Dynamic Strategic Planning for Technology Policy

by

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Abstract

Dynamic Strategic Planning is an effective method for the development of rational policies for the intelligent, effective development of technology or large-scale engineering projects. It is:

- *Dynamic* in that it explicitly recognizes the risk and uncertainties necessarily associated with any forecast about the future performance and acceptance of any technology, and thus the need to build flexibility into the plan and to adjust the plan according to the events that occur;
- *Strategic* in that it seeks long-term benefits rather than myopic, short-term objectives; and
- *Planning* in that it develops a process to follow in order to achieve the best possible results for the prevailing circumstances.

The paper describes the principles of Dynamic Strategic Planning, indicates specific methods that are effective for carrying them out, and illustrates their use through application to the formulation of policy on low-emission automobiles in the United States.

Key Words: Dynamic Strategic Planning; Technology Policy; Systems Analysis; Risk Analysis; Decision Analysis; Economic Evaluation; Real Options; Electric Vehicles; Alternative Fuel Vehicles.

Biographical Note: Professor de Neufville is the Founding Chairman of the Technology and Policy Program at the Massachusetts Institute of Technology (MIT) -- a post-graduate course of about 150 students that prepares future leaders in Technology Policy. He regularly teaches Dynamic Strategic Planning in Engineering and Management programs in Europe, Latin America and Asia, in addition to the United States. He is the author of 4 major textbooks, most recently Applied Systems Analysis (McGraw-Hill). For this work he and his team have received several awards for excellence in teaching and two of the annual awards for “the Most Significant Contributions to MIT Education”. His technical interest is in transport planning, with a specialty in airport systems planning and design.

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Introduction

The intelligent development and effective implementation of major technological projects is a highly complex task, calling on the utmost of our capabilities in engineering and science on the one hand, and in management and policy on the other.

For example, the efficient operation of an electric power network requires a mastery of the physical means of producing and distributing this power, of the pricing and marketing of this service and of the regulatory process in which the system must operate. Likewise, the commercialization of new products requires the ability to design and manufacture these devices, the capability to manage the supply chain of inventories and distribution, and the understanding of how to work effectively with the labor force in a global economy. In short, the strategy for the development and implementation of technological systems -- the definition of technology policy in short -- requires an integration of engineering and of the applied social sciences.

In this connection, systems analysis has made major contributions to the improvement of our effective delivery of technological systems to our communities and clients. Using models of both the physical processes (such as production functions, simulations and technical cost models) and of the responses of customers to the range of products and prices available (for instance models of demand and of competitive behavior), systems analysis can guide designers to vastly improved plans for the creation and operation of technological systems. These achievements in analyzing and improving complex systems have depended, of course, on the development of powerful computers that empower analysts to carry out the necessary calculations in practice.

Since the beginning of systems analysis some 50 years ago, its theory and practice has been improving significantly. [1] Operations researchers are enhancing the wide variety of theoretical methods to analyze complex systems; engineers are developing more accurate models of the production and distribution processes; computer scientists are increasing our ability to use vast quantities of information; and practitioners are still learning how to blend all these elements together productively. This remains a continuing process.

Systems analysis has meanwhile delivered enormous improvements in efficiency in many processes. In ways that were completely impractical a generation ago, for example, systems planners and designers are now able to:

- Manage the generation and distribution of electric power over vast regions, changing prices and deliveries minute by minute so as to optimize jointly the production and use of the service -- a capability that is creating competitive markets for power and catalyzing the deregulation of this service;
- Mass produce products according to the specific desires of the customers, by integrating long-distance telephone or electronic orders with suppliers in various countries, who can then ship directly to customers through integrated delivery services such as Fedex or UPS;
- Operate large fleets of aircraft efficiently by combining optimization of the dispatch of the crews and aircraft, with variable pricing of the seats and space -- flight by flight and hour by

hour -- so as to maximize the yields and, in a competitive world, to provide the services at the prices and frequencies that best meet the collective desires of the passengers and shippers.

Yet the use of systems analysis for the design of technological projects is still marked by a wide range of significant failures. While these arise from many sources, a large number of them are attributable to the fact that the analyses have either not incorporated risks and uncertainty into the process, or have failed to create plans with the flexibility to respond to these risks as they occurred.

There are many examples of the failure of systems analyses to recognize risks and to incorporate strategies for dealing with them into the plans. A few suggest the situation:

- The nuclear power industry worldwide has not recognized the true extent of the uncertainties and risks -- both technical and commercial -- of nuclear power. [2] The result is an industry characterized by massive investments that are uneconomical in a world now having both large quantities of natural gas and the combined gas cycle technology to transform this fuel efficiently into power. [3]
- The electric power company of South Africa, Eskom, optimized the size and design of its plants, yet so ignored the market risks that within 15 years they had created 40% over capacity in power generation meaning that about one-third of the available capacity could have been shut down. Despite this visible problem, the company was unable to halt the further construction of facilities that had no immediate use. [4]
- The telephone company of France committed itself, on the basis of the most careful kind of analyses, to the development of the Minitel communications system without building in the capability to expand to more advanced platforms using improved architecture for the system -- the result is a network that is virtually obsolete in the context of the Internet, and that cannot in practice be adjusted to the new technical realities.

Dynamic Strategic Planning is the improvement to systems analysis that recognizes risks and incorporates strategies for dealing with them into the plans. As discussed in the paper, it incorporates two key methodologies:

- Decision analysis, the procedures for organizing and evaluating efficiently the astronomical number of possible different results (given the inherent uncertainties of markets and competition) and the many choices for a design or a plan, taken at several stages in its development [5]; and
- Real Options, the application of the options analyses (which have transformed the financial markets) to the design of technological projects and systems. [6]

Dynamic Strategic Planning is a process that leads to the implementation of technological projects the flexibility to adjust easily over time to the actual situations and conditions as they arise, either to avoid bad situations or to take advantage of new opportunities. It leads systems planners and managers to recognize the great value of flexibility in the design of technological projects, and thus leads to demonstrable, substantial improvements in technology policy. Specifically, it is a process that leads to a Dynamic Strategic Plan.

The Dynamic Strategic Plan defines a flexible development over several stages. It commits only to a first stage, and then proposes different developments in the second and subsequent stages. A typical dynamic strategic plan for the expansion of a manufacturing venture would have the form, for example, of:

- In the first stage, build a medium sized plant; and
- In the second stage, take different actions depending on the success of the venture observed in the first phase, for example -- if sales are disappointing, close the plant; if sales are satisfactory but not outstanding, keep operations going; and if sales are terrific, expand the plant.

A Dynamic Strategic Plan differs from a standard plan in that it is dynamic -- it adjusts over time to actual situations. Doing dynamic strategic planning is comparable to playing chess: the planner thinks many moves ahead, but only commits to one move at a time, retaining the flexibility to adjust the game plan according to the events as they unfold.

The paper begins by tracing the evolution of systems analysis, to place Dynamic Strategic Planning into context. It then describes the methods of Dynamic Strategic Planning. Finally, it illustrates the application of these methods through a case study of their use in the formulation of policy on low-emission automobiles in the United States.

Evolution in the Best Practice of Systems Analysis and Design

The best practice in Systems Analysis and Design has been undergoing major changes in the last twenty-five years. These reflect the continuously deeper understanding, among practicing professionals, of the important issues for design. They also build upon the expanding and improving stock of computer-based models and methods.

The evolution in the best practice of systems analysis and design has so far exhibited three major phases. From the earliest to the latest, these are:

- <u>Systems Optimization</u>, which was the dominant theme in the 1970s;
- <u>Decision Analysis</u>, which became popular in the 1980s; and finally
- <u>Dynamic Strategic Planning</u>, which is the recent innovation.

These phases represent a logical sequence of intellectual understanding of the issues to be faced in systems design. A few words about them should thus clarify the rationale for the development of dynamic strategic planning.

<u>System optimization</u>: focuses on maximizing the performance that can be obtained from a set of assets or productive facilities. Its principal tools are the mathematical methods of Linear Programming and its extensions such as Mixed-Integer and Integer Programming. These are complemented by other approaches such as Dynamic Programming and Geometric Programming. These methods operate over descriptions of the technological system and its context, such as production functions describing the technically efficient levels of output for any set of inputs; technical cost models defining the actual cost of different kinds of designs; and computer based simulations of the operation of a system. While the techniques of systems analysis continue to evolve, all the basic elements were defined a generation ago, and have long since been integrated into the basic education programs in schools of engineering and management. [7]

Optimization is clearly a most important task. Designers naturally want to know how to be efficient, how to use their resources most economically and cost-effectively. By good fortune, linear programming and its variants can be and now are routinely applied to problems with tens and hundreds of thousands of variables and constraints, such as the scheduling of a fleet of aircraft and its crews scattered over dozens of bases. Optimization has thus been applied extensively and most effectively for many years. [8]

A major practical limitation of optimization techniques is that they require the system to be described by a precisely defined set of conditions. In some cases, for linear programming in particular, it is possible to explore the sensitivity of the “optimum design” to restricted changes in the defined set of conditions. Overall however, the optimization techniques assume that the condition of the system to be optimized is well-known.

The assumption that the system can be described precisely and accurately may be reasonably valid over the short term, before significant changes have the time or occasion to occur. Optimization is thus effective, and is most often applied, for the tactical management of operations in the relative near future. But over the longer term -- over which designers need to define their strategic plans -- the assumption that a technological system can be defined precisely and accurately is almost certainly never valid.

Systems designers thus soon came to recognize that optimization is not a sufficient basis on which to develop strategic designs for technological systems. The conditions under which systems have to function cannot be predicted with any accuracy over significant periods. The longer term forecasts are "always wrong" in that point estimates of future conditions only rarely coincide with the actual conditions that will prevail. [9, 10,11] Optimizing the design for specific conditions, while important, is therefore insufficient. Risk must specifically be taken into account.

<u>Decision Analysis</u>: thus has gained popularity in recent years. Decision analysis provides a clearly structured, systematic method for recognizing risks and for evaluating the sequence of choices that would be best for any particular set of eventualities. It assumes that the system designer knows how to optimize the design for any specific specification of the situation, and focuses on the larger issue of how to integrate system optimization into the larger context that acknowledges risk and uncertainty.

In detail, decision analysis provides the methods for:

- recognizing the risks and uncertainties associated with each possible choice in the design and operation of a system;
- structuring the combination of design choices that can be made in stages as the system evolves over time;
- evaluating these combinations to determine the best pattern of development of the system, conditional on how the uncertainties in the system get resolved over time.

Decision analysis is, in most practical situations, the preferred method for examining the possible consequences of different systems designs, considering the range of risks that might occur. Many proprietary computer programs have been developed to help people structure and analyze designs using decision analysis. Decision analysis has thus been widely used to define an optimal decision given the uncertain future.

It is crucial to recognize that decision analysis defines an optimal *strategy* or policy, rather than a fixed plan. The analysis over two or more stages recognizes the value of flexibility, which makes it possible both to take advantage of new opportunities, and to avoid difficulties that might arise in the future. The result of a decision analysis is thus, for example, a recommendation along the lines of:

- First select a particular system design for the first phase, and
- Then, in the second stage of development, choose to expand production if the market uncertainties resolve favorably, but choose to limit the investment if the market develops slowly or unprofitably, or to convert the plant to another product if the competition proves excessive or the manufacturing uneconomical, etc.

Kimura's analysis of the manufacture of silicon wafers in Japan illustrates the typical result of a decision analysis. The issue here was: what technology policy should a new company adopt about entering the silicon wafer market? Kimura's analysis had to recognize the enormous uncertainties associated with the production efficiency a given company could achieve, the range of possible efficiency and market positions that competitive companies might attain, as well wide range of local and world prices for the products. He used decision analysis to propose that the best strategy for the company would initially be to invest in a medium size plant and sell the product at a low price and then to expand the plant if production difficulties could be overcome and the market grew favorably or to limit further investments if those conditions were not fulfilled. [12]

A complete decision analysis for a realistic practical situation takes enormous effort. Considering the range of possible futures, corresponding to the many different possible outcomes, in several periods, involves a huge number of possibilities, defined by the combination of the number of sites at which investments can be made, the different sizes of the facilities at each location, the number of combinations of price and quality for the product, and the number of stages of development. For example, the simple decision analysis for the expansion of the airport for Mexico City -- which involves only 2 sites, of 4 different sizes, over 3 periods -- implied [{(2)exp. 4}exp. 3] = 4096 logically different possibilities. [13] Efficient analysis of this complexity takes considerable effort, and most recent developments in decision analysis have focused on the development of computer methods for analyzing this complexity.

Decision analysis has two major limitations in terms of designing the most effective plans for developing technology. These are both linked to the method's focus on defining the best choice from a selection of alternatives. This focus is too narrow for two reasons:

- The designer's task is to create the best plan, not just to select from some menu of choices. The designer needs to identify what choices to evaluate. Specifically, the designer, in recognizing that flexibility has value, needs procedures to value flexibility and define which arrangements create the kind of flexibility that maximize the value of the investments.
- The definition of a technology policy normally results from the collective agreement of many parties, for example the investors, the customers who might use the product, the workers who may set limits on its production, government officials who may or may not support the new technology, etc. The definition of how a technology is developed is rarely a "decision" that an individual or company can make. The interests and perspectives of the major stakeholders in the development have to be considered, and the analysis needs to reflect this perspective.

<u>Dynamic Strategic Planning</u>: is an effective method for designing and implementing new technology or large-scale engineering projects. It is the third and latest stage in the evolution of Systems Analysis. It features two new elements: the recognition that planners and designers must (1) deal proactively with risk by identifying and building in the most valuable flexibility, and (2) anticipate and deal with the interests and powers of the range of major stakeholders in the consequences of the plan.

The strength of Dynamic Strategic Planning is that it deals explicitly and realistically with the two critical issues that:

1. The future cannot be anticipated accurately, so that forecasts are typically quite different from what actually occurs, and designers must build in the capability both to take advantage of good opportunities and to avoid difficulties that arise; and
2. There cannot be a single "right" design or plan, since the choice of a policy depends on the values of the different groups effectively participating in the decision -- this means that the selection of a preferred plan for important projects realistically rests upon a negotiation between the interested parties.

Analytically, Dynamic Strategic Planning incorporates, in the practical context of the management and design of real projects, means to evaluate the flexibility built into designs, specifically of what is known as "real options". These methods largely take off from techniques recently developed to evaluate financial options and other derivative instruments traded on stock-market exchanges. The complexity and uniqueness of real systems however stretch the theoretical capability of the formulas suitable for financial options, and the standard financial analyses need to be adapted to the reality of technological planning. [14] In practice, the analysis of the value of the flexibility in a design, that is of the "real option", is often most conveniently calculated using decision analysis, which in any case provides the means for analyzing the risks.

Formally, in the sense of financial analysis and of “real options”, the definition to keep in mind is:

> An Option is the right, but not the obligation, to take an action some time in the future, usually for a predetermined price and a given period.

Options can either be to:

- take advantage of an opportunity, to buy into a good situation -- these are known as “calls” in financial analysis; or
- to get out of a bad situation or, as insurance, to be recompensed for some loss -- these are known as “puts”.

In practice, options can either be purely contractual obligations, as in the financial markets, or else “real options” because they are enabled by some physical part of the design. One example of a contractual option is that companies can (at a price, of course) build “escape clauses” into their contracts so that they can cancel them if this is best -- thus airlines typically have options to cancel orders for aircraft from manufacturers. A classical example of a “real option” is the dual-use fuel burner for a power plant, a physical device that allows the electricity generator to switch from one fuel (such as gas) to another (such a oil) when the switch is financially desirable. [15, 16]

Dynamic Strategic Planning additionally incorporates, when applied to the largest issues in technological development, procedures for presenting and dealing with the perspectives and powers of the different participants in the definition of the technology policy. These consist of two elements: laying out the consequences of the possible policies in terms of the consequences of each of the major stakeholders in the decision, and then identifying points of agreement and sufficient coalitions to establish and implement a policy.

The innovative aspect of Dynamic Strategic Planning is that it involves specific methods for the above methods. This paper cannot present these procedures in detail, but the reader can read about them in detail in the references.

In many ways the development of Dynamic Strategic Plans which can respond to events as they unfold, and that are thus “robust” against the range of eventualities is “common sense”. This overall approach has been advocated before [17], however not with the specific methods identified above for identifying either the most effective kinds of flexibilities or the possibilities for stable, long-term patterns of agreement.

Overall, Dynamic Strategic Planning focuses on the implications, the consequences of applying the above techniques of analysis. It develops useful guidelines for action for the designers and managers of complex systems. It is:

- Dynamic in that it recognizes that in an uncertain and changing world it is important to have flexible plans that can adjust to future conditions, instead of trying to identify an “optimum plan” that will hold for any meaningful time;
- Strategic in that it properly takes the view that systems have to perform well not just in the immediate, but over the long term; and
- Planning in that it does indeed develop a coherent set of guidelines for the system designer or manager as to what should be done, and when and how it should be done.

Methods of Dynamic Strategic Planning

Principles: Dynamic Strategic Planning is based on six fundamental principles. Three concern the nature of the objectives of the plan, and three the evolution of the plan over time.

As regards the nature of the objectives of the plan, it recognizes that:
1. The elements of the plan should be technically efficient, that is that the analysis ought to identify -- by optimization or simulation -- the production possibility frontiers, the sets of designs which are Pareto optimal; however
2. There is no single right or optimal design, since the plan preferred by any group of stakeholders depends on its own particular preferences (technically, the point of tangency of the production possibility frontier with the highest isovalue line for that group); so that
3. The overall aims of the plan must necessarily result from a negotiation or political settlement among the parties having a stake in the plan. [18]

The consequence of the above principles is to shift much of the attention of the planning process away from optimization and modeling, and toward the need to negotiate a strategy for implementation of large projects or new technology, among the interested parties.

As regards the evolution of the plan over time, Dynamic Strategic Planning recognizes that:
1. All forecasts can be expected to be wrong in significant ways, in the sense that what actually occurs will differ significantly from what was originally predicted; so that
2. The plan should build in flexibility to deal effectively with the range of developments that may occur; and
3. The desirable forms of creating flexibility can be identified using the methods of options analysis, derived from modern financial theory, in particular the application of these methods to real projects through what is known as “real options” in contrast to the financial or stock market options. [6]

These six principles together define the combination of methods that define Dynamic Strategic Planning. These methods are the essential methods of traditional systems analysis and of decision analysis, with the addition of procedures to evaluate different means of providing flexibility and of identifying policies that could have a good chance of gaining and maintaining the acceptance of the key stakeholders in the decision-making process.

Methods: For expository purposes it is convenient to think that Dynamic Strategic Planning involves 7 distinct categories of methods that together do the systems analysis, decision analysis and ultimately define the plan. These are:
1. Modeling: The representation of the possible designs and of their consequences is the elementary step. The models basically are production functions that define the technically efficient, that is the maximal outputs that can be achieved with any set of resources. These models can be analytic or statistical. They are often most conveniently defined by computer-based spreadsheets that manipulate the technical relationships and can provide the results for any specified set of inputs.
2. Optimization: In certain circumstances, in particular when the problem concerns the transport of things across a network, it is possible to specify formal optimization procedures that lead to precise answers for any set of conditions. More generally however, the results have to be obtained by simulations which can be achieved relatively easily through the repetitive use of spreadsheet analyses. The results in either case are cost functions which define, based on the combination of the production function and the costs of the resources, the cost-effective means for achieving any specified level of result.
3. Estimation of Probabilities: The fact is that nobody can forecast the performance of any system accurately, any meaningful time in the future. This is because nobody can reliably estimate all the parameters that define a technological system: the costs of resources fluctuate, the performance of the system varies with age and as new technologies are introduced, the loads on the system fluctuate and the desires of the customers shift, etc. It is

therefore necessary to estimate both the ranges of the key parameters and the likely probability distribution of values of each important parameter over that range. This is done most naturally by consulting the historical record on the fluctuations when this is possible, or by consulting expert opinion either directly or through the range of estimates available in the literature.

4. <u>Decision Analysis</u>: Given the assessment of the possible results that can be obtained for any set of parameters (from the optimization) and the distribution of possible values of these parameters under different circumstances (from the estimation of probabilities), it is possible to structure a decision analysis of any set of choices. Carrying out this analysis is instructive in itself because it will indicate the kinds of flexible strategies that appear in a preliminary way to be most attractive. This exercise then focuses attention on the possible kinds of additional flexibilities to build into the plan.
5. <u>Sensitivity Analysis</u>: Just as we know that it is impossible to forecast performance accurately, we know that in general we cannot in general estimate the probabilities of performance well. Much of what we maybe concerned about, for example the future market for a new product, is a one-time event for which we will not have any frequency patterns from which to estimate. Therefore, we must explore the sensitivity of the recommended decisions generated by the analysis to alternative estimates of the probability. We know that if the probabilities of future events are different between analyses, the value of the recommended decision will be different: the crucial question however is whether the preferred action is itself different. For example, we may really want to know whether to choose technology X or Y. A sensitivity analysis will allow the analyst to identify the range over which a recommended action in the first stage of a plan is best. The sensitivity analysis is perhaps most easily done by means of the “data table” features of modern computer based spreadsheets, that allow one to range over different values of probability easily.
6. <u>Evaluation of Real Options</u>: Additional flexibility would always be advantageous -- if it were free. Building flexibility into a strategy however always costs, because it involves extra or redundant capabilities, because it involves making smaller investments and missing out on economies of scale, or because it causes delays and loss of benefits. The questions thus are: what is the value of the different forms of flexibility that might be added to the system? and which ones justify their cost? Estimating the value of the alternative forms of flexibility is the task of the analysis of the “real options”. Once these values are calculated, it is possible to build these options into the decision analysis, and identify a set of the most desirable dynamic strategic plans. [6, 14, 18]
7. <u>Analysis of Implicit Negotiation</u>: Finally, an effective strategy for the development and implementation of the technology policy must be defined. This requires that we look at the possible strategies identified in the previous steps from the point of view of the different key stakeholders in the process. Normally, what looks good from one perspective may not look good from another (for example, the deregulation of telephone services may mean lower costs globally, at the expense of higher relative costs for small customers and the loss of jobs for employees of the telephone company). Because key stakeholders affected by a technology policy may have the power to block or subvert the implementation of the policy, effective implementation of a policy means that we must identify compromises that will compensate potential losers from a policy. The final proposal for an effective technology policy will result from a combination of this analysis of the implicit negotiation and of the plausible strategic plans identified in the previous step. [18, 19]

Case Study Application of Dynamic Strategic Planning

The United States, along with all the other major countries, must face the issue of what to do about air pollution that comes from automobiles. The basic question is: What technologies or control strategies should we implement? This question has several dimensions, of course, such as:

- Technical: Which technologies are most cost-effective in lowering the pollution, both now and later on as new technologies mature? What is the appropriate path of technological development?
- Economic: How much money should be spent on reducing automotive air pollution? What can a nation afford? What is worthwhile?
- Social: How much do people in a specific country or region really care about pollution, in contrast to other problems? To what extent are they willing to be inconvenienced for the sake of a cleaner environment?

Dynamic Strategic Planning provides a suitable basis for the design of the most appropriate technological policy for reducing automotive air pollution in a region. The issue is complex; the outcomes of any choice cannot be forecast accurately given the uncertainties in the performance of future technologies and the prices at which competitive fuels will be available; and the acceptable policy will result from the interaction of the many interest groups that are concerned with the pollution, the cost of the alternatives, the price and convenience of transportation -- that is, nearly everyone.

The results of a dynamic strategic planning in this case illustrate the advantages of this approach. As indicated below, the results contrast strongly with the technological policy previously set in the United States -- the mandate for electric vehicles -- both in substance and in process. The Dynamic Strategic Plan suggests that it is best:

- To focus attention on fuels, which can be introduced quickly to the entire fleet of automobiles, and on hybrid vehicles -- rather than on electric vehicles as the technology of choice; and
- To engage in a flexible process of implementation of the better technologies as they are proven -- rather than to mandate electric vehicles.

The case analysis first of all uses a traditional systems analysis to identify optimal designs, based on models of the technological possibilities for manufacturing and then powering automobiles using different sources of fuel (electric batteries, alternative fuels such as ethanol or methanol, and fuel cells as an alternative modes of transforming energy -- in addition to traditional internal combustion engines powered by gasoline contingent on any assumed set of preferences). It then employs decision analysis and options theory to identify the consequences of uncertainty and the kinds of options that add the most value to the design. Finally, it considers the peculiar situation of the United States to determine which particular plan might most reasonably constitute a basis for acceptance by a broad range of decisions-makers, powerful enough in the American context to achieve initial acceptance of the plan and then, most importantly, to implement it.

Background: For much of the 1990’s the most strongly debated part of the American policy on automotive air pollution has been the mandate to build and sell large numbers of electric vehicles. This mandate was created by the State of California and then copied by the States of Massachusetts and New York.

The mandate specified that as of 1998 2% of all new automobiles sold in California (and the copying States) would have to be “Zero Emission Vehicles” or ZEVs, and that this fraction would rise to 10% in the year 2003. [20] In this context a “Zero Emission Vehicle” was defined as one that did not emit any air pollutants from the drive train. [21] Since no other technology was practical in the 1990’s, ZEVs had in fact to be electric vehicles or EVs.

As a result of this mandate, the American automobile manufacturers spent about 5 years and hundreds of millions of dollars on developing electric vehicles to meet this mandate. They had to, if they wanted to sell cars in California, one of the largest single automobile markets in the United States.

This technology policy has proved to be a disaster, both technologically and as far as meeting the goals of reducing air pollution. The commitment to the 'electric vehicle' technology was, in the face of the numerous technological and market uncertainties, premature at best. Even though demonstration electric vehicles may look attractive, the technology simply is not yet ready for the mass market. [22] General Motors has attempted, through a really major effort in a most favorable location, to establish a market through subsidized leases and guaranteed trade-ins for defective vehicles, and has barely managed to place a few hundred electric vehicles within the first year. [23]

Moreover, even if the number of car sales set by the mandate could be achieved, this policy would have no discernible effect on the overall level of pollution in a region. The high target that 10% of new vehicles in any year would be electric, in fact affects less than 1% of all vehicles in the fleet since vehicles in the United States last about 13 years on average. The effect of the mandate under the best circumstances would be to keep up with the expected increase in automotive air pollution due to the increase in the population and the amount of travel.

The mandate failed as a technology policy. It failed because it:

- Was not based on any systematic analysis of what might be either realistically possible technically, or acceptable to consumers -- let alone of how cost-effective it might be compared to alternative policies;
- Omitted any realistic consideration of the risks inherently associated with the development of new technologies or new markets, and thus did not make any provision to adjust the mandate; and
- Did not consider how the mandate was to be made acceptable either to the producers who would have to subsidize the electric vehicle fleet, or to the consumers that would have to use these vehicles.

The Analysis: An appropriate Dynamic Strategic Analysis should lead to much better technology policy. Improvements should be inevitable, just by avoiding the elementary flaws associated with the policy that mandated electric vehicles for California in 1998.

This analysis focused on the question: What is the most appropriate technology policy for the United States as regards reducing automotive air pollution? More specifically, the question was: What kind of policy toward alternative fuel vehicles should be followed, over the range from none, through modest research and development efforts, to a full-scale implementation?

The analysis was done in a large-scale preliminary investigation conducted at the Massachusetts Institute of Technology by a class of 45 post-graduate students working in teams, and using the methods of Dynamic Strategic Planning described in the previous section. It is described in that order.

Several models were fundamental to the analysis. They described the technological system. The ones used were:

- Models of the performance of different possible vehicles, according to their design characteristics. From data on their source of power (type of batteries, fuel cells, gasoline) and the material from which they were made (steel, aluminum, composite plastics), the spreadsheet models development by the MIT Materials Systems Laboratory could estimate both the cost of manufacture at different levels of production, and the performance through nationally specified 'drive cycles' that specify the mixture of climbs and descents, stops and starts.

- Models to assess the pollution generated by the fleet of automobiles, so that the consequences of different policies for reducing pollution could be determined. This was done through a cohort model which tracked the stock of vehicles from the moment they entered the fleet, as they aged, to when the left the fleet by being junked or destroyed.
- Several small models to define the cost of the fuels, either of the liquid fuels (gasoline, methanol and combinations) or the electric power for the battery powered cars.

The Optimization was carried out by simulation. Given the many non-linearities and discontinuities in any realistic description of the system, none of the standard optimization techniques could conceivably be applied to the system being considered.

Given any policy that specified the number and type of alternative fuel vehicles to be put on the road, the models could estimate both the reduction of air pollution and the several measures of cost -- to society as a whole, to consumers, and to manufacturers. By ranging through many different configurations -- a task that is relatively easy using the 'data tables' options of spreadsheet programs -- it was possible to define the outer limits of performance, the production possibility frontiers and the cost-effectiveness curves.

The results of the optimization depend, of course, on the parameters used to describe the system. The performance of an electric vehicle depends on the batteries, and the future performance of these technologies might change rapidly over the next decade. These results then had to be placed into the context of a decision analysis, in order to get a balanced estimate of the likely future performance of alternative technology policies with regard to the introduction of alternative fuel vehicles.

The Estimation of Probabilities of future performance were obtained from the literature on the current capabilities of the various technologies, on their trends, and on the available opinions of experts in the area.

To estimate these probabilities accurately, it is important to get a reasonable concept of the range of possible outcomes. This is particularly important because experts are demonstrably overconfident [24] in their assessments, and reluctant to admit to how different the reality may be from their forecast [9, 11]. Obtaining a reasonable range can be done in two ways, and is best done by both consulting a wide range of knowledgeable persons, and reviewing the actual range of variation over comparable past periods.

For the current case, the estimation of the ranges and probabilities of the future performance focused on two key issues: prospective improvements in batteries and in fuel cells. These are the key unknowns as regards any significant departure from vehicles propelled by internal combustion engines. These estimates naturally must depend on the level of effort devoted to the improvement of these new technologies, and estimates were made of this relationship.

The Decision Analysis was straightforward in concept. It was basically structured around the question of: What level of funding ought to go into research and development of which technologies over the next ten years, so as to maximize the improvement of air quality.

Several levels of funding were considered (low level laboratory research, medium level involving industrial development of prototypes, and aggressive promotion of demonstration programs involving hundreds of millions of dollars annually). Several alternatives of investments in battery electric vehicles, fuel cell vehicles, and hybrid vehicles were compared against the use of methanol, ethanol and both conventional and reformulated gasolines.

The ten year planning period was divided into phases, based on the fact that intelligent management of any development program requires one to revise goals and effort depending on the previous results. To limit the analytic effort required, only 2 periods were considered, but these were enough to provide the opportunity to exercise flexibility in the definition of the optimal policy.

Figure 1 shows a portion of the decision tree used in the analysis. Although it is conceptually simple, it in fact provides a rich menu of possibilities. In showing a representative view of the number and complexity of the choices it is not practical to show the details of the probabilities and the outcomes, unfortunately.

[Insert Figure 1 -- appended at end of text -- about here]

The Sensitivity Analysis recognized that all the estimates of the probability of future success of future innovations were all speculative. It was therefore important to test the robustness of the results of the decision analysis to variations in these estimates. The sensitivity analysis was carried out by using the “data table” feature of the spreadsheet. This was particularly easy since the Treeplan ® decision analysis software was a macro of Excel ®.

The Evaluation of Real Options was in this case carried out using decision analysis to estimate the value of the real option. Given the lack of statistical information on the evolution of technology and of research and development programs -- in contrast to the wealth of information available on the variation of the prices of commodities over time -- this is generally the preferred approach for complex technological systems. [14]

As regards the development of alternative fuel vehicles for the purpose of reducing air pollution, the analysis made it clear that there was great value in focusing research on the “electrification” of the automobile, that is on the design of more efficient ways to manage electric power in a car, by using both bigger batteries and improved electronics. [25]

Investments in the “electrification” of the automobile would give us the option of developing electric vehicles either powered by batteries or by fuel cells, should either of these technologies develop sufficiently. Moreover, they would have immediate payoffs in the performance of conventional cars powered by internal combustion engines. Many observers in fact think that the complete overhaul of the electric distribution in conventional cars may be the next breakthrough in automobile technology.

The Analysis of Implicit Negotiation is never an easy task. The way that the major stakeholders in a technology policy defend their interests and shape the eventual outcome is ultimately contingent on specific personalities and events. This is amply documented by the literature, in particular as regards the evolution of technology policy for the development of alternative fuel vehicles. [26, 27]

Nonetheless, it is possible to analyze the situation usefully in two major ways. We can:
- anticipate the basic concerns and interests of the major stakeholders concerned with the process, and thus anticipate what they will demand from the eventual negotiation; and
- determine both the sources of the power of each group, and the specific kinds of power they can exercise. See Figure 2. [28]

[Insert Figure 2 -- appended at end of text -- about here]

For example, any review of the debates over reducing air pollution from automobiles in America should recognize that the agricultural interests in the Mid-West part of the United States are concerned with the price of corn -- and thus see ethanol fuel as a major support for their livelihood, and can demonstrate this power by their influence on a core bloc of votes in the United States Senate. Any technology policy concerned with the intelligent development of alternative fuels for vehicles in the United States must deal with this fact. Although good technical arguments for can be presented doing away with the ethanol programs in the United States, no policy to do so will succeed unless it offers alternative ways to deal with the interests of the farmers who have been able to create a sufficient coalition of Senate votes to block any such proposal in the past.

The analysis for our case examined both the consequences of alternative technology policies for the major stakeholders in the process, and considered their core issues and strengths. This analysis was supported by simulations of the negotiation process, in which teams played out the roles of the major stakeholders, and thereby kept the analysis focused on defining a technology policy that would have a reasonable chance of success.

<u>The Results</u>: The Dynamic Strategic Plan that resulted from this process is substantially different from the mandate for electric vehicles that was attempted by California. The recognition of the risks and uncertainties in the future performance of such systems on the one hand, and of the need to craft a technology policy that could be broadly acceptable to the public on the other, led to what we believe is a much more productive proposal.

The proposed technology policy for the development of alternative fuel vehicles for the reducing air pollution from cars has three main features. [29, 30] These are:

1. A commitment to the creation of options, through a sustained investment in a range of prospective technologies that each might, if matters turned out favorably, be the basis for a new kind of automobile. This contrasts sharply with the early commitment to a particular technology adopted by California.
2. These research and development efforts should apply principally to capabilities which have the broadest possible use, that is to platforms that enable several possible future technologies rather than exclude these prematurely before the facts are in. Specifically, the effort should concentrate on the "electrification" of the automobile, on the range of means to create and manage electric power in the car. Together these efforts could advance much improved vehicles of many sorts -- battery-powered electric vehicles, fuel-cell electric vehicles, hybrid vehicles and even conventional vehicles powered by internal combustion engines.
3. In the immediate, substantial attention should be directed to the further commercialization of the use of cleaner fuels in conventional cars. Small improvements in this regard can lead to large reductions in the total level of air pollution, because they apply rapidly to all cars in the fleet, not just to the few percent represented by a small fraction of the new cars sold.

Conclusions

Dynamic Strategic Planning appears to be an effective set of procedures for identifying strategic plans for the development and implementation of technology policy. It certainly provides an important and necessary extension to the basic elements of systems analysis and operations research, as regards the important issues of dealing proactively with risk and identifying the most effective kinds of flexibility to introduce into the design of significant projects.

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References and Notes

[1] For some of the early developments in systems analysis, see, for example: Quade, E. (1967) *Analysis for Military Decisions*, Rand McNally & Co., Chicago, IL.; Quade, E. and Boucher, W. I., eds. (1968) *Systems Analysis and Policy Planning; Applications in Defense*, American Elsevier, New York, NY; and Miser, H. J. and Quade, E. S. eds. (1985) *Handbook of Systems Analysis: Overview of Uses, Procedures, Applications and Practice*, North-Holland, New York, NY.

[2] von Hippel, F. (1991) *Citizen Scientist,* Simon and Shuster, New York, NY. See especially the chapter on "Peer Review of Public Policy" in which he provides some interesting discussions of the difficulty the systems analysts had in recognizing the real, and subsequently demonstrated uncertainties in the demand for electric power -- and then consequent need for flexibility in the pace and type of development of nuclear power, all while they were supposedly investigating risks!

[3] In the United States for example, several power companies have been bankrupted by their inflexible commitment to massive nuclear power plants, such as the Washington State Power Company, the Long Island Lighting Company near New York City that spent about US $ 5 Billion on a plant that was disposed of for virtually nothing, and several others. With the deregulation of the market for electric power in the United States, billions of dollars worth of investments have become uneconomical and are said to be "stranded". Much the same happened in Britain when deregulation of the power market occurred there.

[4] Aberdein, D. (1994) "Incorporating Risk into Power Station Investment Decisions in South Africa," Master of Science thesis, Management of Technology Program, Massachusetts Institute of Technology, Cambridge, MA, USA. This work discusses the South African situation at length.

[5] de Neufville, R. (1990) *Applied Systems Analysis -- Engineering Planning and Technology Management,* McGraw-Hill, New York, NY, USA. This text provides one of many descriptions of how decision analysis applies to systems planning and design.

[6] Trigeorgis, L. (1996) *Real Options -- Managerial Flexibility and Strategy in Resource Allocation,* MIT Press, Cambridge, MA, USA.

[7] de Neufville, R. and Stafford, J. (1971) *Systems Analysis for Engineers and Managers,* McGraw-Hill, New York, NY, USA. This textbook provides an early example of the integration of the methods of operations research into a design process for technological systems.

[8] de Neufville, R. and Marks, D., eds., (1974) *Systems Planning and Design -- Case Studies in Modeling, Optimization and Design,* Prentice-Hall, Englewood Cliffs, NJ, USA. This text provided a collection of examples as early as a generation ago. Recent excellent examples are high-lighted by the annual Franz Edelman Prizes of the Institute for Operations Research and the Management Sciences, and are available on video and as case studies. See their web page: http://www.informs.org/

[9] Ascher, W. (1978) *Forecasting: An Appraisal for Policy-Makers and Planners,* Johns Hopkins University Press, Baltimore, MD, USA. This text is a classic compendium of illustrations of how forecasters are inherently unable to anticipate the surprise developments arising from new technologies, changes in the structure of an industry, and reshuffled political configurations such as the demise of the Soviet bloc or the rise and fall of the Organization of the Oil Producing Countries (OPEC) as a determining force in the petroleum markets.

[10] de Neufville, R. (1976) *Airport Systems Planning and Design -- a Critical Look and the Methods and Experience,* Macmillan, London, UK and MIT Press, Cambridge, MA, USA. See especially Chapter 3: "Guessing at the Future."

[11] Lynch, M. (1996) "The Analysis and Forecasting of Petroleum Supply: Sources of Error and Bias," in *Energy Watchers VII*, ed. by Dorothea H. El Mallakh, International Research Center for Energy and Economic Development. Also (1994) "Bias and Theoretical Error in Long-Term Oil Market Forecasting," in *Advances in the Economics of Energy and Natural Resources*, John R. Moroney, ed., JAI Press. Lynch's work over many years documents the way that the consensus of forecasts on oil prices, the cost of production and the amount of oil available have all been systematically wide of the actual developments.

[12] Kimura, M. (1995) "Strategic Planning for Newcomer in Silicon Wafer Industry," Master of Science thesis, Management of Technology Program, Massachusetts Institute of Technology, Cambridge, MA, USA.

[13] de Neufville, R. and Keeney, R. (1972, 1976) "Use of Decision Analysis in Airport Development for Mexico City," Chapter 24 in de Neufville and Marks (1974) [Note 7], and adapted from Chapter 23 in Drake, A., Keeney. R. and Morse, P. eds., (1972) *Analysis of Public Systems,* MIT Press, Cambridge, MA, USA.

[14] Nichols, N. (1994) "Scientific Management at Merck: An Interview with CFO Judy Lewent," *Harvard Business Review,* Jan.-Feb., pp. 89-99. Faulkner, T. (1996) "Applying 'Options thinking' to R & D Valuation," *Industrial Research*, pp. 50-57. These two articles provide good examples of this adaptation to two major American multinational companies, Merck and Kodak.

[15] Hull, J. C. (1993) *Options, Futures, and other Derivative Securities*, 2nd ed., Prentice-Hall, Englewood Cliffs, NJ provides a textbook approach to financial options.

[16] Kulatilaka, N. (1993) "The value of flexibility: The case of a dual-fuel industrial steam boiler," *Financial Management*, Vol. 22, No. 3, pp. 271-279, provides a description of this case, as a specific example of the real options described in Ref. [6].

[17] See for example Dewar, J. A et al. (1993) *Assumption Based Planning: A Planning Tool for very uncertain times*, Report MR-114-A, RAND, Santa Monica, CA.

[18] See for example Cohen, J. H. (1973) "Multiobjective Analysis in Water Resource Planning," *Water Resources Research*, Vol. 9, No. 4, August, pp. 333-340, or de Neufville and Marks, ref. [8], Chap. 21, pp. 304-321.

[19] Fisher, R. and Ury, W. with Patton, B., ed. (1981) *Getting to Yes; Negotiating Agreement without giving in*, Houghton Mifflin, Boston, MA; and Ury, W. (1991) *Getting past No: Negotiating with Difficult People*, Bantam Books, New York, NY provide useful preliminary guidelines on negotiating.

[20] There are some minor exceptions to this rule, for example for emergency vehicles and for the importers of small numbers of vehicles.

[21] Notice the focus on the 'drive train'. The mandate did not cover other uses of power in the car, as for climate control. Thus the "Zero Emission Vehicle" produced by the Ford Motor company legitimately featured an oil burning heater, together with an exhaust pipe!

[22] de Neufville, R, S. Connors, F. R. Field, D. Marks, D. R. Sadoway, and R. Tabors (1996) "The Electric Car Unplugged," <u>Technology Review</u>, Jan., pp. 30-36; also published as

"Quell'auto con le batterie scariche," Technology Review, editzione italiana, Apr./May., No. 90-91, pp. 22-29.

[23] Child, C. (1997) "Dealers Lease 155 EV-s in 3 Months," Automotive News, Mar. 10, p. 1 and 47; "GM has 240-day supply of EV-1 car; had 31 leases in 2/97, vs. 76 in 12/96," Automotive News No. 5703, p.1.

[24] See [5], chapter 15, for textbook discussion of this phenomenon well-known in psychometrics.

[25] Kassakian, J. et al. (1996) "Automotive Electrical Systems circa 2005," IEEE Spectrum, August, pp. 22 - 27. This article gives a good indication of what might be possible.

[26] Cohen, R. E. (1992) *Washington at Work -- Back Rooms and Clean Air*, Macmillan Publishing, New York, NY, USA. This text illustrates the kinds of negotiations that take place in an overtly political process, in this case in the context of the passage of the Federal Clean Air Act Amendments of 1990 in the United States.

[27] Schnayerson, M. (1996) *The Car that Could -- the inside story of GM's Revolutionary Electric Vehicle,"* Random House, New York, NY, USA. This text complements the Cohen book [26] by showing the political difficulties of implementing a new technology policy within the context of a single major company, as different interest groups within the company fight over priorities and resources.

[28] In teaching post-graduate students about this in the MIT Technology and Policy Program, the diagram of Figure 2, generated by Richard Tabors has been helpful.

[29] Hackney, J. (1997) "Alternative Fuel Vehicle Policy: A Life Cycle Analysis Tool for Emissions, Costs and Energy Efficiency with an Application to the United States," Master of Science thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA, USA.

[30] de Neufville, R. (1997) "Alternative Fuels for Tomorrow's Cars," Proceedings of the 1997 World Methanol Conference, Tampa, FL, USA (Dec.), pp. 199-209.