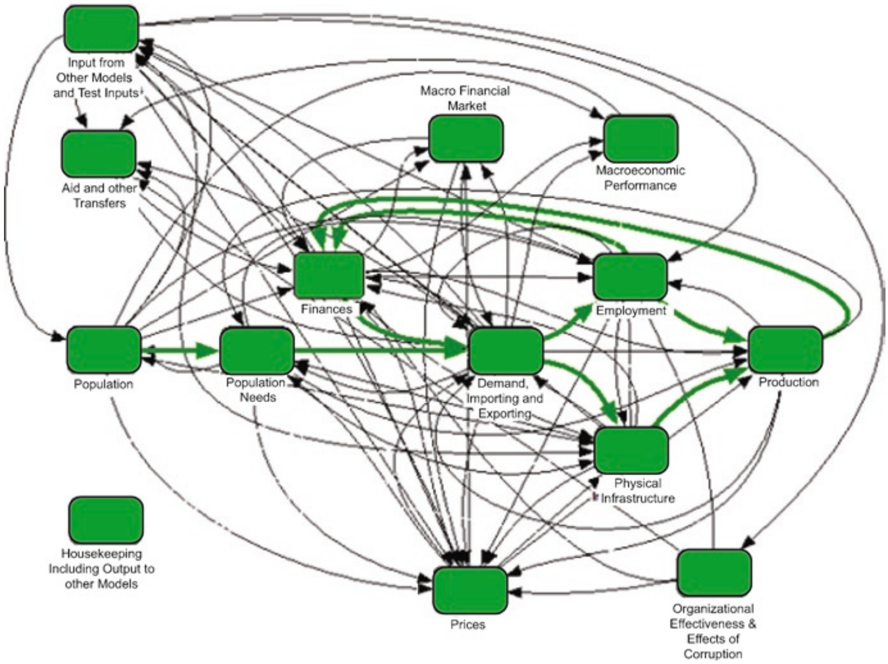


Fig. 5 Top-level view of the COMPOEX Economics Model

5.3 Numerical Example

Both as an entrée to the system dynamics methodology and as a simplified example of one portion of the Economic Model, the Employment Group, this section gives an extremely simplified example of how a system dynamics simulation model works numerically. The commentary will describe some of the issues that differentiate the simple example from what is actually in the model. To give a measure of perspective, the example here is perhaps 20 times simpler than the corresponding piece of structure in the economic model, and the labor sector is perhaps a tenth of the whole model.

5.3.1 Flow Diagram

Figure 6 illustrates several of the key concepts used to structure system dynamics models. The rectangles (Agricultural Employment and Unemployed Workers) represent stock variables. These variables can, in principle, be counted or measured at any moment in time. The "bow tie" variables (Separation Rate, Hiring Rate) represent flow variables, which have no instantaneous meaning and are defined only as

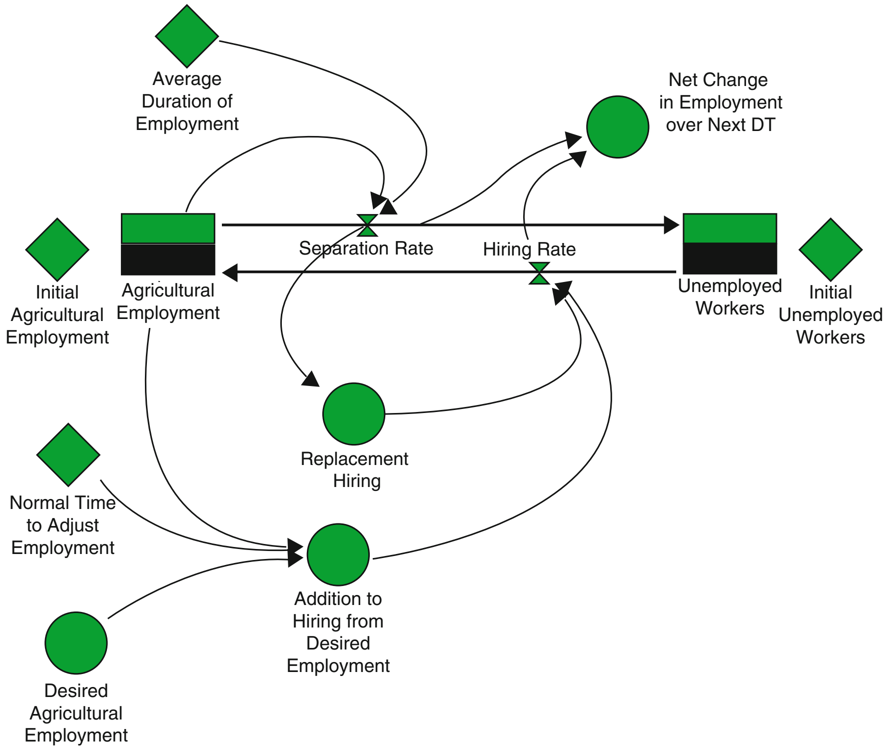


Fig. 6 Flow diagram for numerical example

occurring over an increment of time. Over time, flows accumulate to change stocks, and in a feedback system, the values of the stocks influence the flows.

In Fig. 6, the diamond symbols are constants, which have the same value throughout a simulation. The round symbols represent arithmetic computation performed at a single instant in time. Although they could be folded into the flow equations, they are separated both to simplify the presentation of the algebra and to allow a priori estimation of the constants involved.

The constants next to the stock variables (Initial Agricultural Employment and Initial Unemployed Workers) set the initial values of the respective stock variables. For simplicity, the information flow from initializing constants to stocks are not shown, since they have no further effect once the simulation is started.

Even at the level of flow diagram, several simplifications relative to a full macroeconomic model are evident: there is no feedback from Unemployed Workers. A more complete model would have Unemployed Workers (or their absence) affecting the speed of hiring (constant here, characterized by the Normal Time to Adjust Employment). And Unemployed Workers (or their absence) would also change wages, which eventually would have an impact on the number of workers desired (Desired Agricultural Employment). Of course, that would depend on whether other *factors of production* (such as better irrigation systems, better fertilization and pest control, mechanized planting and harvesting, allowing land to lay fallow, etc.) are available and cost-effective to substitute for labor. Finally, each distinct economic sector (education, power and communications, military, etc.) would need to keep track of its own stocks of employees, both white-collar and blue-collar.

5.3.2 Equations for Stocks

$$Agricultural\ Employment_{(t+dt)} = Agricultural\ Employment_{(t)} + (Hiring\ Rate_{(t)} - Separation\ Rate_{(t)})*\ dt$$

$$Agricultural\ Employment_{(t0)} = Initial\ Agricultural\ Employment$$

$$Unit:\ people$$

$$Initial\ Agricultural\ Employment = 1000$$

$$Unit:\ people$$

$$Unemployed\ workers_{(t+dt)} = Unemployed\ workers_{(t+dt)} + (-Hiring\ Rate_{(t)} + Separation\ Rate_{(t)})*\ dt$$

$$Unemployed\ workers\ _{(t0)} = Initial\ Unemployed\ Workers$$

$$Unit:\ people$$

$$Initial\ Unemployed\ Workers = 100$$

$$Unit:\ people$$

Knowing the initial condition for each stock and the rates of flow, the equations above compute the value of the stock at the point in time, dt (“delta time”) later.

The rates of flow are measured in terms of people per week, so multiplication by dt gives the change that should occur over the time interval of dt. This convention allows convenient units of measure (weeks, months, years) separate from the computation interval. The assumption here is that the dt is short enough that it is a reasonably accurate assumption that the flow rate does not change in the time from t to t+dt. This is a testable assumption.

Those with mathematical background may recognize this arithmetic as simulating the integral form of an ordinary differential equation by Euler integration. But the mathematical terminology does not change the fact that, at heart, this simulation is a straightforward process.

Estimating the initial stocks of people in a real economic sector is usually straightforward; virtually, all national governments estimate the size of their population, keep track of unemployment, and estimate rough distribution of employment by occupation. (For other economic quantities, the Economic Model started from physical units of measure such as square feet of housing, kilowatts of electrical generating capacity, calories per day of food, and so on to facilitate a priori estimation of quantities present in the economy. The monetary transactions regarding these goods and services then had separate equations and were measured in currency units per week.)

5.3.3 Hiring and Separation Rates

$$Hiring\ Rate_{(t)} = Replacement\ Hiring_{(t)} + Addition\ to\ Hiring\ from\ Desired\ Employment_{(t)}$$

$$Unit: people / week$$

$$Replacement\ Hiring_{(t)} = Separation\ Rate_{(t)}$$

$$Unit: people / week$$

$$Separarion\ Rate_{(t)} = Agricutural\ Employment_{(t)} / Average\ Duration\ of\ Employment$$

$$Unit: people / week$$

$$Average\ Duration\ of\ Employment = 50$$

$$Unit: weeks$$

The hiring rate represents a simple heuristic: Hire to replace people who leave plus a bit more if more employees are desired.

The Average Duration of Employment is set to have a round number for computations rather than to be realistic. The equation implies that each week, 1/50th of the workers separate (quit or are fired), for an average duration of slightly less than a year. In industrial economies, the figure is closer to a 2-year average. In the setting of a developing economy, 50 weeks implies separation on average after every season of agricultural employment, which is probably too short. But 50 weeks is a nice round number for the numerical example coming shortly.

5.3.4 Hiring to Change Employment

The component of hiring that deals with a need to change the number of agricultural employees is the simplest possible formulation: If there is a difference between desired and actual employees, hire proportional to that difference:

$$Addition\ to\ Hiring\ from\ Desired\ Employment_{(t)} = (Desired\ Agricultural\ Employment_{(t)} - Agricultural\ Employment_{(t)}) / Normal\ Time\ to\ Adjust\ Employment$$

$$Unit: people / week$$

$$Normal\ Time\ to\ Adjust\ Employment = 2$$

$$Unit: weeks$$

The division by a time constant is usually preferable to multiplication by some number. Here, it is easier to understand "on average it takes 2 weeks to get the number of employees to where you want" than it is to attach any intuitive meaning to "multiply by 0.5." Two weeks is probably short for changing employment in an aggregate economy, but it is conveniently short for the numerical example.

5.3.5 Exogenous Input

In this simple system, Desired Agricultural Employment is considered to be determined outside the dynamic system (exogenous = "born outside"), and so is modeled as a simple function of time:

$$\textit{Desired Agricultural Employment}_{(t)} = \textit{If } t < 2 \textit{ then } 1{,}000, \textit{else } 1{,}050$$

$$\textit{Unit : people}$$

In the Economic Model, the Desired Agricultural Employment is determined by demand for agricultural products, wage rates, productivity,and other factors.

5.3.6 A Supplementary Equation

Sometimes, one defines a variable merely to monitor it, even though it is not needed to conduct the simulation itself. Here, the numerical example will break out the last part of the equation for Agricultural Employment as a separate quantity:

$$\textit{Net Change in Employment over Next DT}_{(t)} = (\textit{Hiring Rate}_{(t)} - \textit{Separation Rate}_{(t)}) * dt$$

$$\textit{Unit : people}$$

5.3.7 Specifying the Simulation Routine

Finally, to conduct a simulation, one defines the parameters of the simulation process: the time when the simulation starts

$$t0 = 0$$

The time interval ("delta time") that occurs between simulation steps

$$\mathrm{d}t = 1$$

The time at which to stop the simulation

$$\mathrm{LENGTH} = 20$$

and (for simulation software), how often (i.e., at what interval) to save the results for later examination.

$$\mathrm{SAVPER} = 1$$

The equations above completely specify a simulation, which starts at the initial conditions and uses the flow equations to compute the stocks at the next time interval, which are the basis for computing the flows, and so on through simulated time until the end.

Figure 7 shows the computation specified by the equations above carried out in a spreadsheet format.

Time (weeks)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Agricultural Employment (people)	1,000.0	1,000.0	1,000.0	1,025.0	1,037.5	1,043.8	1,046.9	1048.4	1,049.2	1,049.6	1,049.9	1,049.9	1,050.0	1,050.0	1,050.0	1,050.0
Separation Rate (people/week)	20.00	20.00	20.00	20.50	20.75	20.88	20.94	20.97	20.98	20.99	21.00	21.00	21.00	21.00	21.00	21.00
Replacement Hiring (people/week)	20.00	20.00	20.00	20.50	20.75	20.88	20.94	20.97	20.98	20.99	21.00	21.00	21.00	21.00	21.00	21.00
Desired Agricultural Employment (people)	1,000.0	1,000.0	1,050.0	1,050.0	1,050.0	1,050.0	1,050.0	1050.0	1,050.0	1,050.0	1,050.0	1,050.0	1,050.0	1,050.0	1,050.0	1,050.0
Addition to Hiring from Desired Employment (people/week)	0.00	0.00	25.00	12.50	6.25	3.13	1.56	0.78	0.39	0.20	0.10	0.05	0.02	0.01	0.01	0.01
Hiring Rate (people/week)	20.00	20.00	45.00	33.00	27.00	24.00	22.50	21.75	21.38	21.19	21.09	21.05	21.02	21.01	21.01	21.00
Net Change in Employment over Next DT (people)	0.00	0.00	25.00	12.50	6.25	3.13	1.56	0.78	0.39	0.20	0.10	0.05	0.02	0.01	0.01	0.01

1. When employment = desired employment...

2. ...there's no addition to hiring at replacement...

3. And there's no net change in employment from one time period to the next...

4. ...which shows up as the starting point for the next time period

5. But when desired employment steps up...

6. ...The discrepancy (50) drives additions to hiring (50 / 2), but replacements are still at 20 / week, so...

7. ...net hiring is just the addition at first, 25 people

8. So employment increases by 25 at the next time period

9. As employment rises and gets closer to...

10. Desired employment,...

11. ...The needed additional hiring is declining toward zero, ...

12. ...as is the change in employment from time period to time period

Fig. 7 Annotated step-by-step computation for the agricultural employment example

The numerical simulation will be familiar to some spreadsheet users, especially those who compute evolution of a balance sheet over time. Spreadsheets can and have simulated models formulated according to system dynamics standards. But for complex models, specialized system dynamics simulation software is vastly easier to use, and creates models that are far more transparent. In addition, the formulas that create future behavior must be the same formulas that create past behavior, which helps make a powerful validation statement: The rules used to project forward are exactly those that created (roughly) the past behavior.

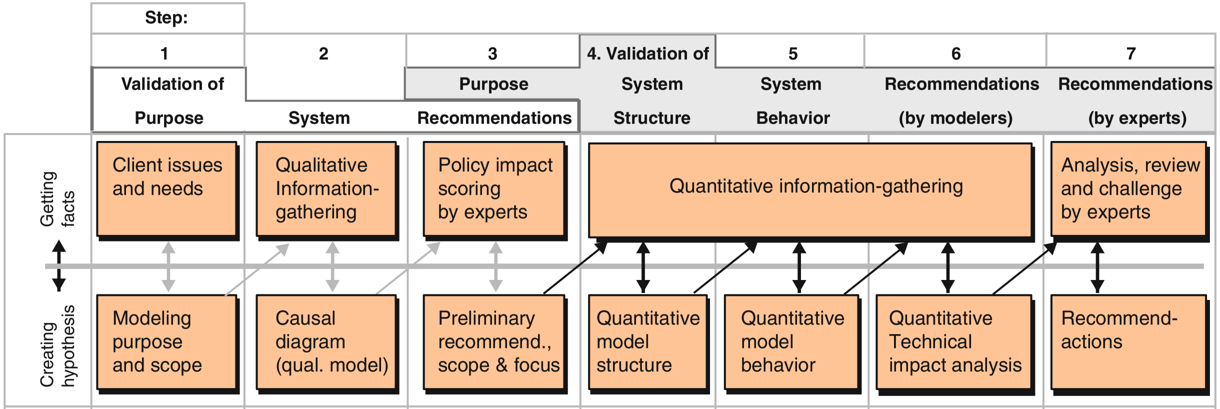
5.4 Validating the Model

In textbooks and academic papers, validation is often pass-fail: The hypothesis fits the data well or not. Modeling to support real-world decisions is more complex. The modeler must (implicitly or explicitly) test three generic hypotheses:

1. That the modeler understands what the user (client) wants to achieve, and what means are available to achieve them – this is the model purpose. Unless the intended model use is for short-term budgeting, forecasts as such are rarely the actual use. More typically, the use is taking action to change one of the behavior modes we discussed earlier or to assess the medium- and long-term investment climate. Both these call for models that deal with the economic (and near economic) behavior modes relevant to a given region. Principles of specifying model purpose are discussed in Sterman (2000, Section 3.5.1). Graham (2009b, Section 2.1) presents diagrammatic tools for validating model purpose.
2. That the modeler has captured in the modeling how the real-world system works, in terms and at a level of detail and scope appropriate to the purpose. Sterman (2000, Ch. 21) describes validation tests of model structure and baseline behavior. Classic statistical tests are a subset of these.
3. That the modeler understands the impacts of the actions being analyzed by the simulation experiments and why they happen, particularly those with favorable outcome that the analysis finally recommends. Such understanding can become a "model of the model" that explains in the simplest possible terms why some actions turn out to be desirable and others do not. Sterman (2000, Ch. 21) describes validation tests of model analysis-based recommendations.

There is one additional wrinkle to system dynamics modeling, which is, the three validations above are often done twice, once with a diagrammatic systems thinking "model" in which SMEs go through scoring exercises to start to quantify the model and policy impacts and once again with a fully quantified simulation model. Lyneis (1999) gives real examples of the whole process in corporate strategy. Mayo et al. (2001) provide a particularly well-worked out public policy example.

Figure 8 gives a stylized view of simulation model construction and validation. Each column represents one round of hypothesis testing and evolution of the analysis. The unshaded headings (steps 1–3) describe the three hypothesis tests for the



	1	2	3	4	5	6	7
Format of hypothesis	Analysis and Use Requirement Diagram, model "will and won't"	Block diagram, Causal diagram	Causal tracing and scoring, interpretation	Equations and parameters	Comparison of simulated to observed behavior, rough expectations in testing	Rough expectations for behavior in policy testing	Expert expectations for heavier in policy testing
Typical validation tests	Kickoff meetings with stakeholders validate purpose of modeling	Boundary adequacy	Structure assessment: Consistency with known facts Level of aggregation consistent w purpose & facts Conservation laws represented Decisions mappable to specific actors or groups?	Structure assessment Dimensional consistency Parameters have real-world counterparts & values Response to extreme conditions	Calibration Input/output Extreme conditions Behavior sensitivity Challenge behavior hypotheses ("model of the model")*	System improvement Policy combination Policy sensitivity Challenge improvement hypotheses 9"model of policy impact")* Fit-constrained parameter Monte Carlo test of improvement*	Expert review of analysis summary and "model of the model"
Validation tests for COMPOEX	COMPOEX user feedback on inputs and outputs, generally correct	Skipped, given development process and reasonably well-known structure for economic behaviors	Modified organization of MIT National Model (Forrester 1989)	Validation by construction for generally neoclassic formulations	Some time series comparison, tested all DIMEFIL actions, some initial condition & other step inputs	Third party tester traced impacts of all DIMEFIL actions	Review of model behaviors and causes during workshops and wargame

Fig. 8 Steps of simulation model evolution, with validation activities

systems thinking model and analysis by scoring. Each shaded column (steps 3–7) represents the hypothesis tests of purpose, system, and analysis for a simulation model. Step 3 shows an overlap between the analysis validation step for the diagrammatic model with the purpose validation step for the simulation model. Step 3 is a decision point, whether the additional effort of creating a simulation model is useful and appropriate. And if a simulator is useful, the diagrammatic exercise will likely have changed the stakeholder's ideas about the model scope and what policies should be analyzed.

Steps 4 and 5 break the validation of the model system into two parts for convenience, since the tests of pieces of the model (step 4) can be quite different from tests of the larger model (step 5). Similarly, steps 6 and 7 break the validation of the analysis into those conducted by the modelers from those conducted by SMEs, again because the tests are quite different.

Each step of hypothesis testing includes a form of fact gathering and summarizing those facts into a hypothesis, which can be tested. These are the first three rows in Fig. 8. The fourth row describes typical tests, generally using the vocabulary of Sterman (2000, Ch. 21). The previous discussion in this chapter has given examples of three of the formats for hypotheses (block diagram, causal diagram, and equations).

Few analysis efforts do all possible validation tests. Indeed, only simulation analysis for legal disputes comes close to doing everything (Stephens et al. 2005). The last row describes the validation testing used for the Economic Model operating within the COMPOEX system. For the COMPOEX purpose of demonstrating sensible and generally plausible and useful results for an economic model working in harmony with other, equally specialized, models, these validation activities seemed sufficient. "Validation by construction" here means using pieces that have been validated individually elsewhere. The COMPOEX economic model was able to borrow heavily from earlier research on economic dynamics, both in overall architecture and organization (Mass 1975; Sterman 1982; Forrester 1989) and more specifically for labor markets (Runge 1976), financial markets (Low 1977), and capital investment (Senge 1978).

One type of validation test is often misunderstood, as it differs fundamentally from a common and seemingly related statistical process. In standard statistical regression, as commonly taught in MBA programs and initial economics courses, one specifies an equation form and uses data (and mathematics embedded in software) to find parameter values that best fit the data.

In system dynamics modeling, the equations and parameter values are both set by a priori information: firsthand knowledge of cause and effect in the real system, derived from background reading and interviews with SMEs. "Calibration" or "behavior reproduction" validation tests are passed when the simulator, driven by a handful of exogenous variables, steps through simulated time to create a simulated history that *independently* reproduces the behavior of time-series data that correspond to model variables. This test is extremely useful in detecting formulation and parameter errors (and data errors).

However, there is one circumstance in which this test can be misleading: Cyclical behavior (such as the business cycle, described briefly in Table 3) that is generated by systems responding primarily to many unknown random events need to be tested differently. To simplify: Simulations of such systems will not have the same inputs as the real system, so simple comparison of simulation to time series data is not meaningful. The economic business cycle and some commodity markets have this characteristic.

For such cases, one must either test for invariant characteristics (e.g., phase and amplitude relationships among variables) (Forrester 1961, Section 31.5) or use some variant of weighted least squares (which includes full-information maximum likelihood) using Kalman filtering (Schweppe 1973), a mathematical technique generally restricted to models in the form of state-space dynamic systems, which system dynamics simulators do have. Graham (2009b) further discusses this issue in model testing.

Figure 9 shows (disguised) behavior reproduction of GDP for three countries in one version of the COMPOEX Economic Model (clearly not dominated by cyclical behavior).

Of course, the simulation will not match any of the time series at first. But the only changes allowed to the modeler are cause-and-effect relationships and parameter values, both to be constrained by the a priori knowledge of what is plausible and what is not. Achieving such consistency is usually a nontrivial challenge. In a feedback system, if one variable differs from what happened in real life, the variables that it drives will be off, which throws off the variables they drive, and so on. Moreover, because any one change usually affects multiple variables, simple curve-fitting is not possible.

Passing a single validation test, even a difficult one like the behavior comparison test, does not prove that the model is correct. The only thing that any validation test ever does is fail to disprove a hypothesis. Therefore, a successful behavior

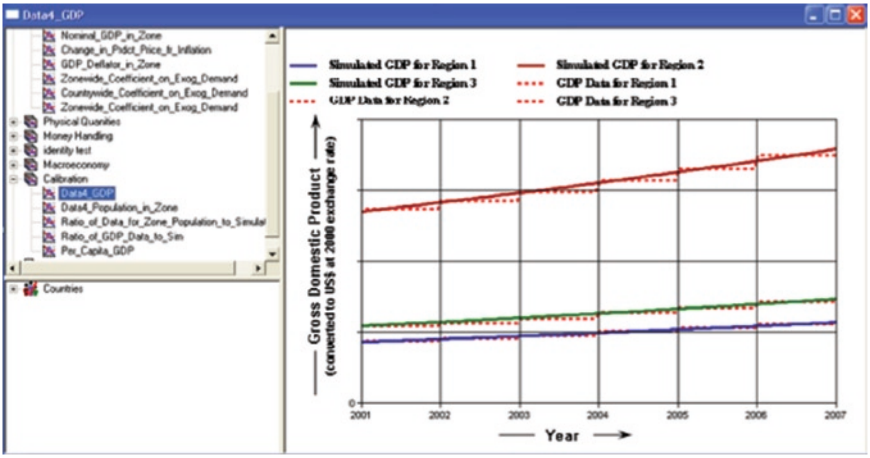


Fig. 9 Example of one (typically of many) validation plots comparing the historical time series for a variable to the independently-produced simulation of that same variable, here gross domestic product (GDP)

comparison test fails to find inconsistencies between the a priori plausible structure and parameter values and the multiple time series of observed behavior.

5.5 Findings: Use of COMPOEX Model

The COMPOEX system has been implemented several times, representing a few different regions of interest. These systems have been tested in workshops involving planners and SME's in hypothetical planning exercises, in addition to formal system testing and review by SMEs. It was also used in a war-game exercise to support white team (referee) adjudications that determined consequences of actions by the various teams after each round.

The experiment might be called reasonably successful, in that the Economic Model functioned much as experts do, pointing out unintended consequences and unexpected (or not entirely expected) results in the exercises. A few of these were:

- *Scale*. Many developing countries have populations in the hundreds of millions. Many have economies that are supported by oil revenues or other natural resource exports. An aid project measured in mere millions of dollars will generally be too small to have a substantial impact on the economies. Yet too often, the planning and intention of aid programs still proceed under the assumption that the U.S. aid in the millions will have an effect that will be noticed and appreciated.
- *Coupling actions to media coverage*. Although too small to have measurable effect on the overall economy, actions can be turned into media events, which are opportunities for a message to reach national audiences. It is all too often the case that the U.S. good works and constructive engagement do not achieve public visibility nor on message communication with the public of the host nations. In COMPOEX, planners were able to couple media actions with economic actions to achieve larger and much broader effects than could be achieved without media effects.
- *Reducing corruption and increasing government effectiveness*. In general, corruption increases investment risk and the effective cost of capital and siphons off cash. Corruption consumes especially white-collar time and productivity in making new capital investments. Moreover, corruption reduces the ability of the host government to collect taxes and thus to finance development. Government lack of effectiveness functions in some aspects similarly to corruption; indeed they can often be closely linked. Actions that reduce corruption or increase the effectiveness of government spending, and government regulation can have a major economic impact.
- *Price or wage feedback*. Giving aid money to one sector will increase wages and prices in the targeted sector. This reduces both the effectiveness of the aid and the free-market demand due to higher prices. For example, a country experiencing high food prices may attempt to get more food for its population by prohibiting food exports. This works partially, but it lowers the incentive to domestic farmers

to produce food, so the additional food obtained for the domestic population will be less than what was exported formerly. Therefore, despite government actions, food would remain a critical issue. This is a textbook example of feedback loops defeating the intent of policy interventions (Forrester 1971).

- *Substitution*. To the extent that giving aid to provide a good or service actually alleviates the shortage of that good or service, the incentives for the host nation government, local corporations, or private individuals to provide that good or service is reduced. Less money will be spent on the targeted goods and services, and more money will be spent in other places. To some extent then, even targeted aid will have a diffuse effect across many goods and services through substitution of aid for other sources of support.
- *Arithmetic for complex situations*. Aggregate economic performance measures can contain hidden surprises. For example, in some circumstances, increased hiring in a sector may cause average wages to go down. This happens when white-collar employees are scarce and their wages are substantially higher than those of blue-collar workers. If the additional hiring is mainly blue-collar workers, even though wages for both white- and blue-collar employees go up, average wages will go down because the mix changes.

6 Practical Tips

- Even if quantitative modeling seems unlikely, collect the available indicator data early in the project; one needs to know where problems are likely to arise. Deep is nice, but broad is necessary. Indicator data helps to control (restrict) the scope of subsequent quantitative modeling. In terms of project management, data collection is usually the longest single task and should be started early, even if all specifics are not nailed down.
- Resist a common request from the modeling client for a broad, unfocused forecast. Such an open-ended mission is bound to fail. The resulting model will forecast the overall economy poorly and miss details and behaviors that are critical to the specific decisions that the model should support. Eventually, good analysis will require searching for specific conditions and events that could undermine the conclusions and recommendations of the analysis. If the modeler does not know what recommendations the analysis will be used to support or reject, it will be impossible to do a good job of sensitivity analysis.
- Involve stakeholders throughout the modeling process and in their terms. Modeling effort is wasted if it does not influence action, which means the modeling must result in believable conclusions for the end user. Certain techniques, such as benchmarking, expert seminars, or war gaming, are compelling for analysts but not for decision-makers. Choose an analysis method with an understandable audit trail from the evidence to conclusions. One benefit of a quantitative systems thinking exercise (described in this chapter) is that all of the process is visible and comprehensible to stakeholders.

- Integrate available knowledge with "quantitative systems thinking" (as in Table 7 and the first case) first, even if quantitative modeling follows. Resist the temptation to dive into equation writing. Identifying an instance of too much detail is far easier to fix on a diagram than in equations.
- Check the capability of candidate models against the behaviors of interest to a client. For instance, in making an investment, currency crises may be important, especially if indicator variables show vulnerability to currency crises. Thus, if a model is to serve as support for investments, it must be able to represent the dynamics of runaway currency crises and indicate whether vulnerability is likely to increase or decrease.
- Use "what would have to be true" analysis to mitigate uncertainty of economic models. An important way to create robust conclusions that help real decision-makers is to use the model to find the assumptions (usually extreme) that would invalidate the recommendation. For example, suppose a billion-dollar investment in a developing country was hedged with certain financial arrangements. And, suppose the model of the investment and its hedges shows that the currency would have to decline to 1% of its current value before the investment lost money. If this decline were judged to be well outside a plausible range, then the investment decision would be robust, even though currency exchange rates are very unpredictable.

7 Summary

To select, and effectively employ the model best suited for a specific economic problem, one starts with understanding the purpose (particularly, the intended decisions) of modeling and analysis, then gathers data on the economies being studied to identify actual and potential "behavior modes," i.e., known patterns of economic behavior and their cause-and-effect origins. They define the elements that the analysis needs to deal with. We classify such behavior modes and analytical and modeling approaches along with zones of applicability for each.

In one case study, the Transport for London (TfL) agency wished to optimize allocation of the available funds, in order to increase public transportation safety and service reliability and to cope with congestion charges on automobile use in central London. Using quantitative systems thinking approach, the analysts and SMEs developed a block diagram and then a causal diagram. Then, SMEs scored the strength and time delays of each link in the causal diagram, and the direct impacts of each potential action on causal diagram variables. Finally, the SMEs traced all major paths from each action to the two outcome measures, safety and reliability. The resulting portfolio of recommendations was implemented, and measures of safety and reliability were substantially improved.

The second case is economic modeling in COMPOEX, a system that helps government planners understand consequences of interventions in a region of interest. The economic model represents supply and private and government demand in government-funded or mixed-funded sectors such as health, power and communications, water and sanitation, and education; also the illicit goods and services sector, which draws revenue from corruption and direct sales. Economic performance in the economic model also feeds the power struggle model and the population satisfaction model within the COMPOEX system.

Validation of decision-oriented economic models occurs during the entire modeling process, e.g., in seven phases for system dynamics models. Validation testing should address three fundamental hypotheses: (1) the purpose is validated; (2) the model is validated; and (3) the results are validated.

8 Resources

8.1 Economic Behaviors and Data

1. "Near-economic" behavior modes

   Theories of political power: (Bueno de Mesquita et al. 2002, 2004)

   Statistics:

   United Nations Universal Human Rights Index
   http://www.universalhumanrightsindex.org/

   World Bank Governance Indicators
   http://info.worldbank.org/governance/wgi/sc_country.asp

   Internet Center for Corruption Research
   http://www.icgg.org/corruption.html

   Transparency International
   http://www.transparency.org/

   Economist Intelligence Unit Country Reports. London: The Economist Group

   Freedom House
   http://www.freedomhouse.org

   Human Rights Watch
   http://www.hrw.org/

   Amnesty International
   http://www.hrw.org/

   Gallup Country Stability Index (Gallup Corporation 2009)

2. Secular industrialization, demographic transition

   (Caldwell 1976; Caldwell et al. 2006)

   Statistics:

   United Nations Economic and Social Development theme
   http://www.un.org/esa/

   UN Development Programme, Human Development Report and Human Development Indices
   http://hdr.undp.org/en/humandev/hdi/
   (IMD various years)

3. General macroeconomics

   General economic theory: (Samuelson and Nordhaus 2004)

   International economic theory: (Curry 2000; Krugman and Obstfeld 2008; Gandolfo 2002)

   Statistics:
   Fedstats (aggregation of US government data) http://www.fedstats.gov/

   International Monetary Fund, Washington, DC
   http://www.imf.org/external/pubs/ft/weo/2008/02/weodata/index.aspx

   United Nations

   World Bank, Washington, DC
   http://www.worldbank.org/

   Federal Reserve System, Flow of Funds Accounts of the United States
   http://www.federalreserve.gov/releases/z1/

4. Business cycles

   Theory: (Mass 1975; Forrester 1982; Forrester 1989; Sterman 2000)

   Statistics:

   US: National Bureau of Economic Research, Cambridge, Massachusetts. http://www.nber.org/
   World: Economic Cycle Research Institute, New York and London. http://www.businesscycle.com/

5. Trade balancing through the exchange rates

   (Curry 2000; Gandolfo 2002)

6. Currency exchange mercantilism

   (Burgess et al. 2009; Das 2009)

7. Import dependence and stagflation

   Models: (Bernanke and Blinder 1988; Godley and Lavoie 2006)

8. Capital flight

   (Shibuya 2001)

9. Debt-deflation spiral

   Models: (Von Peter 2005; Sterman 1986)
   Descriptive analysis: (Graham and Senge 1980; Graham 1982; Koo 2008)

10. Deficit-lead hyperinflation

    Models: (Taylor 1991)
    Description: (Krugman and Obstfeld 2008)

11. Currency crisis/investment boom and bust, currency exchange defense

    Models: (Krugman 1999)
    Descriptive analysis: (Krugman 2009)

8.2 Analytical Methods

1. Economic models generally

   Journal of Economic Literature, which publishes only review articles on economic topics, will intermittently include macroeconomic models.

2. Quantitative systems thinking

   (Lyneis 1999; Mayo et al. 2001; Sterman 2000, Ch. 5)

3. Analytical models

   (Samuelson and Nordhaus 2004; von Peter 2005; Krugman 1999; Solow 1956, 1957)
   http://en.wikipedia.org/wiki/Exogenous_growth_model

4. General equilibrium

   Large numerical GE: (Inforum 2009; Kubler 2008)

   Small analytical GE:

   ISLM analysis in any macroeconomics textbook, e.g., (Samuelson and Nordhaus 2004)

   More modern small GE models are actually market equilibrium and steady-state growth (Solow 1956, 1957; Foley and Sidrauski 1971; Romer 1990)

5. Single-equation regression and stochastic models

   (Theil 1971; Eckstein 1983; Fair 2004.
   http://fairmodel.econ.yale.edu/)

   Discussion of strengths and weaknesses: (Sterman 1988)

6. System dynamics

   General:

   (Forrester 1961; Alfeld and Graham 1976; Sterman 2000)

   System Dynamics Society
   http://www.systemdynamics.org/

   Well-known cases: (Mayo et al. 2001; Lyneis 1999)

   Methodological cases: (Graham et al. 2002; Graham and Ariza 2003; Lyneis 2000)

   Mathematical foundations:

   (Schweppe 1973)

7. Game theory

   (Dixit and Skeathmore 2004; Williams 2007)

8. Agent-based

   Social science applications: (Billari et al. 2006)

   Methodological discussion:

   (Rahmandad and Sterman 2004)

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