Computer Modeling: How Good Is It?

by DONELLA MEADOWS

COMPUTER MODELING IS A BABY THAT NEEDS TO DEVELOP AND TO BE GIVEN SOME TOLERANCE

As I go around telling people I'm in the business of making computer models, I seem to run into two and only two reactions. On the one hand I often get an expression of deep suspicion. I know that person is in the camp that thinks computer models are worthless. On the other hand I sometimes detect a note of awe and almost worship—probably best exemplified by a lady who called us up once at MIT and said she heard we had a world model and she'd like to ask it where she could find her dog. This group of people seems to have the idea that a computer model can deliver perfect information about anything for any time in the future.

I very much dislike both those attitudes. As a member of the field, and a fairly new and still skeptical member, I believe that computer modeling has too much potential to be dismissed or stopped at this point in its development. I also think, however, that computer models should be used tentatively and with a great deal of questioning, especially for the next few decades.

I'd like to summarize here my vision of the future of computer modeling as a tool for understanding how complex social systems behave. Let me start by defining a *model* as any set of assumptions or generalizations about a complex system. All of us carry models around in our heads, which Jay Forrester has called *mental models* (in "The Counterintuitive Behavior of Social Systems," *Technology Review,* January 1971). They are the sets of working assumptions and abstractions that we have drawn together from our experience in dealing with the world. Of course mental models must be great simplifications of the real world. You don't weigh down your mind with every detail of your firm or your town or your household.

All the decisions you make are dependent on mental models—upon simplifications of the world and not upon perfect, detailed knowledge of every aspect of every system that you deal with. The models behind your decisions and mine are incomplete and imperfect. They *must* be to be useful; if they were as complicated as the real world, they would be as hard to understand as the real world. The essence of any good model, mental or mathematical, is insightful simplification, the omission of trivia, and the inclusion of just what is important for solving the problem at hand.

There are many kinds of decisions that we as actors in social systems need to make about the future. Therefore we need many kinds of models. I'll just give you a few examples of the different kinds that are appropriate for the various decisions that may face us.

To start at the easiest and most successful end of the spectrum, as far as computer modeling is concerned, we have to make decisions that involve a very clear set of goals and a clear understanding about the system that has to be dealt with. In this case one can state the problem in terms of some sort of optimization. We want to do things so that profits are maximized, or costs are minimized, perhaps. For example, a city has a lot of streets, and mail has to be delivered on all of them, and there are certain pickup points and a certain number of mail trucks and drivers. What is the most efficient way to deploy the trucks, lay out the routes, and work out the timing so the mail is delivered in the cheapest way possible?

Such well-defined decisions about the detailed implementation of some predetermined strategy toward a clear goal are the places where computer models are most used, most successfully, at present.

Moving toward an area of greater disorder, there are problems where the goals are not quite so clear, where the policy instruments are perhaps identifiable, but the interrelationships among them are uncertain. In many public policy issues, broad social goals are brought into question, and it isn't at all clear whether anything should be optimized. In these problems we want to ask what general combinations of policies will allow us to move in the right direction. We want to help out a poor country. Should we work on family planning or health care or miracle grains or all three or none of them? Having made that decision, *then* we might use an optimization program to determine, for example, the least-cost way of distributing miracle grains.

One model that I feel is successful in this area of general policy formulation is a simulation model of heroin addiction in the New York City area. It was made for a neighborhood mental health clinic during the time when drug addiction was rising in that area. The goal was fairly clear—to stop or reduce the rate of heroin addiction and the street crime associated with it. And some policy instruments were visible. One could hire more police and assign them to arrest addicts and pushers. One could block somehow the inflow of drugs into the region. One could try to set up neighborhood treatment centers and half-way houses. One could establish methadone programs. And so on. There was a huge argument about which of these approaches would be more effective and what the long-term consequences of each would be.

A computer model was made that simulated or duplicated the essence of the heroin system—the flow of the drug and the market for it, the rate of addiction, the movement of addicts in and out of jails and treatment programs, and the effects of all these things on each other. (This has all been described in *The Persistent Poppy* by G. Levin, E. B. Roberts, and G. B. Hirsch, published by Ballinger, Cambridge, Mass., 1975.) As one example, the model came out with the conclusion that stopping the flow of drugs would result, at least in the short term, in an increase in street crime and an increase in addiction rate. As drugs became scarcer and scarcer in the city, the price would go up, and those who were addicted would have to commit more crime in order to buy the same amount of heroin. Furthermore, pushers, finding the supply drying up and the costs going up, would try to hook more people, because pushers are nearly all addicts trying to support their habit. The general conclusion of the model was that no single policy could be very effective alone. Another conclusion was that the two goals of reducing addiction and reducing crime are sometimes in conflict.

That's an example of this middle area—a fairly clear problem with fairly clear interconnections between all the aspects of the problem. A computer model in that particular case was very helpful because it allowed a rather argumentative interchange about alternate policies to be discussed systematically, and the consequences to be laid out explicitly and logically.

At the far end of the spectrum of decisions that have to be made about the future are decisions about systems that are not well defined, where there are many interconnected problems, and where we are hardly even sure where to begin in analyzing the causes of the problem. These are undoubtedly the problems of the future; the problems that encompass an entire complex social system that is not totally understood by anyone. Russell Ackoff in his 1974 book, *Redesigning the Future,* calls problems of this sort "messes." He talks about the urban crime/taxes/housing/employment mess. Or the development/aid/population mess. Or the environment/resources/pollution mess.

I'm going to concentrate on the use of computer models in this area of messes, primarily because these are the problems we understand least, the places where our simplified mental models are most likely to backfire. Another reason for concentrating on this area is that I think this is where the potential of computer modeling is greatest and where the performance of the field at the moment is worst.

I'd like to go through five advantages that I think computer models might have in analyzing the "mess" area of social problems, and indicate my assessment at the moment of how well current models do with regard to each of the five advantages. My statements will be based on my own generalizations, or mental model, derived from a rather intimate knowledge of five global models and nine national models. The national models are reviewed in my forthcoming book, *The Electron Oracle,* written in collaboration with J. M. Robinson.

The first advantage I cite when I try to convince somebody that computer models can be useful is that the process of taking one's assumptions and putting them in a form that can be understood by a computer requires a tremendous amount of rigor, precision, and consistency—much more than one is ever forced to have in one's mental models. The computer forces you to define every term you use and to make all the definitions mutually consistent. If you make a mistake, it gives you back a rude message telling you that you haven't done things correctly. You must be precise. You must look very hard at the data and at your assumptions.

There are many good examples of this, but I'll just cite one. A model has been made of the development of agriculture in Korea. The interdisciplinary team making the model started by looking at all the agricultural statistics of Korea, and they quickly found some puzzling figures. The reported agricultural yields were exactly the same as those in the five-year plan. With a little further checking, they found that the same Korean agency that made the five-year plans for agriculture also collected the data on the actual yields and production values. This had been going on for a decade, and no one had ever realized it until a computer team started to look at the numbers. Well, even before the model was made, that was a useful exercise. As a result, the whole data collection system in Korea was completely revised, and now the numbers, I am told, are considerably more reliable. That's a good example of the enforced rigor of modeling producing better understanding.

But most of the computer models I've looked at are rigorous about easy things, and unrigorous and inconsistent about the difficult things. As an example, one model requires you to predict outside the model, as an input to the model, what the population growth rate of a country will be, what its GNP (Gross National Product) growth rate will be, what the relationship between production and pollution, and production and resource-use will be. And once you have predicted all those things, it tells you such things as how many nine-year-olds there will be in the year 1985 or how much steel will be used.

This is rigorousness, precision, and consistency—that is, the demographic program that generates the number of nine-year-olds is correct—but in fact that model is little more than a glorified mental model. It takes your mental projections of a lot of important things, and then goes through some calculations and gives out some information that looks rigorous, but is probably not consistent, because your projections were probably not consistent. That's deceptive rigorousness, and it's very common.

A second potential advantage of computer models is that they are explicit. They are written down. They are criticizable. One can look at the assumptions and say, I agree with that, or I don't agree with that. That is impossible to do with mental models. If you've tried to pin a friend down on what he thinks about something and what are all the assumptions and experiences that lie underneath his opinion, you'll find that mental models are vague and moving targets. It's even pretty hard to figure out all the assumptions behind your own mental models.

Of the 14 models I have dealt with, I would say that four of them were really criticizable by me as a professional modeler. That is, I could see the equations, and I could understand all of them. These four models are excellent examples of the accessibility and explicitness of computer modeling.

Two of the others, I would guess, could not even be examined by their makers. That is, the programs that led to the published outputs were lost. They couldn't be repeated even by the people who made the models. These were exceedingly complex models. Nobody remembered quite what went into them.

The rest demonstrated intermediate levels of accessibility. The equations were generally around somewhere, though rarely published. Generally the modelers could at least trace what kinds of inputs produced what results. Very often they didn't really understand what was going on in the computer because the models were so complex, and the experiments done with them were so poorly documented.

There are many causes for this problem of impenetrability. One is the very size of many computer models; the modelers have forgotten that the purpose of modeling is to simplify rather than to duplicate every detail of the real world. Another problem is that modelers tend to be modelers and not writers, and therefore they sometimes have a hard time communicating with anything but a computer. I would say that your first basic right as an audience for a computer model is to have that model explained to you in a language you can understand. If the modeler can't do that, he doesn't understand it himself. In that case I think the model should be dismissed.

A third possible advantage is that a computer model can be much more complete and comprehensive than a mental model. There's an interesting psychological rule that says the human mind can handle about seven variables at one time, and after that the mind gets boggled. Well, computers can handle thousands or millions of numbers with no problem. There's no practical limit to the complexity of a computer model, and therefore it can contain and process more information than your head or mine. In fact, it could combine the information from both our heads and in that way come up with a more complete view of the world than either you or I have by ourselves.

Again, there are good examples in this area. Models have served as hubs for interdisciplinary research, where people from a lot of different fields have come together and used a model as a communication mechanism. For example, demographers and economists have been brought together for some modeling efforts, and public health experts and water resource engineers in others.

On the bad side, there are some large holes in the content of nearly all the computer models of social systems I have seen. Computer modelers tend to zero in on that part of a social system that is measured by statistical data bases. Where there are numbers, censuses, national economic accounts, and preferably where there are 25 years worth of consistent numbers, modelers pay attention. But glaringly absent from nearly every model I've looked at are goals and motivations and politics, cultural factors and norms, and the environment and natural resources. The data on these things are scattered, if they exist at all. Information is available, but it is not precise. Therefore it doesn't get included in computer models, although our mental models tell us it might be crucial to the system.

There's nothing to prevent a sociologist or psychologist or ecologist or poet from translating his impressions of how human society works into a computer equation, nothing except the pseudo-scientific prejudices of modelers. They seem to feel that information that comes only from a mental model can't be very good information. I disagree with that very strongly. Our mental models are full of accumulated wisdom about why people do what they do, what their goals are, how political systems work. That wisdom can be put into models, and a few brave modelers are trying to do it. Unfortunately, they tend to get laughed at by other modelers.

If it sounds contradictory for me to bewail large models on the one hand and yet complain that they are incomplete on the other, let me emphasize that there is a distinction between *complicated* models and *comprehensive* models. A comprehensive model need not be complicated (though it might be). I am saying that too many models are unnecessarily complicated and insufficiently comprehensive.

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A fourth advantage—computer models can proceed with logical accuracy from a set of assumptions to the conclusions that follow from those assumptions. Drawing logical conclusions is something that mental models are very bad at. You have undoubtedly heard discussions in which people agree exactly on their assumptions about some system and then get into a big fight about what those assumptions mean. That is one place where computer models can help. The computer doesn't guarantee the assumptions are right, but at least, given those asumptions, the conclusions can be derived error free.

For those four models whose assumptions I was able to penetrate, I believe in each case the conclusions are also correct. For the others, I'm not sure, for two reasons. One is the simple possibility of errors of translation. One of these models has 80,000 numbers in it. There is almost a 100 percent certainty that *one* of those numbers was typed wrong. There is no way of finding it. That model costs about $2,000 each time it's run because it's so huge, and therefore it's not run very often—and testing by doing many runs under different conditions is the most common way of detecting typing mistakes. So when models get very big, I get suspicious about their logical infallibility.

Another kind of error arises in the interpretation process. Even if the computer has proceeded logically from assumptions to conclusions with no typos, conclusions don't come out of a computer in terms of simple wisdom, distilled and delivered to your doorstep. They come out in the form of sheets of paper, covered with numbers. The modeler must sit down with those numbers and form a conclusion from them. In other words, a mental model is required to interpret the results. It's not easy to derive wisdom from a stack of paper six inches thick covered with numbers, even if every one of those numbers is meaningful and correct.

I'll give you a glaringly bad example of an interpretation error. One model was designed to determine what resources might be used in the United States over the next 30 years, and whether there would be any shortages. The conclusion of the study was that there were no serious problems in sight. I took one look at the figures and noted that the model had happily allocated for United States consumption 150 percent of the world's known copper resources and 90 percent of the world's tungsten resources (nearly all of which are in China). The computer modeler had apparently not noticed that. I noticed it only because my bias was opposite from his; otherwise I wouldn't have seen it either. You can assume that every modeler, including me, unconsciously reads his own bias into the numbers on the paper.

That's a bad example. There are good examples. In several models the results surprised the modelers, and when they looked hard they decided the model was right and their mental model was wrong. One model of the Sahel region in Africa led to the conclusion that the Sahel would be much better off if all current foreign aid programs were stopped immediately. That was a conclusion that surprised the aid-donating agency very much, as well as the modeler. I believe that result, because I can reason through with the help of the model why it comes out that way. The modeler now believes it. I don't think the aid agency does yet. But it seems that the assumptions put into the model are roughly agreeable to everyone, and everybody had been coming to the wrong conclusion on the basis of those assumptions.

Fifth, a computer model can be tested and altered a lot easier than things can be tested in the real world. You can try wild ideas in a computer without breaking anything or upsetting people. You can try out wide ranges of numbers where you are uncertain, to see whether your uncertainty makes any difference. It's also cheaper and faster to run a computer model through the next 100 years of history than it is to try something in the real world and evaluate it 100 years later.

Modelers are in fact quite bad at testing models, probably because it's not in their best interests to do it. A model must be really well constructed to produce sensible results under a wide variety of assumptions. Most tests reveal inadequacies of the model, rather than knowledge about the system.

The best-tested model I know is my own world model, and that's only because all of my enemies tested it. I would recommend this procedure. They did things with it that it never would have occurred to me to do, and that was good—we all learned things about both the model and the real world in the process.

Another and more serious problem with testing is that the inherent logic of a number of modeling techniques really prevents policy testing. For example, the relationships in econometric models are derived carefully from historical relationships, data from a real system, operating in one particular way. One cannot use such a model to test the effect of changing any single relationship or any new policy, because the model does not contain any causal hypotheses connecting that change to all the other elements to which it's connected in the real system. That is, in the real system, changing one number *here* will cause hundreds of shifts in other numbers all over the place. But the model won't do that, it will just change the one number here and so it will give misleading results. Econometric models can only project the system continuing to operate in the way it has historically operated; they cannot properly represent a changed system without more data on the changed system. The only kinds of models that are appropriate to test policy changes are simulation models in which politics, goals, and motivations are explicitly represented, so that a new policy can give you back the changed behavior of people who are responding to that policy.

To summarize those five advantages of computer models in analyzing social "mess" areas: (1) Computer models *could* be more rigorous than mental models, but at present they are only rigorous about easy things, such as demographic changes. (2) Computer models *could* be explicit and criticizable, but their large size and the sloppy documentation habits of some modelers make many of them inaccessible. (3) Computer models *could* be more complete than mental models, but usually they are less complete, because they do not include psychological, political, or ecological factors. (4) Computer models *could* proceed without error from assumptions to conclusions, but only if they are small enough to be checked and if their output is interpreted correctly. (5) Computer models *could* be easily tested and altered, if they could be run cheaply, if modelers were trained in testing and motivated to test, and if the logical foundation of the models were causal, so that tests may have some meaning.

To realize the potential advantages of computer models, modelers have to be more responsible, more imaginative, and less pseudoscientific. Clients, meaning the people to whom the models are addressed—the policy-makers and decision-makers—need to be much more sophisticated about the appropriateness of a model, more persistent in finding out what's in it, and more critical all the way along the modeling process.

Believe it or not, after all that criticism, I think that computer modeling is a very promising new field. I wouldn't be in it if I didn't think that. But it is a field that is still in a primitive state of development. It has been catapulted into a position of too much power. Clients are entirely too eager to get information about the future; they need it badly in order to make important and urgent decisions. Modelers are too eager to supply such information, and they seldom provide sufficient warning about what they can really say on the basis of their models and with how much certainty. My fear is that the too-rapid development of the field is likely to lead to a backlash of disillusionment that may result in throwing the baby out with the bath water.

Computer modeling *is* a baby; it needs to develop and to be given some tolerance. It should be regarded as more of a basic research field than an applied one—except for those optimization models I talked about first. But with regard to social messes, the field is just beginning, and neither modelers nor clients should push it too far.

Let me end with a conditional prediction; a prediction of the "if . . . then" sort, which is the kind that mostly comes out of computer models. Over the next 80 years I believe that there could be improvements in our understanding and control of the complex interconnected messes that human society generates. Systems that are now out of control could become understood and regulated to increase human welfare. The tools for gaining this kind of understanding are systems analysis and computer modeling. Whether these tools are actually developed depends, unfortunately, on what I can only call human wisdom. Computer modeling has to be developed carefully and rationally and humbly, and for the benefit of all, rather than the benefit of the elite few who happen to seize the tool first. This could be said of any new technology—and computer modeling is a powerful, and therefore both promising and threatening, new technology. Whether human wisdom will be sufficient to develop that tool and to use it well, I will have to leave to the judgment of your mental models. □