Economic Systems Analysis

Microeconomics for Systems Engineering, Engineering Management, and Project Selection

Series Volume 10

Andrew P. Sage

Preface

The purpose of this text is to provide a background in the fundamentals of economic analysis that is appropriate for engineers and managers concerned with the design and/or management of large-scale systems. It is assumed that readers of this text will have previously studied mathematics through calculus and differential equations, and that they have some background in linear algebra. No prior background in mathematical programming or economics is assumed, although a modest exposure to undergraduate microeconomics will be very helpful. The objectives of this text include a salient discussion of engineering economic systems that will be relevant for those who desire to use the subject matter in their professional practice, for those who must communicate and broker the results of an economic systems analysis between professional economists and clients, and for those who desire to undertake more advanced study in areas of management science and systems engineering that are related to microeconomics.

The primary topics in the book include the following:

economics of the firm
economics of the consumer
supply–demand interactions and economic models
normative or welfare economics
cost–benefit analysis

Earlier drafts of this text have been used for several years in a one-semester graduate course in systems engineering offered at the University of Virginia; portions of it have been used for an undergraduate version of this economic systems analysis course. A large number of classroom-tested exercises for the student follow each chapter. These exercises complement and often extend the discussions in the chapters.

July 1982 Andrew P. Sage

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Chapter 1

Introduction to Economic Systems Analysis

1.1 Introduction

This text is about one of the fundamental concerns in system design: economic systems analysis. In it we discuss the very important role of economics in shaping our lives and how we design our activities and institutions to achieve economic (and other) objectives. The purpose of this text is to present those fundamentals of microeconomic systems analysis that are most necessary in the engineering and management of systems of machines, humans, and organizations that are effective and efficient, and equitable as well. We desire to equip ourselves to answer three questions:

1. What should be "produced" and how much of it should be produced?
2. How should the "produced" goods be produced?
3. Who should get the goods and services that are produced?

The first of these questions relates to effectiveness, the second relates to efficiency, and the third relates to equity concerns.

This chapter will provide an overview of our undertakings. We will first summarize a framework for systems engineering and illustrate the important role of the economics of a firm in attempting to maximize profits and that of the economics of the consumer in attempting to maximize satisfaction by allocating resources—all within the constraints of finite resources. Then we will provide an introductory discussion of the microeconomics of firms and consumers operating together in various markets. Our presentation will stress the information base and other conditions necessary to ensure what we will call a perfectly competitive economy.

These conditions will, as will be apparent, typically not prevail. Various distortions from perfect competition will then result. We will discuss some of these. Our discussions will concern both descriptive economics, that is, how individuals and organizations actually behave, and normative economics, that is, how individuals and organizations should behave in order to best achieve identified objectives.

1.2 A Framework for Systems Engineering and Analysis

A central purpose of systems engineering is to assist clients in the organization of knowledge that contributes to the efficiency, effectiveness, equity, and explicability of decisions and associated resource allocations. Systems engineering methodology provides a framework for the formulation, analysis, and interpretation of issues and problems that will lead to the resolution of issues of large scale and scope. Within this framework, content, concepts, and methods are selected. The systems process, in which client(s) and analyst(s) cooperate to establish useful policies, plans, or designs, involves three fundamental steps:

1. *formulation* of the issue or problem,
2. *analysis* of the (impacts of) alternatives, and
3. *interpretation* of results leading to the *evaluation* and prioritization of alternatives as well as the *selection* and *implementation* of selected alternative(s).

The systems process is typically characterized by

a. a systematic, rational, and purposeful course of action;
b. A holistic approach in which issues or problems are generally examined in full relation with their environment, as well as with due consideration for the causal or symptomatic, institutional, and value aspects of the issue under consideration; and
c. the eclectic use of methods and knowledge based on the mathematical theory of systems science and operations research, as well as the behavioral theory of systems management.

The typical product of a systems engineering study is a plan for action to implement a decision, or a plan to implement another phase of a systems study that will ultimately result in such a plan for action. Economic concerns are vital in developing appropriate plans. It is the study of engineering economic systems analysis that is of interest here. This study is all the more valuable if we first imbed it within a discussion of the entire systems process.

As we have noted, the systems engineering process involves three fundamental steps.

1. *Issue Formulation*
   A descriptive account of the issue or problem under consideration is obtained, including the identification of needs, alterables, constraints, stakeholders, relevant societal sectors or institutions, relevant fields of

knowledge, etc. Next, the objectives of the needed policy or plan are identified and possibly structured, and objectives measures or attributes of desirable states are specified. These will serve as sensors or indicators or instrumental measures of the degree to which alternatives satisfy the objectives. After this, possible alternative actions or system designs are identified or postulated.

In a more detailed description of the systems process, the issue formulation step of the systems engineering framework is subdivided into three more specific steps:

a. *problem definition*—identification and structuring of problem elements, which typically include needs, constraints, alterables, and societal sectors;
b. *value system design*—identification and structuring of objectives and specification of objectives measures or attributes to determine the degree of objectives satisfaction; and
c. *system synthesis*—identification of potential alternatives, policies, controls, or complete systems that are believed capable of needs satisfaction.

2. *Analysis*

The various feasible alternative systems, designs, or action alternatives are analyzed more closely to assess their feasibility, and/or the expected impacts of their realization or implementation. This activity is often referred to as "impact assessment." The forecasting of possible consequences of the implementation of posed alternatives typically play a central part in this effort. Subsequently, in a refinement or fine tuning of alternatives, policy parameters are adjusted, typically by means of various optimization-based approaches, such that each proposed policy is the best one possible in terms of expected satisfaction of the value system. Thus we see that the system analysis step is divided into

d. *systems analysis and modeling* (impact assessment), and
e. *optimization or refinement of alternatives.*

After the issue has been formulated and analyzed, such that there exists a set of alternatives and some knowledge of the impacts of the alternative courses of action in terms of the objectives one desires to satisfy in order to fulfill needs, it becomes possible to implement the final major step of a systems effort.

3. *Interpretation*

This implies an evaluation of the alternatives in terms of how their impacts result in need fulfillment, the prioritization of alternatives, the selection of one or more alternatives, and the implementation of action plans. In interpreting alternative courses of action, systems or policy options are evaluated and ranked in importance with respect to need satisfaction as indicated by the associated objectives measures. This evaluation is made to determine whether one or more policies or systems are worthy of further consideration or implementation. A plan or schedule for implementation, including resource allocation, is determined. This step may be subdivided into

f. *decision making*, and
g. *planning for action*.

A number of efforts have been made to describe systems engineering in a number of phases, such as program planning, project planning, development, and implementation. The underlying idea is that each of these phases represents an important choice-making task in which the formulation, analysis, and interpretation steps are accomplished. When the (logical) steps of systems engineering are listed along one axis and the phases along another, a table or matrix results in which each individual entry represents a specific activity corresponding to one of the steps and one of the phases of a systems effort. Our major concern here will be with the analysis steps of a systems effort, especially those portions that involve the microeconomic concerns of the interactions of firms and consumers in markets and the evaluation and prioritization of alternative projects.

There are several points which merit further discussion here. First of all, neither systems engineering nor economic systems analysis efforts within systems engineering are processed in a sequenced linear way. They involve a process* in which iteration plays a central part. Insights obtained from one part of the effort might lead to a revision of approaches taken earlier, making iteration and feedback necessary. Second, the steps just outlined are intended to be helpful as a guide, not as a restrictive format. Flexibility in the procedures and methods used is a central feature of systems engineering. It should be noted, however, that each of the steps outlined above represents an important ingredient in a systems effort, and omission or neglect of any step increases the risks of failure. Third, since systems engineering is a process in which people work together to realize the various steps of the effort, the selection of an appropriate combination of capable analysts, experts, or other participants, and methods or aids in the process, is at least as important as adherence to the several steps of the systems engineering framework. Figure 1.2-1 presents a conceptual flow chart of the systems process.

The systems engineering approach is most appropriate for use when one or more of the following is the case with respect to the problem or issue under consideration:

a. There are many considerations and interrelations.
b. There are far-reaching and controversial value judgments.
c. There are multidisciplinary and interdisciplinary considerations.

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*We shall not expand upon this notion here, but a process is the interaction of a method, or methodology, with human judgment. See the chapter by Sage in *Large Scale Systems* (1982) for a fuller discussion.

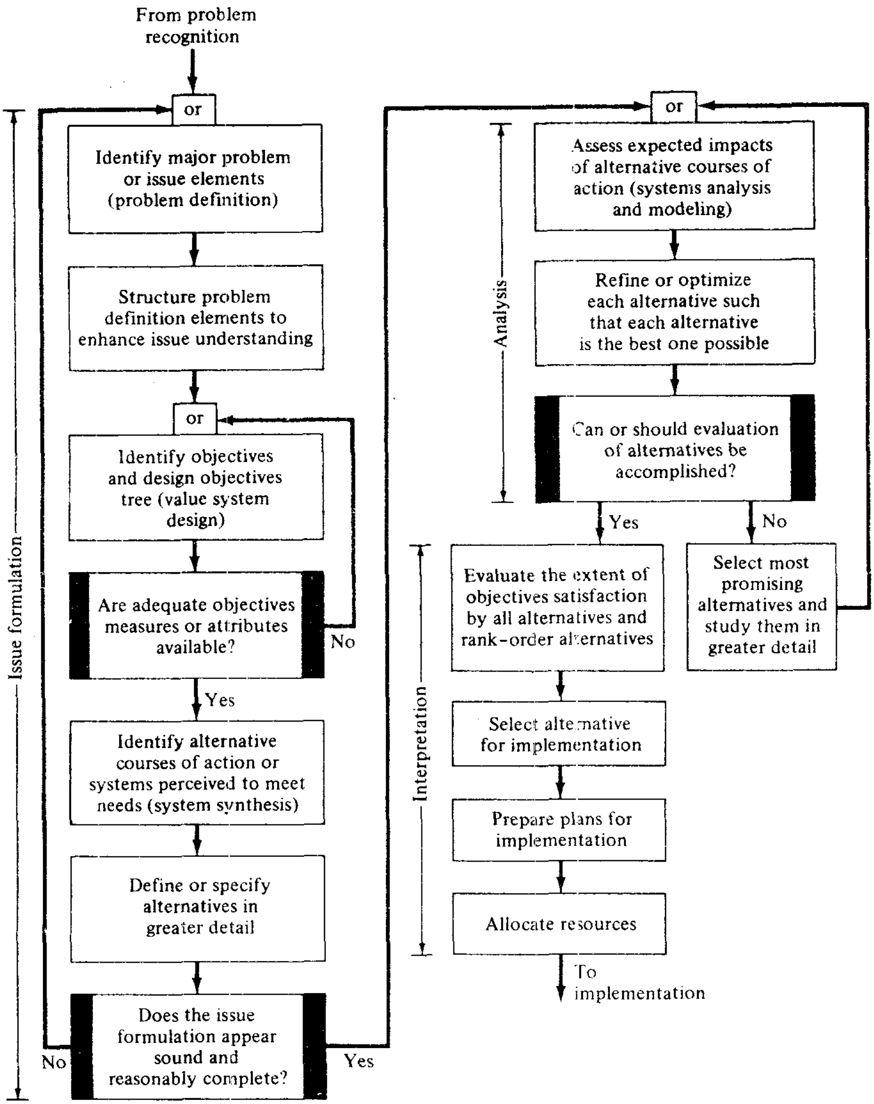

Figure 1.2-1 Flow chart outlining the systems engineering process.

d. Future events are difficult to predict.
e. Structural and institutional considerations play an important role.

There are many methods which are potentially useful in various steps of a systems study. An overview of the methods typically useful in each of the three basic steps of a systems effort is of interest here.

1. Issue Formulation

Typically, idea generation and collection methods are very helpful to identify the various needs, stakeholders, alterables, alternatives, constraints, etc. Among the idea generation and collection methods are brainstorming, nominal group techniques, Delphi, and very important approaches based on surveys, interviews, and questionnaires. Also useful are methods for structuring the elements identified, such as interaction matrices, cognitive maps, causal loop diagrams, and other forms of structural models.

2. Analysis

The forecasting or assessment of impacts and the analysis of alternatives generally require more precise analytical tools than used in issue formulation. However, when data or theory are insufficient, and/or time and resources are lacking, qualitative, expert opinion-based impact assessments and forecasting methods may be appropriate, possibly in conjunction with more precise quantitative techniques. One of these quantitative techniques is economic systems analysis. The remaining sections of this chapter as well as the rest of this text will be devoted to a study of this topic.

3. Interpretation

Various decision aids have been developed to assist decision makers in the evaluation and prioritization of alternatives. Among these are various approaches in decision analysis. The methods of economic systems analysis provide valuable data concerning the impacts of alternatives that assist in this evaluation and prioritization of alternatives.

Let us now briefly examine some of the economic systems analysis topics that comprise this text.

1.3 Theory of the Firm

Chapter 2 will be concerned with the theory of the firm. We will adopt as a fundamental hypothesis the assumption that the goal of a firm is to maximize profit. In order to do this, the firm will need to know the costs of production. These costs will depend upon the market conditions extant for the three fundamental types of economic resources: land,* capital, and labor.

If we know the way in which the quantity of a product depends upon the input supply of land, capital, and labor to production, then it becomes

*More generally, this would be raw materials or natural resources (M) and would include land (L).

possible to determine the cost of a given quantity of produced goods in terms of the unit costs of the inputs to production and the quantity of these that are used. If we use amounts T, K, and L of land, capital, and labor and if the known wages* of these factor inputs to production are w_T, w_K, and w_L, then the costs of production are

$$C(T, K, L) = w_T T + w_K K + w_L L + F \tag{1.3-1}$$

where F denotes the fixed costs of production. The revenue to the firm for selling a production quantity q at a fixed price p is

$$R = pq \tag{1.3-2}$$

The quantity of goods produced by the firm is related to the input factors of production (land, capital, and labor) by the production relation

$$q = f(T, K, L) \tag{1.3-3}$$

The profit to the firm is just the difference between the revenue and the production costs, or

$$\Pi = R - C \tag{1.3-4}$$

There are several questions we might pose here:

1. How can we maximize profit to the firm?
2. How can we minimize production costs for the production of a given quantity of the product?
3. Are there circumstances under which we will not produce?

It turns out that the answers to the first two questions are equivalent. To obtain maximum profit, we maximize Π given by Eq. (1.3-4) subject to the equality constraints of Eqs. (1.3-1)–(1.3-3). The result of doing this is that we obtain a production or supply curve for the producer that gives the quantity of goods which will be produced as a function of the price received for the goods (or services). To minimize production costs we minimize C of Eq. (1.3-1) subject to the equality constraints of Eqs. (1.3-2) and (1.3-3). Doing this results in a relation for the minimum production cost $C(q)$ for producing a quantity of goods q. The answer to the third question is that we should produce as long as we can obtain a nonnegative profit.

We will explore issues such as these in considerably greater detail in Chapter 2. A number of extensions will be undertaken. In particular, we will consider the case where there is a sole producer of a given product who has perfect information about consumer demand for the product. This situation is known as a monopoly. This will be the first of several situations that we will examine in which one or more of the conditions for "perfect economic competition" are violated.

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*It is interesting to conjecture on the meaning of the wages for capital. The difference between the wages for capital and capital represents interest.

1.4 Theory of the Consumer

Why should a firm produce a product or service? One answer is that there is a *demand* for the product or service, because the firm is *effective* in fulfilling some (perceived) need, and that the firm is *efficient* in producing it and can make a profit by doing so. In Chapter 3 we examine various aspects of the economic theory of the consumer. We assume that the consumer has a utility function that expresses the satisfaction received from the consumption* of a bundle of goods and services. The consumer is assumed to have a utility function

$$U = U(x_1, x_2, \ldots, x_N) = U(\mathbf{x}) \tag{1.4-1}$$

where $\mathbf{x} = [x_1, x_2, \ldots, x_N]^T$ is a bundle of goods and services or commodity bundle. There is a price vector $\mathbf{p} = [p_1, p_2, \ldots, p_N]^T$ that represents the fixed price which has to be paid for a unit of each of the N goods and services.

The consumer is greedy and selfish, in that "more" of any given good or service is always better than "less." Sadly, the consumer has limited resources and cannot pay more than some fixed "income" T for these. The fundamental problem of the consumer is to maximize utility, given by Eq. (1.4-1) subject to the resource constraint

$$I \geqslant \sum_{i=1}^{N} p_i x_i = \mathbf{p}^T\mathbf{x} \tag{1.4-2}$$

We will explore various facets of consumer behavior in attempting to maximize the effectiveness of limited resources in maximizing satisfaction. The result of resolving the maximization of utility with a constraint on disposable income is the demand curve for a consumer. Figure 1.5-2 shows six supply–demand curves for various factors and consumer goods and services.

1.5 The Interaction of the Theories of the Firms and Consumers—Microeconomic Models of Economic Activity

Chapters 2 and 3 discuss the theories of firms and consumers. In Chapter 4 we will extend these concepts to microeconomic models that describe the behavior of economic agents such as firms, consumers, and resource owners in a market economy. We will be primarily concerned with the conditions that will prevail in a market system which is in equilibrium and in which no imperfections (monopolies, externalities, etc.) exist. Microeconomic models such as these serve primarily as guides to the behavior that will result in the greatest satisfaction for each economic agent.

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*And savings or investment, which is included in the model we use.

The foundation for a microeconomic model is a set of relations that describes

a. the price and quantity of goods and services that will be desired by a consumer who is maximizing utility.
b. the price and quantity of goods and services that will be desired by a firm which is maximizing profits, and
c. the general conditions characterizing the markets in which firms and consumers interact.

These relations are combined to determine the equilibrium market conditions that will result in the greatest mutual satisfaction for all the firms and consumers in the economic system. This equilibrium is, mathematically, the intersection of the supply and demand curves for products and the intersection of the supply and demand curves for the factor inputs to production.

Microeconomic models provide insight into the workings and effects of "ideal" market systems and can be used to evaluate alternative policies designed to regulate economic behavior or alter economic conditions. They can be used to investigate the effects of changes in such elements as preferences of consumers, technologies of firms, and the availability and costs of the various factor resource inputs to production.

Typical final results or products of the use of supply–demand models of microeconomic activity include

a. a quantitative model describing the interaction of some set of economic agents, including firms and consumers, in a market economy;
b. a determination of the market conditions that will exist in equilibrium when all economic agents are deriving maximum satisfaction;
c. increased understanding of the workings and effects of a free-market system.
d. a set of relations describing the quantity of commodities and resources that each economic agent will desire for a given price; and
e. a determination of those economic decisions that will result in maximum utility for the consumers and maximum profit for the firms.

The first step in building a microeconomic model of the supply–demand relations describing economic activity is to identify the basic components of the economic system under consideration. These components will generally include

a. a "consumption sector," generally represented by a set of consumers or households;
b. a "production sector," generally represented by a set of firms;
c. a set of final goods, commodities, or services; and
d. a set of economic resources that are the factor inputs to production.

Generally these consist of capital (K), land (T), and labor (L). The set of relations that provide the foundation for a microeconomic model are derived from theoretical considerations of

a. the economic behavior of firms (Chapter 2),
b. the economic behavior of households (Chapter 3), and
c. the equilibrium conditions that prevail in the markets where households and firms exchange resources and commodities (Chapter 4).

Let us provide some more perspective on each of these.

The Economic Behavior of Productive Units. The role of a firm in an economic system generally consists in buying factor inputs in the form of land, capital, and labor; producing goods and services from these resources; and finally selling these goods to households and other firms for consumption. In economic systems, it will be necessary for some firms to use goods and services produced by other firms as factor inputs to their own production. For example, a firm that manufactures television sets may purchase components from another firm which manufactures electronic parts. It is assumed that associated with each firm is a *production function* that describes the maximum amount of final goods a firm can produce for a given quantity of factor inputs. The form of this production function will depend upon the firm's technology and productive capacity. The *profit* of a particular firm is the total value of goods and services sold (revenues) minus the cost of producing these commodities. It is assumed that the basic goal of the firm is to maximize profits subject to the constraints on its technology and capacity as reflected in its production function. The solution to this optimization problem will result in the quantity of commodities produced and sold for consumption for given and assumed fixed prices.* This will be the supply curve for the firm in question. Solution of this profit maximization equation will also result in a factor demand equation. We will obtain a relation that gives the demand for factor inputs to production in terms of their prices. Of course, we could postulate a supply equation for a firm with several unspecified parameters. Regression techniques could, in principal, be used to identify parameters such that we identify a supply curve for a firm.

The Economic Behavior of Consumers. The role of the household or consumer in an economic system generally consists in selling resources, such as labor, or factor inputs for production to firms and in buying commodities (final goods) for consumption with the income received from selling these factors. The utility function describes the amount of satisfaction a household derives from the possession of a given set of commodities and a given

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*The firm is assumed to be a price taker in the sense that it accepts prices, which may vary over time, of course, as given. The firm is "too small" to attempt to control prices.

set of factor inputs. The form of this utility function will depend upon the tastes and preferences of each consumer or household. Each consumer will also have a budget constraint, which reflects the total amount of income a household has to spend on final goods and services. The income of a household comes from the sales of factor inputs and from the ownership of firms. The basic goal of a household is to maximize its utility function subject to the budget constraint.* The solution to this optimization problem identifies an "optimum" quantity of commodities demanded for consumption and an "optimum" quantity of factor inputs supplied to firms for given commodity and factor input prices. The quantities that are optimum for a particular household will depend upon its resources and preferences as reflected in its utility function and budget constraint. For example, consumers will sell factor inputs, such as labor for wages, in order to increase their incomes. Consumers will also derive some utility from unsold factor inputs. Labor hours not supplied by a consumer can be interpreted, for example, as leisure time.

Market Equilibrium Conditions. An economic market is in *equilibrium* when the quantity of all the goods and services demanded is equal to that which is supplied. In a microeconomic model in which firms, consumers, factor inputs, and commodities are all involved, equilibrium conditions require that the following conditions hold:

a. For each final good or commodity produced, the total quantity supplied by all firms is equal to the total quantity demanded by all households. This gives rise to a set of commodity market clearing equations.
b. For each economic factor input to production, the total quantity supplied by all households is equal to the total quantity demanded by all firms. This gives rise to a set of factor market clearing equations.

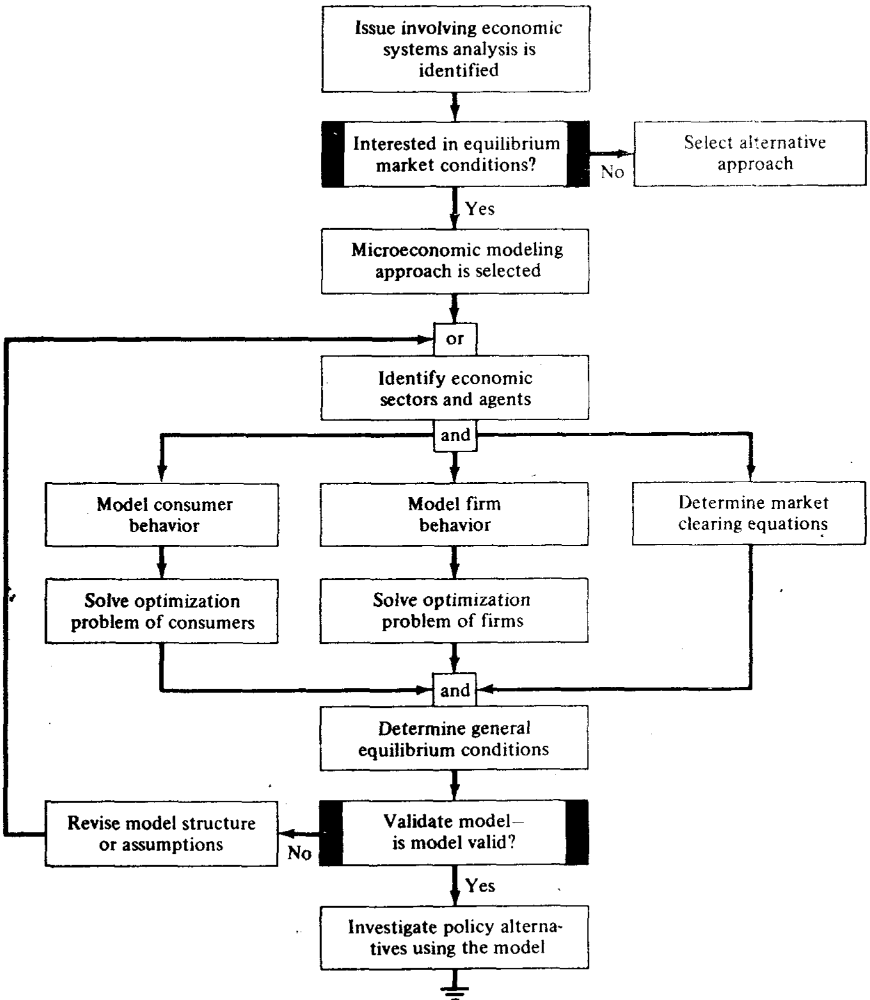
After the basic structure of the model has been identified according to the issue formulation guidelines presented earlier, data need to be collected and used to determine the precise forms of the production function and consumers' utility functions. Utility functions might be reconstructed from observed past behavior, or elicited in a more direct form. Statistical techniques, such as regression analysis and estimation theory, are also useful in constructing models of production functions for firms and utility curves for consumers.

The next step in the construction of a microeconomic supply–demand model is to actually solve the equations describing economic equilibrium. In theory, this requires the solution of the optimization problem for each

*The household also accepts prices as given; it needs such a small fraction of any available product or service that it cannot control price.

household and each firm, subject to constraints and the market clearing conditions. The resulting solution will give the quantities of commodities and factor inputs that will, theoretically, be exchanged in equilibrium, together with the market prices at which they will be exchanged. This information can then be used to investigate the effects of changes in such factors as consumer preference, firm technology, income distribution, market structure, and resource availability on equilibrium market conditions. It can be used to evaluate the consequences of alternative policies designed to regulate or improve existing economic conditions. Figure 1.5-1 illustrates a

Figure 1.5-1 Flow chart for a microeconomic model.



flow chart that we might use to describe the steps involved in constructing a microeconomic model. Figure 1.5-2 illustrates, conceptually, the results that we might obtain from the construction of a simple microeconomic model. In Fig. 1.5-2 are two fundamental feedback loops: one involving the flow of products and one involving the flow of capital. We will expand on this diagram in Chapter 4. Here it is especially important to note the flows into and out of the firms and consumer sectors. The input to the firms is the income due to sales and the factors for production; the output from the firms is the products of goods and services, the aggregate total of which is the gross national product (GNP), and payments for the factor inputs to production.

Microeconomic models can be used to gain insight into the behavior of economic systems, as well as to assess the impact of alternative policies designed to alter or regulate behavior. They can also be used to determine market structures that will result in some desired utilization of resources. Thus microeconomic models may be useful for identifying alternatives, as well as for the analysis of their impacts. A simple example will illustrate some of the concepts involved in constructing a microeconomic model.

Figure 1.5-2 Simple flows in economic systems.