On the Connections Among Activity-Based Costing, Mathematical Programming Models for Analyzing Strategic Decisions, And the Resource Based View of the Firm

Jeremy F. Shapiro
Sloan School of Management
Massachusetts Institute of Technology

Sloan WP # 4018 April, 1998

© Copyright 1998, Jeremy F. Shapiro
ON THE CONNECTIONS AMONG
ACTIVITY-BASED COSTING,
MATHEMATICAL PROGRAMMING MODELS
FOR ANALYZING STRATEGIC DECISIONS,
AND THE RESOURCE-BASED VIEW OF THE FIRM*

Jeremy F. Shapiro
December, 1997

Abstract

This paper examines connections between data-driven models for analyzing a firm’s strategic plans, which use activity-based costing and mathematical programming, and the resource-based view of the firm. After brief reviews of the three disciplines, extensions of activity-based costing methods to mathematical programming models for strategic resource planning are discussed. Applications of these models to supply chain planning in a multi-national food manufacturer, a specialty chemicals company, and a wholesaling/retailing company are presented. The paper concludes by using concepts from the resource-based view of the firm to interpret optimal solutions from mathematical programming models. Extensions to strategic planning under uncertainty using stochastic programming are also discussed briefly.

Keywords: Strategic planning, activity-based costing, mathematical programming, resource-based view of the firm.


© Copyright, Jeremy F. Shapiro, 1998
ON THE CONNECTIONS AMONG
ACTIVITY-BASED COSTING,
MATHEMATICAL PROGRAMMING MODELS
FOR ANALYZING STRATEGIC DECISIONS,
AND THE RESOURCE-BASED VIEW OF THE FIRM

Jeremy F. Shapiro
December, 1997

1. Introduction

The purpose of this paper is to discuss connections among three disciplines concerned with strategic resource planning in the firm, activity-based costing (ABC) (Turney, 1992, Atkinson et al, 1997), mathematical programming (MP) (Schrage, 1991, Winston, 1995), and the resource-based view of the firm (RBV) (Mahoney and Pandian, 1992, Peteraf, 1993). Judging from the literature, these disciplines do not overlap. Nevertheless, we believe there are important synergies worth exploring. ABC and MP are approaches for creating data-driven models to analyze decisions about acquiring, adjusting, allocating and divesting the firm’s resources. RBV is an abstract discipline for studying how the firm can create and maintain resources that will provide it with a sustained competitive advantage. In particular, RBV suggests that firms realizing superior profits possess and exploit heterogeneous resources, which cannot be imitated or transferred, and for which there are no substitutes.

We shall argue that ABC analysis of the firm’s general ledger defines resources that the firm uses to compete in its markets, and their costs. To optimize its resource decisions, this information must be imbedded in an MP model for evaluating the firm’s strategic options. The MP model also serves as a template for cost and resource data to be extracted by ABC methods. Moreover, economic interpretation of an optimal solution to the MP model provides insights about the firm’s heterogeneous resources. Conversely, RBV concepts, when translated into model constructs, can help the practitioner to expand the scope of the MP model.

An underlying theme of this paper is to call attention to the tension that exists between data-driven models based on ABC and MP, which tend to be cautious and limited in scope, and abstract theories of competition based on RBV, which tend to be audacious and vast in scope. Modeling practitioners and managers for whom models are developed can benefit by challenging themselves to devise quantitative descriptions actualizing abstract concepts about strategy and incorporating these descriptions in data-driven models. Conversely, the theorist of corporate strategy can profit from “reality checks” that such models can provide, and by refinements and extensions to the theory that will undoubtedly result.
In order to focus our discussion, we will restrict ourselves to strategic issues arising in supply chain management. A company’s supply chain is comprised of geographically distributed facilities such as plants, distribution centers, supplier warehouses, or retail outlets, and transportation links carrying products between facilities. The facilities may include physical entities operated by the company’s suppliers and the company’s customers as well as those operated by the company itself.

Thus, we will limit our attention to firms that manufacture and/or distribute physical products. The ideas presented below are also applicable to service companies. Indeed, a large and increasing proportion of the total activity within a manufacturing or distribution company is concerned with servicing external and internal customers.

In the next section, we address a taxonomy of resources pertinent to strategic planning. In the three sections after that, we review concepts from ABC, MP modeling and RBV that are appropriate to synthesizing the three disciplines. In the following section, we discuss extensions of ABC to MP models. Applications of ABC and MP in three specific firms are reviewed in the section after that. Then, we discuss connections between data driven models based on ABC and MP and RBV. The final section of the paper is devoted mainly to areas of future research.

2. Taxonomy of Resources

In reviewing a firm’s resource profile, Barney, 1991 and Mahoney and Pandian, 1992, suggest several categories, which we adapt here as:

1. Physical resources (e.g., plants, distribution centers, inventories)
2. Human resources (e.g., machine operators, production managers, scientists)
3. Financial resources (e.g., cash flow, debt capacity, equity availability)
4. Information technology resources (e.g., inventory management system, communication network, supply chain modeling system)
5. Marketing resources (e.g., market share, brand recognition, goodwill)
6. Organizational resources (e.g., training systems, corporate culture, supplier relationships)
7. Legal resources (e.g., patents, copyrights, contracts)

Except for legal resources, these categories underlie much of the RBV literature, including books and papers written before the discipline was founded.

Clearly, some resources, such as plants, machine operators, or cash flow, are tangible and possess measurable characteristics. Other resources, such as scientists or corporate culture, are intangible with characteristics that are difficult to measure, at least directly. A challenge for the modeling practitioner is to devise descriptive approaches for measuring the impact of intangible resources on the firm’s strategy. For example, the construction of a decision tree describing an R&D scientist’s assessment of the likely outcomes of his/her research.
Understanding and evaluating the role of information technology (IT) resources in corporate strategy formation has proven difficult and ambiguous (see Powell and Dent-Micallef, 1997, 376 – 378, for a literature review). Recent analysis using RBV principles, however, suggests that IT resources are necessary, but not sufficient, elements of a firm’s competitive advantage (Kettinger et al, 1994, Mata, Fuerst and Barney, 1995, Powell and Dent-Micallef, 1997). IT resources are different than other types of resources because they serve only to manage other resources and have no intrinsic value per se.

The RBV literature has apparently ignored legal resources as a distinct category. We included it in the above list because the existence of patents or contracts protecting the firm’s valuable resources can have a large impact on its competitive position, especially in an era of rapid technological change. The value of these legal resources may be an explanation, if not a justification, of the litigious nature of doing business in recent years in the United States.

3. Activity-Based Costing

The information revolution has facilitated advances in management accounting, which is defined by Atkinson et al, 1997, 3, as “the process of identifying, measuring, reporting, and analyzing information about the economic events of the (firm)” for the purposes of internal planning and control. Its focus is significantly different than financial accounting, which is concerned with reporting historical results to external audiences. ABC is a new approach of management accounting for determining accurate product and customer costs.

ABC methodology is comprised of three stages as shown in Figure 1 (Cooper and Kaplan, 1991, Turney, 1992). For the sake of simplicity, we assume ABC is being carried out for a single facility in the company’s supply chain. Moreover, we assume the planning horizon is one year. Similar analyses can be carried out for other company activities such as marketing and sales, or customer service (Atkinson et al, 1997).

In the first stage, detailed indirect costs in the general ledger, or in next year’s budget, are aggregated into homogeneous pools of indirect costs, such as supervisory labor or utility costs. Direct costs from the general ledger or budget are aggregated directly into activity cost pools without this intermediate step. Although the indirect cost pools are called resources by ABC practitioners, they are not the resources we seek to define for our MP models and RBV analysis. Instead, as we discuss in Section 6, such resources are derived from the second and third stages of ABC analysis, which consist of an allocation of the indirect cost pools to activity cost pools, otherwise called activities, and an attribution of these activities to cost objects (e.g., product and customer costs). The third stage mapping is carried out by cost drivers that determine how the various activities contribute to the total cost of the cost objects. Table 1 lists typical activities and activity cost drivers in a manufacturing plant. See Ellram et al, 1994, for similar analysis at a distribution center.
ABC Methodology

Figure 1
Most of the cost drivers in Table 1 are directly related to volume (production hours), but the cost driver for production scheduling depends on the number of batches to be scheduled over the planning horizon. An important principle of ABC is that the cost driver for an activity including its unit of measure be selected to reflect the underlying nature of the activity. Moreover, ABC distinguishes between indirect costs related to products and those related to the facility as a whole. Thus, a complete categorization of activities and their cost drivers entails four levels: Unit-related activities, batch-related activities, product-sustaining activities, and facility-sustaining activities (Cooper and Kaplan, 1991). As we shall see, this categorization is similar to the categorization used in MP supply chain models.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cost Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Labor:</td>
<td></td>
</tr>
<tr>
<td>Casting</td>
<td>Direct labor hours</td>
</tr>
<tr>
<td>Machining</td>
<td>Direct labor hours</td>
</tr>
<tr>
<td>Assembly</td>
<td>Direct labor hours</td>
</tr>
<tr>
<td>Packing</td>
<td>Direct labor hours</td>
</tr>
<tr>
<td>Direct materials:</td>
<td></td>
</tr>
<tr>
<td>Casting</td>
<td>Pounds</td>
</tr>
<tr>
<td>Assembly</td>
<td>Units</td>
</tr>
<tr>
<td>Packing</td>
<td>Units</td>
</tr>
<tr>
<td>Supervision:</td>
<td></td>
</tr>
<tr>
<td>Casting</td>
<td>Casting setup hours</td>
</tr>
<tr>
<td>Machining</td>
<td>Machining setup hours</td>
</tr>
<tr>
<td>Assembly</td>
<td>Assembly setup hours</td>
</tr>
<tr>
<td>Packing</td>
<td>Packing setup hours</td>
</tr>
<tr>
<td>Depreciation:</td>
<td></td>
</tr>
<tr>
<td>Casting</td>
<td>Machine hours</td>
</tr>
<tr>
<td>Machining</td>
<td>Machine hours</td>
</tr>
<tr>
<td>Assembly</td>
<td>Machine hours</td>
</tr>
<tr>
<td>Packing</td>
<td>Machine hours</td>
</tr>
<tr>
<td>Machine maintenance</td>
<td>Total machine hours</td>
</tr>
<tr>
<td>Machine setup</td>
<td>Total setup hours</td>
</tr>
<tr>
<td>Production scheduling</td>
<td>Number of batches</td>
</tr>
<tr>
<td>Production engineering</td>
<td>Engineering change orders</td>
</tr>
<tr>
<td>Energy</td>
<td>Total machine hours</td>
</tr>
<tr>
<td>General and administrative</td>
<td>Total machine hours</td>
</tr>
</tbody>
</table>

Activities and Cost Drivers
Medical Equipment Manufacturing Plant
Table 1

Source: Atkinson et al., 1997, 265

For the purpose of optimizing strategic supply chain decisions, extrapolation of historical cost figures requires the development of **cost relationships** describing how
costs will vary as a function of the cost drivers. Since ABC often represents costs as linear functions of the cost drivers, additional analysis is needed to estimate cost relationships that are non-linear with discontinuities. Such relationships characterize complex manufacturing and distribution operations.

4. Mathematical Programming Models

In this paper, we address three types of MP models that provide formal systems for analyzing managerial decisions:

- **linear programming models**, which identify efficient resource allocation schemes;

- **mixed integer programming models**, which extend linear programming models to capture fixed (lumpy) investment and resource costs, locational decisions, economies of scale and non-numeric policy constraints; and

- **stochastic programming models**, which extend both linear and mixed integer programming in explicitly addressing uncertainties associated with the future to identify optimal contingency plans and hedging strategies for the firm (e.g., see Bienstock and Shapiro, 1988, Birge and Louveaux, 1997).

Linear programming is the cornerstone of mathematical programming because linear programming models can be easily optimized and because linear programming approximations are used to optimize more complex models. Economic interpretations of linear programming also provide qualitative insights into resource allocation processes in the firm that are relevant to RBV.

The premises underlying linear programming models, such as assumptions that all cost and resource utilization relationships are linear and infinitely divisible, are too simplistic. Mixed integer programming extensions provide a much more realistic description of supply chain management problems. Such models use zero-one integer variables to describe more accurate cost and resource relationships, and to capture locational decisions. A typical supply chain network optimization model is depicted in Figure 2. The squares represent facility sub-models based on ABC and mixed integer programming that we will discuss in Section 6.

The added realism of mixed integer programming is achieved at a cost because such models must be optimized as a series of linear programming approximations. Despite their computational complexity, mixed integer programming models are a practical and powerful method for evaluating supply chains (e.g., see Shapiro, Singhal and Wagner, 1993, Arntzen et al, 1995). Comprehensive mixed integer programming models can be rapidly and reliably optimized on today’s platforms.
Stochastic programming models combine probabilistic decision trees with linear and mixed integer programming models in creating an approach that explicitly evaluates resource planning in the face of uncertainty. They offer an enticing paradigm for strategy analysis in the firm that is beyond, but not too far beyond, the state-of-the-art of MP modeling. Our aim in discussing them here is to promote their application and to relate them to RBV.

Figure 3 depicts extensions of current MP models to strategic decision-making in manufacturing and distribution companies. The state-of-the-art is represented by model type 1 (single-period, deterministic minimization of the total supply chain cost of meeting given demand) depicted in Figure 2. The arrows in the diagram reflect natural extensions of the models of a given type to those that are more ambitious.

For example, the immediate extensions of model type 1 to model type 2 represent management's interest in varying product mix, probably in a cautious manner, to the maximization of net revenues. By cautious, we mean the model allows small deviations in product mix that involve little or no change in unit price. An example of such an analysis applied at International Paper is given in IBM Application Brief, 1981. Alternatively, extensions of model type 1 to model type 4 represent management's interest in the timing and phasing of capital investments in supply chain resources over multiple time periods, while still minimizing the total discounted costs of managing the supply chain (Goreux and Manne, 1973).
Mathematical Programming Models for Analyzing Strategy in Manufacturing and Distribution Companies

Figure 3
Extensions of model type 2 to model type 3 are ambitious exercises aimed at identifying company strategies that maximize net revenue in a competitive environment (Miller, Friesz and Tobin, 1996). MP theory, especially decomposition methods, can be adapted to the computation of such equilibria (Mehring, Sarkar and Shapiro, 1983, Murphy, Sherali and Soyster, 1982), but it has not yet been widely applied. Nevertheless, we report that such analysis was performed by a forest products company to identify geographical markets where their products are price competitive. Of course, model type 3 could also be extended to multiple period and stochastic versions. We have omitted such extensions in the Figure since they would be stretching the state-of-the art beyond the bounds of likely implementation over the foreseeable future.

Extensions of model type 2 or 4 to model type 5 (multiple-period, deterministic maximization of discounted net revenues) are also ambitious. They require the development of models relating marketing strategies for new and existing products, which are multiple-period in nature, and their integration with supply chain models. In other words, these models address product mix changes that are more audacious than those of model type 2. Such constructions are discussed from the marketing viewpoint in Eliashberg and Steinberg, 1993.

Finally, we consider extensions of the deterministic model types 4 and 5 to the stochastic model types 6 and 7. A cautious approach to effecting the extensions to model type is to create a stochastic programming model by merging a small number of deterministic models of different scenarios. A willingness to pursue this approach is in the air. During the past year, we have discussed stochastic programming modeling projects with analysts in two large firms, one a computer manufacturer, the other a pharmaceutical company. In both cases, the firms were seeking production strategies for making major components of finished products that optimally hedge against uncertain demand for these products.

5. Resource-based View of the Firm

RBV is a recently articulated theory that is still under development. Its origin dates to the seminal paper by Wernerfelt, 1984, although earlier publications anticipated some of the later work. Our review is based mainly on Mahoney and Pandian, 1992, and Peteraf, 1993, who provide extensive bibliographies. The connections between RBV and closely related disciplines, such as organization economics or the theory of industrial organizations, are well developed by Conner, 1991, and Mahoney and Pandian, 1992. Our particular interest in RBV is due to its explicit treatment of the role of resources in strategy formation.

According to RBV, a firm’s sustainable competitive advantage depends heavily on its resources and how they are used. In particular, the theory assumes that superior firms possess heterogenous resources that differentiate it from other firms and allow it to earn rents; that is, the average and even marginal costs of their products are below, perhaps
significantly below, the market prices they receive. The rents may be converted to sustainable profits if forces exist which limit competition for critical resources, once the industry has recognized their value.

Two factors limiting competition are **imperfect imitability** and **imperfect substitutability** of heterogeneous resources. Such factors exist when there are barriers due to patents, contracts, learning effects, or market preferences that make imitation and substitution by other firms difficult or impossible. Moreover, critical resources of the superior firm will be **perfectly immobile**, which means they are idiosyncratic and have no use in other firms, or **imperfectly mobile**, which means they can be traded but have higher value within the firm. Finally, the theory states that a firm can establish heterogenous new resources only if there are limits to competition prior to efforts on the part of the firm to create them. Otherwise, the rents that the superior firm can realize will be dissipated by excessive costs of initial competition.

In reviewing connections between RBV and other research on strategy, Mahoney and Pandian, 1992, discuss four types of rents accruing to the superior firm. Ownership of scarce resources such as valuable land, production facilities near markets, or patents lead to **Ricardian rents**. As the result of collusion or government protection, the firm may achieve **monopoly rents**. Firms that undertake risky and entrepreneurial ventures in an environment characterized by significant uncertainty or complexity may realize **Schumpeterian**, or **entrepreneurial, rents**. Firms with idiosyncratic resources that are scarce, but less scarce and less sustainable than Ricardian resources, may receive **quasi-rents**.

Dierickx and Cool, 1989, address the issue of sustainability, which they suggest is linked to characteristics of the stock asset (heterogeneous resource) accumulation process. They identify six phenomena affecting the efficacy of such processes. Inefficiencies associated with attempting to too quickly create and exploit heterogeneous resources are called **time compression diseconomies**. The phenomena of “success breeding success” in competitive endeavors leads to **asset mass efficiencies**; they are akin to barriers to entry for late entrants in a market. When creation of a valuable asset does not necessarily lead to competitive advantage because complementary assets are absent, the firm has failed to recognize the **interconnectedness of stock assets**. A loss of competitive advantage through deterioration of heterogeneous resources is called **asset erosion**. Finally, **causal ambiguity** refers to the uncertainties and discontinuities associated with a successful effort in creating a heterogeneous resource. If the causes of initial success are difficult to identify, the firm may be hard pressed to sustain the ensuing advantage, or to repeat the success.

The concept of a firm’s **core competencies** is an important idea linked to RBV (Prahalad and Hamel, 1990). Core competencies refer to those heterogeneous resources that provide the superior firm with sustainable competitive advantage. Often, senior managers in a firm do not clearly understand the precise nature of its core competencies, how they should be protected, and how new ones should be created. One of the objectives of this paper is to suggest that research into quantitative methods for
identifying and measuring core competencies, based in part on ABC and MP models, should be pursued.

6. Extending ABC to MP Models

ABC has been extolled as a valuable tool for determining product and customer costs, and, in general, for support of managerial decision-making. In fact, it is a descriptive rather than a normative methodology. For example, it cannot address fundamental questions such as:

- What are optimal levels of the firm’s resources at each of its facilities over medium and long term planning horizons?
- How should resources be allocated to production activities at each facility so as to minimize total supply chain cost?
- Which products should be manufactured and which production transformation activities should be employed at each facility to minimize total supply chain cost?
- Which facilities should optimally source each market for each product family?

An MP model is needed to answer these and other questions. Moreover, accurate product and customer costs can only be extracted from an optimal solution to the MP model. In other words, the logic of Figure 1 needs to be altered by interposing an MP model between the Activity Cost Pools and the Cost Objects.

Thus, ABC can and must be extended in natural ways to MP models. We illustrate this by discussing how to model individual facilities (plants, distribution centers) in the supply chain network of Figure 2. Similar ABC and MP constructions may be developed for other areas of strategic supply chain decision-making, such as long-term supply contracts or the re-location of capital equipment, but space prevents us from further elaboration.

We also discuss how facility sub-models can be linked to strategic investment decisions, which we assume for the sake of simplicity are limited for each facility to decisions about whether the facility should be open (built) or closed (not built or shut-down) in the single period considered by the model. The objective function driving the global network analysis is to minimize total supply chain investment and operating costs of meeting fixed and given demand. Thus, we consider model type 1 of Figure 3.

Implicit in our construction of an MP model for strategic planning is the need to integrate details of future facility operations, suitably aggregated, with details describing investment costs and constraints. Such integration is critical to studying how investments will impact operations. ABC has the responsibility of extrapolating historical costs and
cost relationships to ones that are appropriate to the planning horizon of the strategic analysis.

Optimization of the MP model may suggest new resource acquisition options that were previously unrecognized. Such options may include new facilities, new transformation processes, or expansion of existing resources beyond levels that were previously thought to be sufficient. Again, ABC methodologies will be applied to develop much of the necessary cost data.

The critical step in extending ABC to MP models is the use of ABC in developing forecasts of how costs will vary as functions of the cost drivers. In developing such functions, we distinguish between those for which the cost driver is a resource that may be scarce and therefore may constrain an optimal strategy, and those for which the cost driver is merely an accounting device and not a resource that will constrain the strategy. We refer to the former functions as cost/resource functions, and to the latter as cost/accounting functions. Resources in the former category will be called sustaining resources while resources in the latter category will be called accounting resources.

Referring to the activities and costs in Table 1, casting depreciation with machine hours as the cost driver and machining supervision with machining setup hours as the cost driver might be sustaining resources. This is because casting machine hours and machining supervision are potentially scarce resources that the company may be forced to allocate to production. By contrast, energy with total machine hours as the cost driver and packing supervision with packing setup hours as the cost driver might be accounting resources. This is because energy and packing supervision are commodities that may be acquired in any quantity at a homogeneous cost.

Figure 4 depicts a typical cost/resource function for a given period of operations (e.g., one year). For example, it might refer to machine hours as a cost driver on equipment used in making several products. In this case, machine hours would be treated as a process sustaining resource.

The parameters describing the cost/resource function are:

- A fixed cost $F_1$ associated with using the resource at any level;
- A shut-down cost $S$ associated with a zero level of resource utilization;
- A conditional minimum level $m$ of resource utilization above which it must be if it is not zero;
- A break point of $b$ above which the variable cost measured in dollars per hour decreases ($c_2 < c_1$);
- A maximal level of resource utilization of $M_1$ possible during the period if additional resource is not acquired;
- A fixed cost $F_2$ associated with acquiring additional resources for use during the period;
- A variable cost in dollars per hour of $c_3$ ($c_3 > c_1$) for using the new resource up to a total maximal level of $M_2$ possible during the period.

![Cost/Resource Function](image)

Figure 4
Figure 4 is only representative of the many cost/resource functions we might develop to analyze a firm's supply chain decisions. For example, the number of changes in unit cost as well as the number of increments of resource addition with fixed costs can be arbitrary. Mixed integer programming modeling constructs can be used to capture the nonlinearities and discontinuities.

Note that we have also displayed last year’s resource level and the traditional accounting rate of c dollars per hour based on it. The dotted line in the figure clearly shows that the projected sustaining cost will be inaccurate, even when the cost driver is an appropriate one.

The partition of cost drivers into sustaining resources and accounting resources is a judgment made by the modeling practitioner based on his/her knowledge of the firm. Although it would be safe to treat all cost drivers as potentially scarce resources, more parsimonious models will result if cost drivers that almost certainly will never be constrained by physical, human, or financial resources be treated as accounting resources. For example, the number of orders taken in a year by telephone salespeople may be a meaningful cost driver for describing sales department costs, but unless the firm’s volume of business doubles, which we consider to be highly unlikely, this number will not be constrained by physical limitations. Moreover, assuming a significant number of additional sales people can be hired at a constant cost rate, the firm will not encounter human constraints on its order taking and other sales activities.

The major step in extending ABC relationships to an optimization model is to describe the interactions of transformation activities at facilities with cost/resource and cost/accounting functions, and with other relationships describing the constraints and strategy options of the firm. We illustrate such a construction with an example of a facility sub-model. We assume the planning horizon of the snapshot model is one year. Moreover, the facility may be open or closed (either shut-down or sold) during that year.

First, we must define indices, parameters and functions and decision variables:

Indices

\[ s \in S: \] suppliers of raw materials

\[ i \in I: \] raw materials

\[ j \in J: \] transformation activities

\[ k \in K_1: \] accounting resources

\[ k \in K_2: \] sustaining resources
$k \in K_3$: fixed resources

$k \in K_4$: design and policy constraints

$p \in P$: output products

Parameters and Functions

- $a_{ij}$ = rate at which activity $j$ consumes raw material $i$
- $a_{kj}$ = rate at which activity $j$ consumes resource $k$
- $a_{pj}$ = rate at which activity $j$ produces output product $p$
- $r_k$ = fixed level of resource $k$ ($k \in K_3$)
- $b_k$ = design or policy parameter $k$ ($k \in K_4$)
- $L_j$ = upper bound on activity $j$
- $R$ = facility throughput capacity
- $c_j$ = product sustaining unit cost
- $u_k$ = process and facility resource accounting unit cost ($k \in K_1$)
- $f_k(r_k)$ = function describing the cost of the sustaining resource $r_k$ ($k \in K_2$)
- $F$ = annualized facility replacement cost
- $S$ = annualized facility shutdown cost

Decision Variables

- $w_{is}$ = quantity of raw material $i$ to be acquired by facility from supplier $s$
- $r_k$ = utilization of resource $k$
- $x_j$ = level of activity $j$
\[ y_{pm} = \text{quantity of output of product p to be shipped from facility to market m} \]

\[ z = \begin{cases} 
1 & \text{if facility open during planning horizon} \\
0 & \text{if facility closed during planning horizon} 
\end{cases} \]

The above parameters, functions and variables are used to construct the following:

**Facility Sub-Model**

1. Raw material balance equations
   \[ \sum_j a_{ij} x_j - \sum_s w_{si} = 0, \quad i \in I \]
   (1)

2. Accounting resource balances
   \[ \sum_j a_{kj} x_j - r_{k} = 0, \quad k \in K_i \]
   (2)

3. Sustaining resource constraints
   \[ \sum_j a_{kj} x_j - r_{k} \leq 0, \quad k \in K_2 \]
   (3)

4. Fixed resource constraints
   \[ \sum_j a_{kj} x_j \leq r_{k}, \quad k \in K_3 \]
   (4)

5. Design and policy constraints
   \[ \sum_j a_{kj} x_j \leq b_{k}, \quad k \in K_4 \]
   (5)

6. Output product balance equations
   \[ -\sum_j a_{pj} x_j + \sum_{m \in M} y_{pm} = 0, \quad p \in P \]
   (6)

7. Production bounds
   \[ x_j \leq L_j, \quad j \in J \]
   (7)

8. Facility throughput constraint
   \[ \sum_{p \in P} \sum_{m \in M} y_{pm} - R_z \leq 0 \]
   (8)

**Objective Function Costs to be Minimized**

9. Product sustaining costs
   \[ \sum_j c_j x_j \]
   (9)

10. Accounting resource costs
    \[ + \sum_{k \in K_1} u_k r_k \]
    (10)
The system of equations and inequalities (1) to (7) of the facility sub-model, along with other constraints and relationships describing activities at other facilities and flows between facilities, determine the optimal levels of the production activity variables $x_j$ at the facility, along with optimal levels of the raw material, resource and product output variables. The throughput constraint (8) controls whether or not the facility operates during the planning horizon.

The raw material balance equations (1) describe how the transformation activities consume raw materials. The output product balance equations (6) describe how product output shipped to the markets $m$ equals that produced at the plant. Note that in this strategic, snapshot model, inventories do not enter into the decision-making process. The accounting balances (2) mechanize cost/accounting functions by computing the levels of the cost drivers $r_k$ which are costed at the rates $u_k$ in (9). The sustaining resource constraints (3) mechanize the cost/resource functions by determining the optimal levels of the sustaining resources whose costs are determined by the functions $f_k(r_k)$ in the sums in (10). These constraints may not be binding in the sense that the sum of the activity levels may be strictly less the resource level. The functions $f_k(r_k)$ have a form similar to the one depicted in Figure 4. Mixed integer programming modeling constructs are used to represent the nonlinear and discontinuous forms of these functions; we omit details here.

The resource $k \in K_2$ is a facility sustaining resource if all, or at least most, of the coefficients $a_{kj}$ in constraint (3) are positive. By contrast, the resource $k \in K_2$ is a process sustaining resource if only a limited number of the coefficients $a_{kj}$ in constraint (3) are non-zero (i.e., positive). In short, the distinction between facility and process sustaining resources and costs may be ambiguous and ultimately depend on human judgment.

The fixed resource constraints (4) correspond to resources at the facility that cannot be varied and whose costs are sunk. The extent to which such costs are sunk depends in large part on the planning horizon of the model. For example, a labor resource dictated by a union contract for a fixed number of hours for next year would be treated as a fixed resource with a sunk cost in a model of next year's plans. Over the longer term, this resource would not be viewed as fixed.

The design and policy constraints (5) refer to constraints on production that do not involve resources; in some instances $b_j$ will be zero on such constraints. Blending constraints at an oil refinery are a typical design constraint. A constraint stating that the

\[ + \sum_{k \in K_2} f_k(r_k) \]  
sustaining resource costs \hfill (11)

\[ + Fz + S(l-z) \]  
facility replacement and shut-down cost \hfill (12)
facility must produce at least as much as one product group as it does of a second product group is an example of a policy constraint.

7. Applications in Specific Firms

In this section, we review recent implementations and applications of ABC and MP models to the strategic analysis of supply chains in three companies:

- A multi-national food manufacturer
- A specialty chemicals company
- A wholesaling/retailing company

Multi-national food manufacturer

This company has more than 15 plants in the US, Canada and Mexico. Following passage of NAFTA, senior management engaged a team of external consultants to implement an MP model for studying consolidation of their sourcing, manufacturing and distribution supply chain. Two major reasons for performing the study were:

- For some time, the company had been operating under conditions of excess capacity among their manufacturing facilities;
- Passage of NAFTA eliminated or greatly reduced tariffs and import/export restrictions between countries thereby making it economically feasible to manufacture most products in fewer locations and, where appropriate, ship them across national boundaries.

The most difficult task of the project was the development of compatible cost and resource descriptions of the company's plants. As shown in Figure 4, each of the plants had its own, locally developed general ledger of accounts which required translation into product, process and facility sustaining cost/resource functions of the type discussed in the previous section. The ABC analysis served to homogenize the disparate accounting schemes at the various plants in constructing cost/resource functions that could be compared across plants. In the final analysis, the consulting team was successful in developing general procedures and programs, the template T, for mapping any plant’s general ledger into its cost/resource functions.

ABC models were useful in providing metrics contrasting facility, process and product sustaining costs among the plants. The integrating MP model played a critical role, however, in deciding on optimal resource levels for each plant and the quantities of individual products to be manufactured there. The objective driving the evaluation was to minimize the total delivered cost of all products to meet projected demand in the study years. In other words, metrics about production costs at individual plants could not determine an optimal supply chain strategy because they could not decide optimal
Facility sustaining costs and resources
Process sustaining costs and resources
Product sustaining costs

General Ledger
Plant 1

Integrating supply chain optimization model

Other data

ABC Models Feed Supply Chain Optimization Model
Figure 5
resource levels, and could not account for plant locations relative to geographically dispersed markets.

The supply chain optimization model was successfully validated and then run under a number of scenarios to assess potential consolidation strategies. Cost savings of more than 10% on avoidable costs exceeding $100 Million were identified. The company intends to continue using the ABC and supply chain optimization models after the study has been completed. Their strategic plans will require frequent adjustment in response to external factors.

**Specialty chemicals company**

This company supplies a range of specialty chemicals products to worldwide markets. It also has manufacturing facilities around the world, with movement of intermediate products among plants as well as movement of finished products to the markets. Capital investments in process manufacturing equipment and manufacturing operating costs, are high and represent a large percentage of the total cost of the products.

Given the complexity of their operations and the growth of markets for new products, senior management engaged a consulting team to implement an MP modeling system to assist in evaluating their strategic plans. The models address

- Sourcing costs and constraints
- In-bound transportation costs and constraints on links between sources and plants
- Product, process and facility sustaining costs and resources at manufacturing plants
- Multi-stage processes and transformation recipes at the plants
- Inter-facility product transfers
- Out-bound transportation costs and capacities on links between plants and markets

The models may be optimized so as to minimize total supply chain costs or to maximize total supply chain net revenues. They are being used to evaluate global asset utilization, raw material sourcing strategies, and global production/distribution strategies.

For the purposes of our discussion here, an important aspect of the project was, and continues to be, an accurate mapping of manufacturing costs into product, process and facility sustaining cost/resource functions. Formal application of ABC methods to this task is new to the company and was stimulated by the model development project. ABC representations that accurately reflect economies of scale in manufacturing, particularly as they relate to specific processes, are crucial in determining effective strategies via the optimization model.

In addition, the company developed cost and resource utilization data for potential new products to assess their profitabilities from a global supply chain viewpoint. Unlike traditional ABC analyses that draw on historical data, the data for new products require extrapolation of data about relevant existing products. Moreover,
learning associated with the manufacture of new products needs to be quantified and incorporated in the models.

**Wholesaling/retailing company**

This wholesaling company buys and distributes consumer products to approximately 500 franchised, retailing outlets throughout Canada. Originally, it had 7 distribution centers (DC’s) of various sizes, locations, and missions. The number of different SKU’s sold in a year exceeds 50,000.

Although profits remained healthy, senior management decided in the early 1990’s to re-engineer the wholesaling company, largely because they could see increasing competition in many of their markets just over the horizon. The goals of re-engineering were

- To improve the cost effectiveness of transportation, warehousing and inventory management practices;
- Working with the retailers, to develop more effective purchasing and product replenishment processes;
- To implement new operational procedures exploiting point of sales information, electronic data interchange arrangements with suppliers, and other information technology advances.

To address the first goal, the company acquired off-the-shelf software for supply chain modeling, and assembled a team of internal consultants to develop the decision data base from which the models would be constructed.

Although the wholesaling company is not involved in manufacturing products, there is a form of “production” at the DC’s. Products arriving there from many suppliers are received, sorted, sometimes stored, sometimes assembled, and then dispatched. The internal consultants used ABC methods to identify product, process sustaining and facility sustaining costs, cost drivers and resource functions based on these “production” activities. They also developed new information to forecast the costs and resource requirements of potential new operating procedures to be evaluated by the supply chain model.

For example, the product line was divided into fast moving goods (FMG) and slow moving goods (SMG). As shown in Figure 6, the model was used to study the economics of using flow-through equipment to handle FMG while centralizing the storage of SMG in a single DC. With this scheme, suppliers package FMG with bar codes indicating their final store destinations. Equipment at the flow-through DC reads the codes and automatically sorts the FMG into full truckload shipments to individual stores.
If managed properly, this type of operation can achieve considerable cost savings by eliminating handling and inventories of FMG. In addition, SMG are stored in a single DC, thereby reducing their inventory holding costs by a significant amount. Store initiated orders for SMG are handled by the SMG DC as a flow-through supplier.

The company has used the optimization modeling system to great advantage in identifying more effective supply chain configurations and in simulating the impact of new procedures on their operations before committing to the time and expense of implementing them. The models sometimes indicated supply chain strategies that, at first, seemed counter intuitive, but upon further study, proved themselves to be meritorious.
8. Connections Between Data Driven Models and the Resource Based View of the Firm

The data driven models for analyzing supply chain strategies that we just discussed focused heavily on resource planning. Since the central premise of RBV is that the firm’s competitive advantage stems in large part from its ownership and utilization of heterogeneous resources, we are naturally drawn to ask:

What information can data driven models of a firm’s supply chain provide about the heterogeneity of the firm’s resources?

Wernerfelt [1994] confirms that measurement methods such as these that map the space of resources are needed to make RBV more useful.

To answer this question, we exploit marginal cost information provided by optimization algorithms that solve the supply chain models. Specifically, by fixing all zero-one variables in a mixed integer programming model of the firm’s supply chain at their optimal values and solving the residual linear programming model, we can compute optimal shadow prices on all resource constraints. To keep our discussion simple, we assume that the model being optimized is of type 1 or 2 as shown in Figure 3. Depending on the objective function driving the model, these shadow prices measure the decrease in minimal cost, or increase in maximal net revenues, that would occur if another unit of resource were available. They need not be unique, but we can treat this ambiguity as of secondary importance.

As shown in Figure 7, relative to an optimal supply chain strategy and industry average unit costs for a resource, we have posited five categories into which the resource may fall:

- strongly heterogeneous
- weakly heterogeneous
- homogeneous
- weakly stranded
- strongly stranded

If the resource is unique to the firm and no meaningful industry average unit cost exists, then the Figure simplifies to two ranges: Heterogeneous if the shadow price is positive and stranded if the price is non-positive. Moreover, a cost/accounting function, corresponds only to a homogeneous resource for which perfect markets allow expansion or contraction, virtually without limit, at approximately the industry average unit cost of the resource.
We elaborate briefly on this taxonomy with examples. Consider the cost/resource function in Figure 4 that may describe a heterogeneous, homogeneous or stranded resource for which expansion and contraction is to be considered. Suppose the resource corresponds to hours of skilled labor used to manufacture many products in a net revenue maximizing model. Suppose further that the resource achieves the upper bound M2 in an optimal solution. We consider this to be a hard upper bound in that the firm cannot acquire additional resources of this type, at least not without prohibitive expense, within the scope of the model. Suppose still further that the shadow price is ten times greater than the hourly compensation of the skilled employees. One could then justifiably view the resource as strongly heterogeneous.
An option for stretching strongly heterogeneous resources is for the firm to outsource the manufacture of components or parts using these resources. This will free up the firm's use of the resources in other value adding activities. Such make-or-buy decisions can be evaluated by supply chain models (see Shapiro [1994] for an example).

On the other hand, if the resource lies strictly between \( m \) and \( M_1 \) or \( M_1 \) and \( M_2 \) in an optimal solution, mathematical analysis shows that the shadow price will always lie between \( c_2 \) and \( c_3 \) (recall that \( c_2 < c_1 < c_3 \)). Assuming this range is small and straddles the industry average, the resource can be considered homogeneous. If future conditions should change, such as an increase in raw materials without an increase in product sales price for products using the resource, the firm might find it wishes to reduce the quantity it makes of these products and thereby reduce its use of this resource.

Finally, if the optimal resource level equals the conditional minimum \( m \), this resource might well have a shadow price significantly below the industry average, including the possibility that it is negative, which indicates that the resource is weakly or strongly stranded. The need for the firm to decrease or eliminate its holdings of stranded resources has been largely ignored by RBV researchers despite the importance of excess capacity as a competitive factor influencing many industries (Prahalad and Hamel, 1994).

The sustainability of heterogeneous resources identified by the model depends on inter-temporal dynamics of the firm and its industry. This point is discussed briefly below. We point out here that MP modeling and duality theory underlying the computation of shadow prices can address issues of sustainability discussed in Section 5. Asset mass efficiencies refer to fixed costs and economies of scale that can be captured by mixed integer programming models, if these costs can be accurately measured by ABC methods. Interconnectedness of stock assets is explicitly captured by the constraints and activities of MP models. Causal ambiguities may be identified by analyzing primal and dual LP sub-models to explain why unusually high shadow prices were computed for some resources.

As we discussed in Section 7, the multi-national food manufacturer was motivated to implement a model for strategic supply chain analysis because senior management recognized that total North American manufacturing capacity was in excess. The model determined, in effect, which plants had stranded product and facility sustaining resources. In this case, management's interest was to decide on which facility or facilities to close. There was no effort made to investigate how some product markets might be expanded, thereby causing the stranded resources to be more profitably employed. Since the companies product lines are quite mature, the decision to ignore options on the marketing and sales side of the business was probably well founded. The model also demonstrated the low marginal value of opening a new plant, a pet project of the management team in the country where the plant was to be located.

The wholesaling/retailing company developed and used a supply chain model to evaluate new designs of their distribution network. Since they took a "greenfield
approach” to the location and sizing of new facilities, the supply chain model, in effect, sought to establish facilities with only heterogeneous and homogeneous resources. In studying the supply chain of the specialty chemicals company, the model consistently identified optimal strategies under a range of scenarios for which certain process sustaining resources reached their upper bounds and represented significantly heterogeneous resources. The company is investigating investment alternatives for expanding them, as well as acquisitions and joint ventures to add capacities in these categories in new locations. The firm’s supply chain model will be used to study the economics of these alternatives.

The extent to which the firm's resources are heterogeneous, homogeneous, or stranded depends on the activities using them. The intersection of activities with resources was discussed in an earlier section. The schema discussed there is not intended to convey the idea that a firm can make existing activities more profitable, or create profitable new activities, in a mechanistic manner. Rather, the firm’s activities reflect organizational realities within the firm and between the firm and its suppliers and customers.

For example, the new flow-through activities being investigated by the wholesaling/retailing company can be implemented only for products from suppliers who have the capability and willingness to organize and bar code their shipments by final store destination. Similarly, when considering manufacturing products in Mexico for the US and vice versa, the multinational food company must determine if plants in the respective companies can efficiently execute different product recipes for the two countries. To evaluate the introduction of a new product, the specialty chemicals company considers activities only at those production sites that have personnel with expertise in starting up new processes for products that have not previously been manufactured in large volumes.

The resource categories of Figure 7 are based on shadow prices of the resources. Since they are marginal prices, further analysis is needed to compute the range of resource increase (decrease) in which the category of the resource remains unchanged. The range is also limited by the fixed values of the zero-one variables in the model that determine which facilities are open and closed and impose upper and lower bounds on operating levels for resources with economies of scale. Moreover, the modeling practitioner and the decision-makers might wish to expand the resource acquisition and divestment options considered by the model in order to extend the acquisition and divesting of resources identified as strongly heterogeneous and strongly stranded.

Dynamic and stochastic MP model types 4, 5, 6, 7, from Figure 3 would provide a deeper analysis of the firm’s strategic resources. For the purposes of discussion, we have depicted in Figure 8 a simple stochastic programming model spanning three years with binary random events at the ends of years 1 and 2. The boxes in Figure 8 are MP sub-models, which correspond to states in the tree, and the circles are chance nodes. The probability of occurrence of each state is shown to the right of each box. The optimal shadow price associated with a resource under investigation is shown on top of the box.
The values of the shadow prices across time and scenarios indicate the sustainable nature of the resource. For example, the resource might be strongly heterogeneous in all years and all scenarios. Such a result would strongly indicate that the resource provides the firm with sustainable competitive advantage. By contrast, the resource might be strongly heterogeneous in year 1, but both heterogeneous and homogeneous, depending on the scenario, in years 2 and 3. To an extent depending on the probabilities of the various scenarios, the resource is in this case less important to the firm’s sustainable competitive advantage.

A single measure of the resource is the discounted expected value of the shadow price given by

\[ \pi_1 + \pi_{21}P_{21} + \pi_{22} + \pi_{31}P_{31} + \pi_{32}P_{32} + \pi_{33}P_{33} + \pi_{34}P_{34} \]

In writing out this formula, we assume the objective function is either to minimize expected discounted cost or maximize expected discounted net revenue. Therefore, the shadow prices implicitly include discount factors. In assessing its category, this value should be compared to the expected discounted industry cost of the resource.

The process of constructing the decision tree and its scenarios is a critical step in the implementation of a stochastic programming modeling for strategic planning. This construction must be based on managerial judgment about the firm’s major areas of strategic initiative and the uncertainties associated with them. The model practitioner and the decision-makers should base their thinking in large part on the concepts of RBV. Factors affecting the imitation and mobility of and substitution for heterogeneous resources over time must be quantified. Similarly, complex interactions among resource acquisition decisions must be also captured (Black and Boal, 1994). The construction of stochastic programming models should also draw on ideas from the emerging discipline of scenario planning (e.g., see Georgantzis and Acar, 1995). Unfortunately, we must leave further discussion of these issues to another paper.
Stochastic Programming Tree
Figure 8
References


