Massachusetts Institute of Technology
Engineering Systems Division

Working Paper Series

ESD-WP-2003-01.08-*ESD Internal Symposium*

THE EVOLVING ROLE OF SYSTEMS ANALYSIS IN PROCESS AND METHODS IN LARGE-SCALE PUBLIC SOCIO-TECHNICAL SYSTEMS

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MAY 29-30, 2002

Systems Symposium –
May 2002

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Abstract

The ESD definition of Large-Scale Socio-Technical Systems is large-scale and complex systems in which both human and non-human elements interact where the social and/or management dimensions tend to dominate. The word public has been added here to indicate that subset which are quasi public systems, i.e. the problems of public management of resources such as clean air and water or energy in which public policy is needed to drive and set the context for public investment and regulation which in turn influence private individual and corporate decisions. Systems analysis plays an important role in the formation of strategic policy for managing these resources. The paradigm of systems analysis as applied to large-scale open systems has not changed over the years. It is still the mantra of Problem Identification, Systems Modeling, Generation of Alternatives (Optimization), Evaluation and Implementation. However, both the process by which systems analysis is carried out, and the systems methods used in that process have evolved significantly and for the better. This paper deals with a description of these evolving methods and processes in the context of large-scale energy and environmental systems. In particular, pathways to the future in energy and environmental management are discussed as long-term system analysis problems. Systems Analysis process changes and methods changes, which have occurred and will need evolution in the future, are identified.

Introduction

The ESD definition of Large-Scale Socio-Technical Systems is large-scale and complex systems in which both human and non-human elements interact where the social and/or management dimensions tend to dominate. I have added the word public to indicate that these are quasi public systems; i.e., the problems of public management of resources such as clean air and water, or energy in which public policy is needed to drive and set the context for public investment and regulation which, in turn, influence private individual and corporate decisions. These are classic welfare economics problems in which the lack of private ownership of resources leads to non-optimal resource uses by individuals who need not consider the impacts of their usage on others. To bring about collective actions requires the intervention of government into the market system without a great deal of guidance and at an investment and scope of project level in which guessing wrong can be extremely damaging.

Systems analysis has been a primary tool in helping the process of deciding how to manage such public resources. The author has worked on this type of systems analysis for almost forty years and would like to demonstrate an evolution in approaches to these problems over time.

The paradigm of systems analysis as applied to large-scale public systems has not changed. It is still the mantra of Problem Identification, Systems Modeling, Generation of Alternatives (Optimization), Evaluation and Implementation (See Table 1).

Table 1: Systems Analysis for the Management of Large Scale Socio Technical Systems

STEPS	DESCRIPTION
Problem Identification	Defining the Problem to be worked on: Goals Objectives Constraints, Measures of Effectiveness.
System Modeling	Understanding Cause and Effect in the System.
Generation of Alternatives	Optimizing over different conditions potential. "Good" Feasible Solutions. Implicit consideration of the "ilities".
Evaluation	Bringing a stakeholder perspective to the choice of alternatives - Multiobjective analysis. Implementability. Tradeoff analysis among objectives.
Implementation	Providing the basis for organizing, funding the implementation of the chosen solution.

However, both the process by which systems analysis is carried out, and the systems methods used in that process, have evolved significantly and for the better. First some of this change is driven by problem complexity. As the questions being asked about the management of large-scale open systems have become more complex, methods to address this complexity have been added. Or, is the opposite true? As methods and experience have increased, are we attempting more complex analysis? Nonetheless, methods like systems dynamics, regional input analysis, data mining and even behavioral reactions to use incentives or disincentives are now routine parts of public systems analysis. They allow models to be much more complex, and to incorporate social and economic interactions with the physical system. Second, the relationship between the analyst and the client has significantly evolved with the analysis being more often used as a platform for dialog between stakeholders with very different objectives and problem views, rather than a simple delivery of a best solution . Third, the role of classical optimization has diminished, as economic cost has become one of many attributes of the system to be managed rather than being just the main one. Systems characteristics defined by Moses as the ilities reliability, sustainability, stability, flexibility to future unknown outcomes, and survivability have evolved - which are much more difficult to define and characterize, much less be optimized by classical optimization algorithms. Fourth, uncertainty is dealt with in a much more satisfying way. Instead of designing for worst cases or extreme events, it is now possible using systems models and decision analysis to better understand risk profiles and results of decision making under uncertainty. In previous analysis, abstract projections of demand had to carry the burden of uncertainty about customer reactions to events and stimuli - now we attempt to show supply demand interactions under uncertainty. This paper deals with a description of these evolving methods and processes in the context of large-scale energy and environmental systems.

Background: An Early Public Systems Study of Water Quality Management on the Delaware Estuary (Philadelphia, PA USA area) 1964-66

The author began his professional career in 1964 as a Commissioned Officer in The United States Public Health Service (the predecessor to EPA) working on the cleanup of water pollution in the Delaware Estuary in the United States. It was one of the first uses of computer modeling and systems analysis used to present alternative management schemes for the cleanup of a major polluted industrial water system. It is amusing to look back on the elementary linear programming model, with the simplex solution model programmed by the study staff in Fortran to fit into a 32k memory, that was used to look at cost effective waste management investment tradeoffs for pollution abatement. The underlying physical model of the estuary showing increase in water quality for a unit of pollution abatement required the inversion of a thirty-by-thirty matrix, which took 30 to 45 minutes to calculate on a Bendix 400 computer that we traveled 300 miles to use. Today we would use a spreadsheet to calculate it in seconds. Uncertainty was handled by assuming a set of worst-case conditions for temperature, flow, and pollution from other sources, and designing a program for essentially the 1/100-year case. Most of the time the investment plan would provide better results, but little thought was given to the investment cost and damage cost tradeoffs. The three-year study was mostly spent on doing model building and data collection with very little discussion with the various and diverse stakeholders. In retrospect, our resulting elegant systems problem solution, when finally seen by the public, was rejected as non-implementable because of issues such as lack of institutions to administer it, and lack of acceptable cost allocation means. When such problems are considered today, the process is reversed. Models are essentially all in place and take almost no time to develop. Therefore a great deal of time is spent talking to stakeholders separately and together, using the modeling system to show tradeoffs between objectives and the response of the system to uncertainties. An emphasis on graphical summary of outputs, and even models and games that let stakeholders explore individually by themselves, have come to the four.

How has Systems Analysis Evolved in the Past Thirty Years in the Application to these Public Systems? Does all this mean that Systems Analysis has structurally changed when it is applied to large-scale public systems of this nature? I would argue not. Table 2 gives the ways that problems of this nature in the area of environment and energy would be looked at in the early 1970 s and how they might be looked at today and into the future.

The first period might well be called the applications of operations research - mainly optimization and statistical techniques - to problems largely formulated by analysts. In the 60 s and early 70 s, goals were generally given in terms of economic cost with other system objectives being represented as constraints. Systems models were simple, largely based on physical systems cause and effect, and deterministic. Looking at average and worst case conditions represented uncertainties. Optimization was generally the main focus as we saw piecewise linear cost minimization models replaced by mixed-integer and non-linear algorithms; but without a change in basic formulation. Unfortunately, in most cases we searched for problems that would fit the current new optimization method - not the more logical vice-versa. Evaluation was quite ephemeral since ideally it represented a stakeholder process that was then too difficult to manage

Table 2

STEPS	**EARLY PERIOD** *Largely Operations Research Approach*	**NOW AND THE FUTURE** *Advances in Computation and Methods make this more a Systems and less an OR approach*
Problem Identification	Little time spent on this or on education of clients about this. The problem as symptom.	Great Deal of time spent in gathering and analyzing underlying problem - data mining, easier access to large data sets. What is the present base line condition is non trivial question. Identifying stakeholders early and learning to interact with them and they with each other. Physical Data from GIS and Remote Sensing.
System Modeling	Largely models of physical systems, uncertainty through worst cases or extreme event as well as average events.	Much more complex models with strong social as well as technical components - ability to run many times for sensitivity and uncertainty analysis. Attempting to predict human as well as physical system behavior.
Generation of Alternatives	Optimization with other system goals as constraints.	Analysis under uncertainty - introduction of "ilities" more formally. Greater computational ability allows simulation, optimization, decision analysis interactions for looking at risk profiles and decision analysis realizations. Increased use of graphics to help in educating stakeholders.
Evaluation	Multiobjectives, tradeoff analyses. Discussions with stakeholders.	Using graphics and games to help stakeholders identify areas of consensus. Study of new types of institutions, policies, market incentives.
Implementation	Often founder here since many good solutions do not have institutions nor stakeholder buy into implement or methods for cost allocation. Late attempts at stakeholder education lead to distrust and lack of convergence.	Implementation becomes a continuous and hopefully flexible process- keeping together a long-term group to help solutions evolve over time, as uncertainties are resolved.

Technical people had little feeling for the social dynamics of understanding different interest groups and working with them towards more implementable solutions. It was all soft stuff and the stakeholders would just have to understand that we knew best. Our initial work was in multi-objective optimization models with objectives not always representative in commensurate units. What is the economic value of a unit of recreational activity gained, or for a duck saved? Finally, implementation was simply not part of our vocabulary. The idea was to show elegance in modeling alone, particularly if you were an academic. Getting dirty with real large-scale problems with long multi-year study times, interdisciplinary project teams where it was often hard to identify an individual swork, and embarrassing implementation questions of why the outcome was not the study outcome, were all far too dangerous for careers. As a matter of fact, this is equally true today. Academic rewards are far more likely to go to those who can solve a difficult problem analytically - rather than to those working to make sure it is the right problem to solve and to manage the evaluation and implementation process.

Today both the process and methods part of system analysis for large-scale systems have evolved significantly while still following the systems analysis. There are two ways of addressing this. Process: How are such exercises carried out? and Methods: Are new methodological advances emerging and how will they change the business of looking for pathways to the future?

Consider the following process changes:

1. Problem definition has become much more important. Far more time and effort is being spent on the project trying to fully understand the problem to be solved. How do we characterize the current baseline? As we look to future problems, it is necessary to characterize the current state of affairs and the trends and actions that put us here. This is a non-trivial exercise, which involves extensive data collection. How are goals for the system better articulated? Who are the stakeholders and how will we interact with them? How will solutions be implemented? What are the past trends and policies that put us where we are now? These are all questions that receive far more thought right upfront. It is the place where stakeholder alliances are forged and rules of engagement set for a successful process.

2. The level of problem complexity has increased, as have the analysis methods for dealing with it. The simple waste management study on the Delaware Estuary would be analyzed today from a far more in-depth and insightful perspective. Economic interactions between water and the regional and global economy, the role of uncertainty and the implications on different stakeholders of different alternatives, were all external to our study. It was the best we could do and it took us some time to assimilate what more was needed to be done, as well as what our simple models accomplished. Thirty-plus years of dealing with this class of problem has moved us up the learning curve of what sort of information and analyses are appropriate; and this learning points to far greater complexity in the analysis. It is a classic chicken-and-egg problem. Did the growth of regional input/output analyses cause us to include them, or did our need for this information lead to attempts to develop them? It doesn't really matter. We have them now and have the computational ability to easily incorporate them. Now, water is looked upon as a component of the regional economy. A new generation of system simulation techniques based on systems dynamics has allowed system models to be much more complex, and to incorporate social and economic interactions with the physical system. The simple waste management problem we dealt with in the 60's would now be done very differently. Systems modeling, new advances in information technologies and computation, deeper thought about the metrics for measuring system performance (the "ilities"), and better systems methods in simulation, and dealing with uncertainty and consumer psychology will make this process more productive and more insightful. How soon will we be able to combine analyses of technologic alternatives along with a better understanding of institutional structures, regulations, business strategic planning and economic incentives in detailed simulations?

3. The relationship between the analyst and the client has significantly evolved with the analysis being more often used as a platform for dialog between stakeholders with very different objectives and problem views - rather than from a simple delivery of a "best solution". Stakeholders are present from the beginning and the systems analyst freed from programming from scratch can now use data mining, advanced visualization tools, statistical techniques, revealed preference analysis, among other things, to help along the process. While the analyst him/herself may not be neutral, the analysis must be with extensive tradeoff analyses and even game playing to show the interrelationships between different objectives. We are just beginning here but this is a major paradigm shift from the analyst, problem definer and solution provider to the analyst aiding in a complex stakeholder consensus building process providing neutral information and convening - but not dominating - the debate. Information technologies will make it

possible for stakeholders to convene more often without leaving their locations. Advances will help us to educate stakeholders about their roles, especially in seeking more sophisticated ways to seek information and interaction with each other. At the extreme, many of the problems we will be working on will require the careful education of the public at large as well as their representatives . When building towards consensus is there really a concept of an optimal path? Or, rather is the best path one that can be agreed upon and implemented? This is probably the main attribute of public systems analysis that differentiates it from less social systems.

4. Is optimization as a design objective dead in large-scale open systems analysis? Classical one and multi-objective techniques will still certainly be used to help fine tune different alternatives. The role of classical optimization, however, has and will continue to diminish, as economic cost has become one of many attributes of the system to be managed - rather than just the main one. It is hard to see how there will ever be the ability to quantify the unquantifiable in economic terms so that dollars can be added to ducks for a single objective function. And given our growing sophistication about multiple objectives/multiple stakeholders, it is not clear that we would want to.

   Systems characteristics defined by Moses as the ilities : Flexibility, agility, robustness, fail-safe, adaptability, scalability, modularity, safety and durability are all getting deeper consideration. How are they quantified and represented in analyses of the system? How are they traded off one against another? In the large-scale public systems that I work in there are two very different levels of looking at this.

4.a Robustness and Survivability. The first is most related to robustness of a given system, say a regional water supply system. It requires the ability of the system to work over extremes in input conditions and other uncertainties. Water systems in particular have always been designed for extreme conditions and are very supply-oriented. The water engineer will always work to get as much concrete infrastructure (i.e. water capturing, treatment and transmission) in place as possible and to make the system as redundant as possible. His/her goal is to make sure that any future realization of water demand will be anticipated and supplied, as they understand that utility in outcomes is asymmetric. There are ample rewards for the system that is invisible to users most of the time because it performs so well even if very expensive, but there are bad penalties if an extreme event disrupts users. The economic and social damages of shortfall are very great so the engineer strives to prevent them almost at any cost. He/she likes supply increase infrastructures and has little regard for demand modifications since they are normally behavioral and not structural and hence more difficult to control. What would happen during an extreme event if everyone decided to ignore restrictions and water their lawns anyway? As investments for the future become more complex and costly and potential damages thus more costly as well, we must now move beyond physical models to those that include economic and social parameters as well. We must, for the future, learn someway to do tradeoff analyses about the proper mix with demand modifications being more flexible and implementable quickly while supply increases are much more expensive, are there forever, and take a very long time to put in place. In the age of growing security concerns the best system may not be the one that can be protected from every possible attack scenario but the one that can be brought back into active use as soon as possible after an event. This survivability is not unknown to us since we have already planned for naturally occurring system interrupters like earthquakes, tornados, etc. But these different concepts of a system, robustness, survivability, etc., are presently not quantifiable and thus difficult to design for. This is a major area for new research.

4.b <u>A Broader ility Sustainability</u>. At a level up from the previous concerns for a specific system, how would one go about long-term planning for general development in particular sectors? This has led to an area called Sustainability, which at its highest level asks how economic development can take place to be consistent with environmental and social goals. In 1987, the World Commission on Environment and Development (the Brundtland Commission) developed what has since become the most widely accepted general definition of sustainable development.

> *Humanity has the ability to make development sustainable —to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987: p8 — also known as the Brundtland definition.

The wide acceptance of the Brundtland definition is partly due to its simplicity. People of all nations are able to understand the definition since it is easy to relate to their current needs and the future needs of their children and grandchildren. Unfortunately, the simplicity of the Brundtland definition means that it does not provide decision-makers with a robust set of objectives that can guide the effective and consistent development of legislation, and transportation plans and programs. Hence, the practical application of the Brundtland definition has spawned much discussion centered on the concept of sustainability.

This type of discussion of sustainability has spawned a vigorous discussion about definitions of sustainable development that strive to protect the environment, achieve social equity, and establish a stable economic environment.

Ralph Hall, in a recent SM/TPP thesis, (Hall 2002) pulls together the discussion on sustainable transportation systems. He notes, the international community has reached a consensus that sustainable transportation can be defined under the Three E s of Environment, Equity and Economy. The following Table 3 provides a summary of the key definitions presented under each of these categories.

Table 3: Definitions of Sustainable Transportation

Environment

	A Sustainable Transportation System …
Health & Environmental Damage	minimizes activities that cause serious public health concerns and damage to the environment;
Standards	maintains high environmental quality standards throughout urban and rural areas;
Emissions and Waste	limits emissions and waste to levels within the planet's ability to absorb them, and does not aggravate adverse global phenomena, including climate change, stratospheric ozone depletion, and the spread of persistent organic pollutants;
Noise	minimizes the production of noise;
Land Use	minimizes the use of land;
Renewable Resources	ensures that renewable resources are managed and used in ways which do not diminish the capacity of ecological systems to continue providing those resources;
Energy	is powered by renewable energy sources;
Non-renewable Resources	ensures that non-renewables are managed and used in ways which account for future needs and the availability of alternative resources; and
Recycling	recycles its components.

Equity

	A Sustainable Transportation System …
Safety	allows the basic needs of individuals and societies to be met safely;
	ensures the secure movement of people and goods;
Economic Equity	ensures the equitable distribution of economic benefits derived from the transportation sector's role in national economic growth;
Intergeneration Equity	ensures equity within and between generations; and
Access	provides access to goods and services in an efficient way.

Economy

	A Sustainable Transportation System …
Affordability	is affordable; and
Efficiency	operates efficiently to support a vibrant economy.
	▪

Figure 1 provides a useful visualization of the definition, which shows how the Three E s — Environment, Economy, and Equity interact:

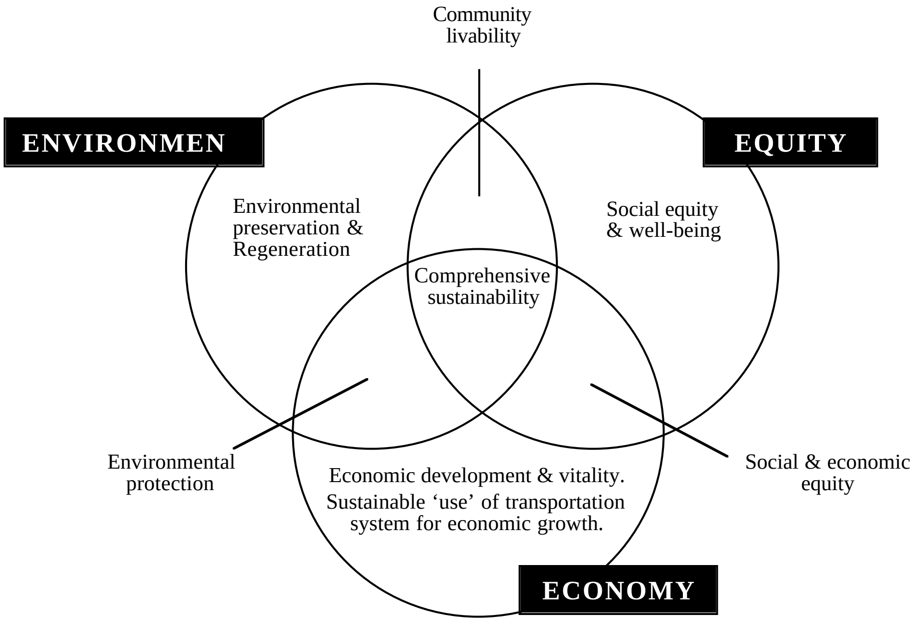


Figure 1: Visualization of Sustainable Transportation Definition[i]

This is heady stuff and an important conceptual change in the way that large-scale systems like transportation might be looked at. But in a systems analysis sense how is this ility sustainability to be operationalized. A major challenge for the future is the building of the systems model that can begin to capture elements of these interactions over time as new policies are imposed to deal with the overall growing needs for transportation. To do so would require, in addition to good systems dynamics tools, some real thinking about the characteristics of the system in terms of the ilities . To date this has been rudimentary and basically comparative. A recent report on sustainable mobility for instance took each such objective and gave it a color-coding to show if the direction towards that objective was positive or negative (WBCSD, 2001). While one can certainly improve on this it is hard to see how in the near future we can effectively develop a systems model to provide quantified information towards each attribute over time. So thinking about the ilities has just begun and needs serious research.

5. <u>New methods for characterizing and dealing with uncertainty</u>. It is not so much new methods of dealing with uncertainty as much as having the computational ability to deal with traditional methods. Decision Analysis, a classical tool for exploring ranges of uncertainty, is now combined with systems modeling in a new way. As the tree is developed, Monte Carlo analysis of the systems model (often with thousands of runs) is used to provide the probability distributions for decision analysis. In essence, decision analysis becomes a method for ordering and explaining the analysis of future policies under uncertainty. And instead of just looking at worst or average cases, it is now possible to do risk profiles showing the possible distributions of outcomes. Public systems analysis is very concerned about the tails of the risk profile, i.e., what are the potential damages that may occur once-in-one-hundred and even more rare

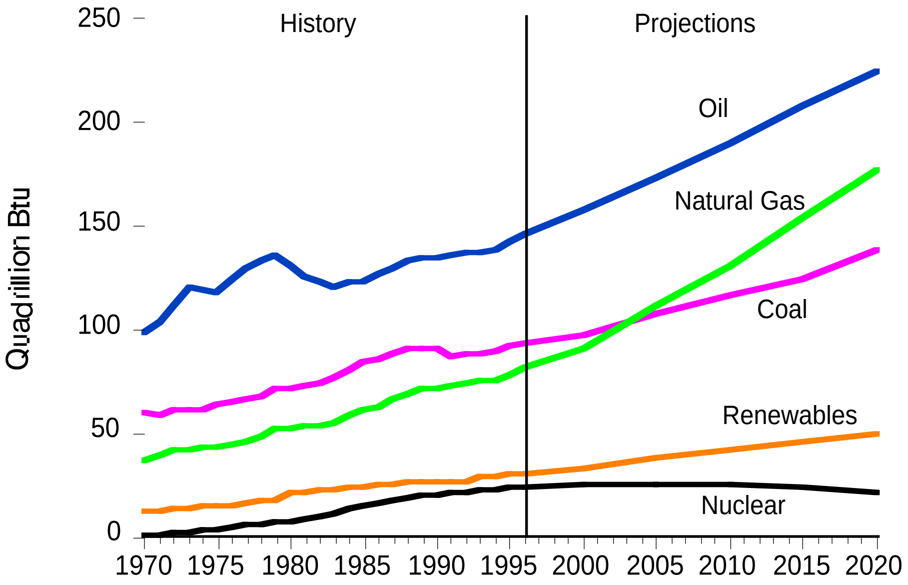
> events since it is there that events define proper system reliability. Evolution away from the demand forecast, as a surrogate for uncertainty to a look at supply and demand interactions under uncertainty, is a future new area of methodological research.

As the role of systems analysis aided by both increases in computational ability and new methods increases, problems of a longer scale and wider perspective may be carried out.

The Role of Systems Analysis in Planning for Energy for the Future

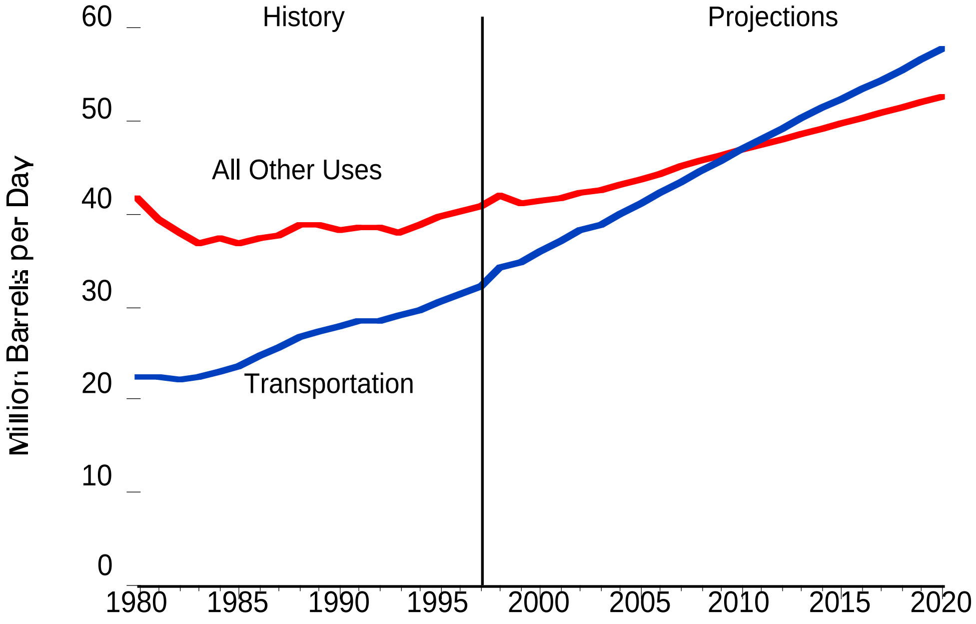
MIT, through the Laboratory for Energy and the Environment (with the MIT Joint Program on the Science and Policy of Global Change and the MIT Center for Economic and Environmental Policy Research) has been a leader in policy analysis on Energy and related environmental problems for several decades. Thinking about the future of these issues is confounded by many concerns related to supply availability, the impact of supply extraction and use on the environment and society and the way that energy is used in major sectors.

Let us start from the premise often stated by our esteemed colleague Greg McRae of MIT Chemical Engineering. He always exhorts that it is important to get the sign right in estimates for the future (i.e., analysis should at least point us in the right direction regardless of magnitude) and that the future is not to be predicted - but rather to be managed by our current choices. Both are very sound advice. So lets look at the nature of the future of energy and the environment and the role that MIT is now playing and might play in the future. First of all consider the following two figures concerning projections of energy consumption and use by mobile and stationary sources in the next 20 years. Figure 2 shows the total amount of energy by source expected to be used in the world. These estimates show that not only will energy use continue to grow but also that fossil fuels will continue to predominate. Implicit in these estimates are a variety of assumptions about availability, technology change and tolerance for the environmental and security aspects of fossil fuels. Figure 3 shows the divide between stationary uses and mobile uses, which indicates that the moving of people and freight will predominate world energy use soon. Should we believe these estimates, which by the way are from a very reliable US government source? (EIA 1999) The devil is in the details and the usefulness of forecasts like this must very much rely heavily on the assumptions made. Perhaps the greatest problem with them is that they seem inevitable when in fact decisions made now about research investments, technology transfer, government policies on use and evolving knowledge about green house issues can strongly influence the future shape of these graphs. Further uncertainty about the world conditions, consumer preferences and response to damages as yet undetermined are implicit in the estimates not explicit. They really represent the tension between two different possible future paths. Consider two motivating examples for pathways to the future for energy choices in the 21st century. One is a long-term Fossil Fuel-based scenario (probably the one that led to figure 2) - in which our concerns about global warming and the environmental impacts of use are not strong enough to change quickly from a fossil fuel pathway. In this scenario, Fossil Fuels, perhaps aided by Nuclear Energy and carbon mitigation techniques such as carbon sequestration of green house gases at the production site, will be kept vibrant by advances in production, transmission, and use, which will allow us to be more energy efficient and reduce environmental - but not greenhouse gas - impacts. In the second scenario, Decentralized Energy —in which global warming issues do become much more important —we will see a movement towards an electricity-based and/or hydrogen-based largely decentralized energy carrier system. Here energy production would depend more on renewables to manufacture hydrogen and/or electricity in distributed place, rather than in large complex central facilities, and a replacement of mobility of people by information technologies in a great many cases. More intelligent use would be the hallmarks of both approaches.



Source: EIA, International Energy Outlook 1999

Figure 2: World Energy Consumption by Fuel Type, 1970-2020



Source: EIA, International Energy Outlook 1999

Figure 3: Petroleum Use for Transportation and Other Purposes, 1980-2020

The answer that will evolve is probably somewhere in between the two, especially in the aftermath of September 11, as security of fossil fuel availability becomes more questionable. We see a merging of these two streams of thought towards a much more decentralized production of energy for stationary and mobile needs even before fossil fuel sources are stressed. To quote an OPEC official Just as the stone age did not end for lack of stones, the oil age will not end for lack of oil . But fossil fuels will be around for quite a while as our search for cost effective substitutes, whether via demand or supply modifications, is proceeding much slower than the need for energy is increasing. We are at the beginning of a detailed analysis of this problem. At the heart of the analysis of this transition are complex system models, which can help to evaluate strategies for the operation and location of small almost self-generating power, mobility systems, employment, education, and health care delivery. These are, at their core, socially driven technical systems with strong inputs from public decision-making, as well as private strategy. The interplay between public policy designs and the instruments to implement them, and proactive and reactive private response, will be better understood by systems-based methodological advances and their implementation in new methodological frameworks. From an academic prospective, these analyses are strange ducks. They are not about individual technologies but about assessment of technologies for the future under uncertainty, and they are of little meaning unless we can capture the role of uncertainties and the role of supply demand interaction. This is not the usual playground for technologists. It is for economists; but they work at a much more abstract level without a lot of in-depth insight about the alternatives. So public systems analysis becomes a true meeting point between technology, economics, management and policy with none of the groups feeling entirely comfortable since each are bending disciplinary boundaries.

It is not my suggestion that we are prepared now to build large-scale integrated models of the entire problem. There is just too much unknown to come up with a good systems model to show the interplay between all sectors of the economy and between supply and demand modifications in each. But we are already seeing work at MIT to begin capturing some parts and using systems analysis to provide guidance. For the time being we must settle for systems analysis work on various components such as transportation use, freight movement, new energy technologies, carbon sequestration, economic impacts of climate change, market based mechanisms for environmental and energy management, security studies of energy networks, energy system decentralization, more efficient use of fossil fuels and use of renewables in transportation, building, construction and in new concepts for nuclear energy. We have also been doing major international studies worldwide to help systematically guide energy and environmental policy, including work on China in coke production, megacities, residential and commercial energy consumption and use and nuclear regulation.

How long will it be until we have good systems models for each sector and begin thinking about linking them together? It will take time but the trajectory of better computational methods and better analytical methods will converge here. In the previous sections we have covered how process improvements in systems analysis is improving the management of public large-scale socio technical systems. But there are major advances in methods that still require a great deal of thought and development.

Needed Research on methods

1. Linking Data to Models

The presence of new technologies for data mining has led to major advances in rapid and inexpensive system modeling. David Wallace (Ines Sousa, Approximate Life-cycle Assessment of Product Concepts Using Learning Systems, Thesis Dissertation, Engineering Systems Division, MIT, June 2002) has been building new life-cycle product design models that use the internet and data mining to prototype analyses in seconds rather than months and at a fraction of the cost. For those of us who are interested in spatially distributed analyses, rapidly increasing data availability from geographic information systems and remote sensing is rapidly becoming available. Perhaps too rapidly as there is so much data that we do not always know what to effectively do with it How is raw data from geographic, remote sensing, economic statistics, census data, etc. rapidly and inexpensively accessed and converted into model structure and parameters? Solving this will allow much more sensitivity analysis and more complete models.

2. Complex Simulation Under Uncertainty

New generations of stochastic tools capable of exploring risk vs. efficiency tradeoffs in large-scale quasi-public systems (water, energy, etc.) are now evolving. A rebirth of interest in Systems Dynamics and other simulation tools, combined with economic and decision analysis tools, are forming a whole new way of looking at options. In these large quasi-public systems, issues such as redundancy and resilient protection from extreme events vs. efficient systems and their impacts on economic and social goals will need to be studied.

3. Decentralized Systems Management Tools

Strategies for the decentralized operational management of complex Systems from traffic - to home energy use - will be developed depending heavily on information technologies.

4 A Focus on the Behavioral

Understanding of end-use demands and consumer preference and the impacts economic and other regulatory instruments have on them will become a more central theme. This requires a movement from the more traditional concept of building to meet externally specified demands (a supply philosophy) - to a greater consideration of how demand modifications in types, locations, and timing of use can be integrated into decision-making (supply demand interaction). Much closer alliances with the social science outside of economics and political science will be needed.

5. Tools for Stakeholder Involvement

As these systems have stakeholders outside of industry and government, tools for educating and building consensus about difficult tradeoffs will evolve much more quickly. Here visualization and tools for exploring complex tradeoffs between important economic environmental and social goals will be a central theme.

6. Operationalizing the ilities

It would be very interesting to see a new round of research that attempts to bring more quantitative considerations of the ilities (especially redundancy, resilience, survivability and sustainability) into systems analysis. How are two different system designs compared in any or all of these attributes? Can there be cardinal rankings? Probably not for these measures are in themselves multi-attribute with not all attributes quantifiable. But it is an area where ESD can make a significant contribution.

Conclusion: In an increasingly urbanized and increasingly populated world, how will societies deal with basic concerns for security, education, clean water and air, mobility, employment, and other components of an adequate quality of life? The 33% increase in world population projected in the next 30 years will occur largely in rapidly urbanizing developing world countries. Only by viewing the sustainability of future settlements as complex systems can these basic tools needs be met. Key elements will be new institutions, and a greater emphasis on technical systems powered by information technologies. Systems methods will be at the heart of tools needed for decision-making about future trajectories. The past thirty years have prepared us to now use the tremendous computational advances that will continue to evolve our processes and to develop new methods. This is an exciting time for public systems analysis.

References:

Energy Information Administration. (1999) International Energy Outlook. Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC 20585.

Energy Information Administration. (2002) International Energy Outlook. Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC 20585.

Hall, R. P.. (2002) Introducing the Concept of Sustainable Transportation to the U.S. DOT Through the Reauthorization of TEA-21. Masters Thesis, Massachusetts Institute of Technology.

Ontario Round Table on the Environment and the Economy in co-sponsorship with the National Round Table. (1995) *A Strategy for Sustainable Transportation in Ontario*.

Sousa, Ines, (2002) Approximate Life-Cycle Assessment of Product Concepts Using Learning Systems, Ph.D Thesis, Massachusetts Institute of Technology.

The Center for Sustainable Transport (CTS). (1997) *Definition and Vision of Sustainable Transportation*. http://www.cstctd.org/CSTadobefiles/definitionvisionadobe.pdf (11/13/01).

World Commission on Environment and Development (WCED). (1987) Our Common Future, Oxford University Press. http://www.oup.co.U.K./isbn/0-19-282080-X (11/19/01).
