ON INTEGRATING THEORIES OF INTERNATIONAL ECONOMICS IN THE STRATEGIC PLANNING OF GLOBAL SUPPLY CHAINS AND DYNAMIC SUPPLY CHAIN RECONFIGURATION WITH CAPACITY EXPANSION AND CONTRACTION

A Dissertation

by

CHAEHWA LEE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2011

Major Subject: Industrial Engineering

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Approved by:

Chair of Committee:	Wilbert E. Wilhelm
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	Halit Uster
	David R. Larson
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ABSTRACT

On Integrating Theories of International Economics in the Strategic Planning of Global Supply Chains and Dynamic Supply Chain Reconfiguration with Capacity Expansion and Contraction. (December 2011)

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Chair of Advisory Committee: Dr. Wilbert E. Wilhelm

This dissertation discusses two independent topics. The first part of the dissertation relates three theories of international economics (comparative advantage, competitive advantage, and competitiveness), and formulates the thesis that incorporating them in the form of readily available individual competitiveness indicators in OR/MS models offers promise to enhance decision-support for the strategic planning of global supply chains in general, and for locating facilities in particular. The objectives of this research were to relate each of these theories and to describe their interrelationships; to describe measures provided by two well-known annual competitiveness reports; and to illustrate application of the theories as a means of supporting the thesis of the research, and justifying the research questions we pose for future research. While this research discusses topics relative to the broader background of global supply chain design, it illustrates applications associated with facility location, a component of the global supply chain design. In the last chapter of the first part of the dissertation, we provide a vision to foster future research that will enhance the profitability of international enterprises under NAFTA.

The second part of the dissertation deals with the DSCR model with capacity expansion and contraction. The strategic dynamic supply chain reconfiguration (DSCR) problem is to prescribe the location and capacity of each facility, select links used for transportation, and plan material flows through the supply chain, including production, inventory, backorder, and outsourcing levels. The objective is to minimize total cost. The configuration must be dynamically redesigned over time to accommodate changing trends in demand and/or costs by opening facilities, expanding and/or contracting their capacities, and closing facilities. The problem involves a multi-period, multi-product, multi-echelon supply chain. Research objectives are alternative formulations of DSCR and tests that identify the computational characteristics of each model to determine if one offers superior solvability in comparison with the others. To achieve the first objective, we present an initial MIP model, a refined model that relates decision variables according to a convenient structure, and branch and price (B&P) schemes for the refined model. We found that the network-based formulation offered superior solvability compared to the traditional formulation.

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I am also grateful to Dr. Lewis Ntaimo, Dr. Halit Uster, and Dr. David R. Larson for serving as members of my advisory committee and for giving helpful suggestions. Thanks also to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. Finally, I am grateful to my parents, my wife, Jaerang Kwon, and two sons, Soohyun and Soobum, for all the sacrifices they have made.

The first part of the dissertation has been published in Lee and Wilhelm (2010). The second part will be published in refereed journals, which will hold the associated copyrights.

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CHAPTER I

INTRODUCTION*

This dissertation discusses two independent topics: (Part I) on integrating theories of international economics in the strategic planning of global supply chains and (Part II) dynamic supply chain reconfiguration (DSCR) with capacity expansion and contraction.

The first part of the dissertation relates three theories of international economics (comparative advantage, competitive advantage, and competitiveness) and formulates the thesis that incorporating them in the form of readily available individual competitiveness indicators in OR/MS models offers promise to enhance decision-support for the strategic planning of global supply chains in general and for locating facilities in particular. The purpose of this research is to relate these theories from the field of international economics, to give a roadmap of related measures that are provided by annual competitiveness reports, and to pose several research questions as challenges to the OR/MS community as it seeks to improve models to support the strategic planning process. Accordingly, specific objectives of this research are to relate each of these theories and to describe their interrelationships; to describe measures provided by two well-known annual competitiveness reports; and to illustrate application of the theories

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This dissertation follows the style and format of *IIE Transactions*.

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as a means of supporting the thesis of the research and justifying the research questions we pose for future research. While this research discusses topics relative to the broader background of global supply chain design, it illustrates applications associated with facility location, a component of the global supply chain design, since it has a rich history within the OR/MS community and since it is central to strategic planning in the global economy.

The North American Free Trade Agreement (NAFTA) has increased trade among member countries (Canada, Mexico, and the U.S.) by removing tariffs and barriers to trade, stimulating investment. While NAFTA has enhanced the economies of member countries, little research has been directed specifically to help companies and their supply chains exploit the agreement or the geographical proximity and competitive advantages of member countries to the fullest advantage. Thus we provide a vision to foster future research that will enhance the profitability of international enterprises under NAFTA. More specifically, we provide a vision of research needs relative to four different arenas to promote academic OR/MS research that will stimulate the continued economic development of NAFTA member countries, the well being of their citizens, and the profitability of their businesses.

The second part of the dissertation deals with the DSCR model with capacity expansion and contraction. The strategic DSCR problem is to prescribe the location and capacity of each facility, select links used for transportation, and plan material flows through the supply chain, including production, inventory, backorder, and outsourcing levels. The objective is to minimize total cost. The configuration must be dynamically redesigned over time to accommodate changing trends in demand and/or costs by opening facilities, expanding and/or contracting their capacities, and closing facilities. The problem involves a multi-period, multi-product, multi-echelon supply chain. Research objectives of this part of dissertation are alternative formulations of DSCR and tests that identify the computational characteristics of each model to determine if one offers superior solvability in comparison with the others. To achieve the first objective, we presents an initial MIP model, a refined model that relates decision variables according to a convenient structure, and branch and price (B&P) schemes for the refined model.

CHAPTER II

INTERNATIONAL ECONOMICS THEORY AND GLOBAL SUPPLY CHAINS*

This chapter presents the overview of research on the theories of international economics and research objectives (Section 2.1) and vision on NAFTA trade research (Section 2.2), research contributions (Section 2.3); and the organization of Part I of the dissertation (Section 2.4).

2.1 International economics theories and research objectives

The global economy has evolved rapidly over the last decade and will, optimists agree, continue to do so after the current recession runs its course. The Operations research (OR) / management science (MS)[1] community has played a role in the development of the global economy, formulating models to provide decision support for managers of international enterprises as they form strategic plans such as determining what products to produce and market, sourcing globally, expanding capacities, designing supply chains, and locating facilities (e.g., production and assembly plant and distribution centers).

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[1]Operations research (OR) and management science (MS) form an interdisciplinary branch of applied mathematics, engineering, and science that employs analytical approaches including mathematical modeling, statistics, and algorithms to improve an organization's ability to make better decisions by arriving at optimal or near optimal solutions to complex management problems (Lee and Wilhelm, 2010).

As a specific example, strategic supply chain design involves decisions that prescribe facilities, including the location, capacity, and technology of each employed for production, assembly, and distribution; and design the associated supply chain by selecting suppliers; designating transportation modes; and planning production quantities, inventories, and backorders. In particular, models that address the international setting incorporate trade regulations such as local content rules and financial issues such as transfer prices, border crossing costs, incomes taxes in different countries, and transportation costs (e.g., Wilhelm *et al*., 2005).

While accounting for a number of the actual issues involved in the global business setting, prior OR/MS studies have not explicitly incorporated the theories of international economics (*i.e., in the form of parameters, constraints, or decision variables*). We use the word "explicit" since, according to a dictionary definition, "explicit" means "fully revealed or expressed without vagueness, implication, or ambiguity; fully developed or formulated (Merriam-Webster, 2009)." According to this definition, the theories of international economics (i.e., comparative advantage, competitive advantage, and the competitiveness of a country, including Porter's Diamond explanation of competitive advantage) have not been explicitly incorporated in OR/MS models for global supply chain design. A host of indicators (i.e., measures) related to these theories is published in annual competitiveness reports that provide a wealth of information that might potentially be used to enhance strategic planning, including the Global Competitiveness Report (GCR) of the World Economic Forum

(WEF) and the World Competitiveness Yearbook (WCY) of the International Institute for Management Development (IMD) (Ambastha and Momaya, 2004).

One of our assumptions is that each industry can identify a unique subset of individual competitiveness indicators that are most closely related to its success so they can be incorporated in models that support its strategic planning process. Accordingly, this research formulates the **thesis** that incorporating the theories of international economics in the form of individual competitiveness indicators in OR/MS models offers promise to enhance decision-support for the strategic planning of global supply chains in general and for locating facilities in particular.

The **purpose** of this research is to relate these theories from the field of international economics, to give a roadmap of related measures that are provided by annual competitiveness reports, and to pose several research questions as challenges to the OR/MS community as it seeks to improve models to support the strategic planning process. Therefore, specific **objectives** of this research are (1) to relate each of these theories and to describe their interrelationships; (2) to describe measures provided by the GCR and WCY, two well-known annual competitiveness reports; and (3) to illustrate application of the theories as a means of supporting the thesis of the paper and justifying the research questions we pose for future research. Even though this paper discusses topics relative to the broader background of global supply chain design, it illustrates applications associated with facility location, a component of global supply chain design, since it has a rich history within the OR/MS community and since it is central to strategic planning in the global economy. We have used the term *theory* and now define it from two complementary viewpoints: “a theory is a set of interrelated principles and definitions that present a systematic view of phenomena by specifying relationships among variables with the purpose of explaining natural phenomena” (Kerlinger, 1986) and “any set of hypotheses or principles linked by logical or mathematical arguments which is advanced to explain an area of empirical reality or type of phenomenon” (Jary and Jary, 1991).

2.2 NAFTA trade and research objectives

The environment of the global economy has stimulated enterprises to internationalize, employing global sourcing and the production sharing strategy to locate operations in countries that offer comparative advantages. International trade induces countries to allocate resources (i.e., natural, labor, and capital) more efficiently, leading to productivity increases and economic gains that improve income and living standards. A number of free trade agreements have been initiated around the world (e.g. regional and bilateral free trade agreements (FTA); the North American Free Trade Agreement (NAFTA) (1994), the Central America-Dominican Republic-United States Free Trade Agreement (CAFTA-DR) (2005), the Association of Southeast Asian Nations(ASEAN) FTA (1992), Australia FTA (2004), Chile FTA (2004), Korea FTA (2007), Singapore FTA(2003)) to eliminate tariffs and reduce barriers to trade with the goal of enhancing the economies of participating countries.

In particular, NAFTA (The NAFTA Secretariat, 2007) has been a catalyst for the economies of member countries: Canada, Mexico, and the U.S. A Wall Street Journal editorial (The Wall Street Journal, 2004) noted that the point of free trade is to allow resources to find their most efficient use and re-deploy workers to better paying jobs. The comparative advantages of all three NAFTA members have made North America an attractive investment for global capital. While NAFTA has enhanced the economies of member countries, little research has been directed specifically to help companies and their supply chains exploit the agreement or the geographical proximity and competitive advantages of member countries to the fullest advantage.

The objective of this research is to provide a vision to foster future research that will enhance the profitability of international enterprises under NAFTA. The short range goal of this research is to promote academic research on international trade under NAFTA through this vision of research needs. The long-range goal is to stimulate the continued economic development of NAFTA-member countries, the well being of their citizens, and the profitability of their businesses.

2.3 Research contributions

The contribution of this research is that this is the first investigation on how to enhance existing OR/MS models that prescribe the strategic supply chain planning of international enterprise by incorporating the theories and ideas from the field of international economics, which are important factors for the strategic decision making procedure of international enterprises. The theories of international economics have been studied by economists to primarily explain international trade between countries. However, in this research, we explain, from the OR/MS community perspective, how the theories of international economics are interrelated to each other and how they have evolved over time to show how the theories might be used for the strategic planning.

The specific contributions of this research include a presentation of the three theories of international economics and a number of competitiveness reports that reflect the comparative and competitive advantage and competitiveness of nations, which contains a wealth of useful information readily available for the OR/MS models for strategic decision. This dissertation demonstrates how past location decisions can be explained by competitiveness indicators of selected competitiveness reports and, based on the previous studies that employed competitive indicators partially, illustrates how existing OR/MS model can be further enhanced by incorporating competitiveness indicators for the strategic planning of global supply chains in general and for locating facilities in particular. This study poses several research questions as challenges to the OR/MS community as it seeks to improve models to support the strategic planning process, offering fertile research avenue for future research.

Based on the feedbacks from a number of practitioners from three NAFTA member countries and a literature survey, the major contributions of the research on the vision of research needs under NAFTA are to promote academic OR/MS research relative to NAFTA trade and to help international enterprise in the three countries make a more profitable long- and short -term decisions.

2.4 Organization of part I

The rest of the first part of this dissertation comprises five Chapters III to VIII. Chapter III reviews literature related to OR/MS models formulated to design global supply chains in general and locate facilities in particular. It also notes milestones in the evolution of location theory as posited by economists. Chapter IV addresses objective (1), relating the theories of comparative advantage, competitive advantage, and competitiveness, including Porter’s Diamond model, and discussing how they might be used in the strategic planning process. Chapter V addresses objective (2), describing the GCR and WCY and giving examples of how measures can be applied to selected countries. In particular, we analyze these two reports, suggesting how information they provide might be extracted for use in models that support strategic planning. Chapters VI and VII address objective (3). In particular, Chapter VI relates recent economic phenomena to facility location decisions and draws from the literature to support our thesis. This chapter also discusses studies that have suggested how competitiveness indicators might be employed to analyze logistics systems and facility location. Chapter VII discusses how competitiveness indicators from annual competitiveness reports might be incorporated in an example model to enhance strategic planning. Chapter VIII presents research opportunities to enhance NAFTA logistics relative to four different arenas, proving a background on the research and previous related works.

CHAPTER III

LITERATURE REVIEW: INTERNATIONAL ECONOMICS THEORY AND GLOBAL SUPPLY CHAINS*

This chapter comprises two sections. The first (Section 3.1) reviews selected OR/MS models that have been proposed to prescribe strategic supply chain designs and emphasizes which factors have been considered in each study and which have not been considered relative to the theories of international economics. The second (Section 3.2) discusses economics theories of location as well as OR/MS models that deal with facility location.

3.1 Strategic planning models for global supply chain design

The strategic supply chain design problem prescribes the numbers, locations, and capacities of manufacturing, assembly, and distribution facilities and then the flow of the materials from selected suppliers to customers, including inventory levels and transportation modes (Melo *et al*., 2009). While domestic supply chain design deals with a single country, global supply chain design involves international trade rules and financial issues and allows suppliers and facilities to be located in multiple countries (Vidal and Goetschalckx, 1997), as shown in Figure 1. Trade rules typically deal with

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issues like trade barriers, local contents rules, and quotas; governmental and financial issues include taxes and duties, exchange rates, transfer prices, and duty drawbacks. In addition, uncertainties (e.g., government stability and exchange rates) and qualitative factors (e.g., economic freedom and infrastructure) are important considerations in designing global supply chains.

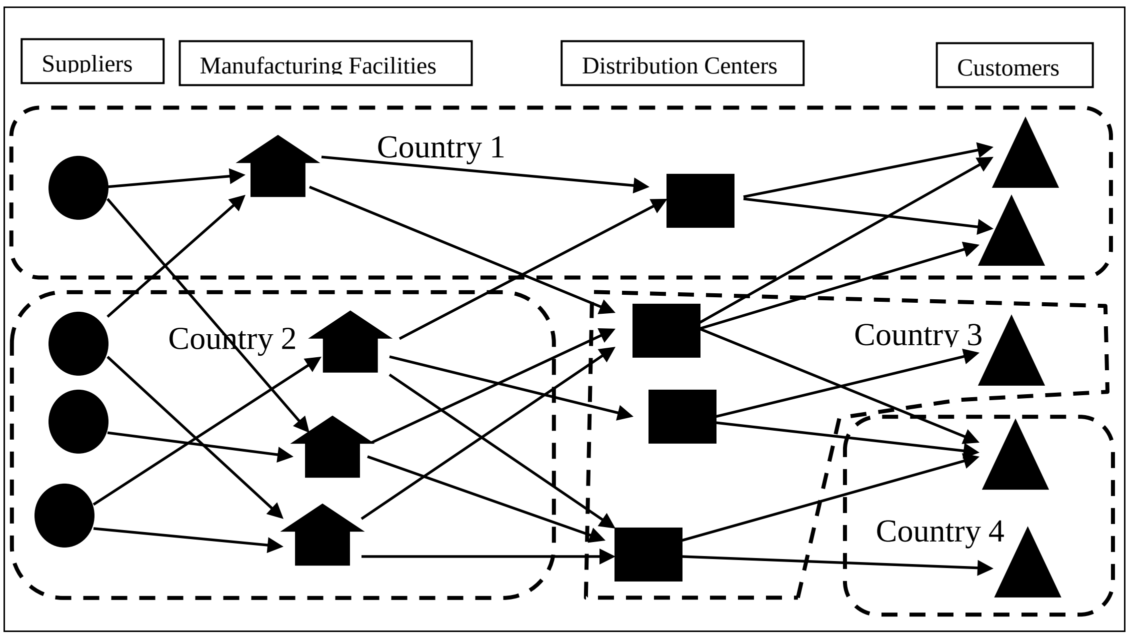

Figure 1. Global supply chain network

Reviews (Geunes and Pardalos, 2003; Sarmiento and Nagi, 1999; Vidal and Goetschalckx, 1997; Melo *et al*., 2009) describe OR/MS models - mostly mixed integer programs (MIPs) - that have been formulated to design international supply chains. Cohen *et al*. (1989) proposed a MIP that includes the impact of economies of scale, duties and tariffs, exchange rates, differences in corporate tax rates in each country, market penetration strategies, and local content rules. Schmidt and Wilhelm (2000) formulated a prototype model for strategic planning, emphasizing that a global logistics network should reflect labor and transportation costs, infrastructure, general business environment, proximity to markets and to suppliers, taxes and duties, strategic alliances, and joint ventures.

Vidal and Goetschalckx (2001) presented a detailed model to maximize after-tax profits, considering transfer prices and transportation charges. Goetschalckx *et al*. (2002) classified features, which have been incorporated in six strategic models, into four categories, as detailed in Table 1: stochastic, non-international, taxation and cash flow, and trade barriers. Three features listed in Table 1 (i.e., reliability of transportation channels, political environment, and customer service level) are closely related to indicators provided by annual competitiveness reports but have not been addressed in OR/MS models; Vidal and Goetschalckx (1997) and Goetschalckx *et al*. (2002) recommended that they be incorporated in the future. Bhutta *et al*. (2003) formulated a production, location, distribution, and investment model, which deals with international features such as tariffs, shipping costs, investments, and exchange rates.

Table 1. International features that have been incorporated in strategic models

1. Stochastic	**2. Non-international**
Exchange rate fluctuation, uncertainty Suppliers' reliability Reliability of transportation channels Lead times Facility fixed costs Demand Uncertainty of market prices Political environment Customer service level	Selection of manufacturing technology Product differentiation by country Bill of materials (BOM) relationships Impact of economies of scale Capacity determination Financial decisions, cash flow modeling Infrastructure modeling, information flow modeling Global supply chain coordination Modeling of competitors' actions Modeling of alliances

Table 1. Continued

3. Taxation and cash flow	**4. Trade barriers**
Taxes and duties	Quotas
Profit repatriation	Local content rules
Duty drawback and duty relief	Offset requirements
Transfer prices	Governmental subsidies

Only a few studies have addressed uncertainty explicitly in global supply chain design models. Santoso *et al*. (2005) addressed uncertain processing and/or transportation costs, demands, supplies, and capacities in a stochastic programming approach to supply chain design. While prior OR/MS models have addressed a range of traditional factors, none has explicitly incorporated (*i.e., in the form of parameters, constraints, or variables*) the theories of international economics and related (individual) indicators (i.e., measures) from annual competitiveness reports. Further, none has considered how such measures change over time and how these changes might affect strategic planning, which must position – and perhaps reposition - the enterprise over the long term.

3.2 Facility location

This section discusses milestones in the evolution of location theory, related theories of international economics, and OR/MS models that have been formulated to optimize facility locations. Location theory addresses several important questions: *who produces what goods or services in which locations and why*. Johann-Heinrich von Thunen (1783-1850) initiated thought about the optimal location for agriculture, considering land and transportation costs. Alfred Weber's subsequent work (1909) is considered to have established the foundations of modern location theory, which deals with transportation and production costs (Badri, 2007). Hotelling (1929) postulated that an enterprise tends to locate toward the center of its market area rather than at dispersed sites. Isard (1956) attempted to develop principles for a general theory of location by combining the thoughts of earlier location theorists. He used the substitution framework, which explains that an enterprise can substitute inputs (e.g., labor for capital), depending on their relative prices as well as transportation cost to explain industrial location.

Product life-cycle theory, initiated by Vernon (1966), was first to explain the location of production facilities overseas. The theory holds that, early in its product's life-cycle, all parts and labor come from the area in which the product was invented. After the product is adopted in the global market, production becomes routine and gradually moves away from the point of origin, so that the originating country ends up importing it. The personal computer is one example that demonstrates this theory. Personal computers were invented in the U.S. and quickly spread throughout the industrialized world. Subsequently, copies were produced at lower cost overseas and exported to the U.S. and elsewhere. The U.S. has struggled to compete in this evolving market and now imports many personal computers. Readers are referred to Badri (2007) for more about location theory.

Theories of location and trade share a number of commonalities. Krugman (1993), the 2008 Nobel laureate economist, compared and contrasted location and trade theories, concluding that, despite some differences, the two are quite similar in that they ask the same basic question (i.e., *who produces what goods in which locations)* and make similar assumptions. Location theory deals with the optimal location of production, given the costs of the factors of production and transportation. Trade theory deals with characteristics of production locations, such as relative endowments of the factors of production, giving rise to comparative advantages in producing one good relative to another. We note that Krugman(1993) used the term “trade theory” in the 1990s to refer to Ricardo’s theory of comparative advantage and, more recently, he used “international economics” (Krugman and Obstfeld, 2006). In this dissertation, we focus on theories of international economics as a means of demonstrating their application to potentially enhance strategic OR/MS models.

Several studies have proposed that the inflow of foreign direct investment (FDI) explains the locations that an international enterprise will select in various countries. A location decision may lead the enterprise to make an FDI, forming a subsidiary company under its management control (i.e., by controlling at least 10% of the subsidiary’s voting stock) (Krugman and Obstfeld, 2006). For example, the *eclectic paradigm* (Dunning, 1988, 1995) analyzes investments relative to a framework that includes ownership, location, and internationalization (OLI). Empirical studies of OLI have suggested that market size; market growth; barriers to trade; wages; production, transportation, and other costs; political stability; and trade and taxation regulations can be related to explain location decisions (Dunning, 1995).

Sethi *et al*. (2003) developed a regression model that relates the inflow of FDI to European and Asian countries from the U.S. to five independent variables: wages, population, gross national product (GNP), political and economical stability, and cultural attributes. They concluded that low wage rates and the liberalization of Asian economies were important factors that explained the transition of U.S.-based international enterprises' FDI flow from Western Europe to Asia. Location decisions based on the inflow of FDI assume that international enterprises select locations based on their relative advantages (Dunning, 1988). In contrast, Nachum and Wymbs (2005) used a statistical model, which showed that product differentiation – the modification of a product to make it more attractive to a targeted market segment – is an important determinant of location choices. That is, production differentiation and proximity to other enterprises are closely associated, either negatively or positively, depending on product and industry type.

Globerman and Shapiro (2003) showed that U.S.-based companies are not likely to make FDIs in countries that fail to achieve a minimum threshold of effective governance (i.e., regulation and legal systems that assure freedom of transactions, security of property rights, and transparency of government and legal processes). Other primary inducements that attract FDIs include the quality of infrastructure and labor force, the size and growth of the domestic market, and the accessibility of the location; financial incentives provided by host countries are less important (Farrell *et al*., 2004). Other (macro- and micro-economics) factors that influence the location of a facility include those offered by a particular country (e.g., input factors needed for production, levels of R&D investments made by the host country), and those that characterize the firm (e.g., technological and workforce competence, size, and organizational structure) (Nachum and Wymbs, 2005).

The facility location problem addressed by the OR/MS community involves siting a set of facilities to serve a set of customer demands with the objective of minimizing total distance (or time or cost) between customers and facilities (Melo *et al*. 2009). Hodder and Jucker (1985) incorporated price and exchange-rate uncertainty in a mixed-integer, quadratic programming model to select the international plant location that maximizes profit. Hodder and Dincer (1986) studied both facility location and financial decisions in an uncertain environment to assess the overall profitability of potential locations.

Bartmess and Cerny (1993) proposed a capability-focused approach to facility location, dealing with exchange rates, political impacts, taxes, transfer prices, and costs as well as advantages that might result from locating facilities near customers, suppliers, and/or competitors. MacCormack *et al*. (1994) argued that small manufacturing facilities, which tend to be located in large regional markets, are successful because they differentiate their products to suit the local markets. They concluded that global manufacturing networks are based on the advantages offered by host countries, including infrastructure and local skill levels, rather than purely cost-based factors (e.g., labor rates, taxes, transportation costs). The next chapter discusses relevant theories of international economics, *which have not been incorporated explicitly* in strategic supply chain design models in general or facility location models in particular.

CHAPTER IV

THEORIES OF INTERNATIONAL ECONOMICS*

This chapter relates the theories of comparative advantage (Section 4.1), competitive advantage (Section 4.2), and competitiveness (Section 4.3), including Porter's Diamond model, which have not been incorporated in OR/MS models for global supply chain design and facility location, and discusses their interrelationships (Section 4.4).

4.1 Comparative advantage

This classical theory of international trade, which was proposed by David Ricardo, explains why it can be beneficial for two countries to trade, even though one of them may be able to produce every kind of good more cheaply than the other. It invokes six assumptions: (1) two countries each produce two different goods using labor as the only input factor for production; (2) the two goods are assumed to be homogeneous across enterprises and countries; (3) skills of laborers are identical within a country but not across countries; (4) labor, always fully employed, can be reallocated at no cost between industries within a country but cannot move between countries; (5) goods can be transported at no cost between two countries; and (6) labor productivity reflects production technology differences across industries and countries (Krugman and

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Obstfeld, 2006).

The absolute cost of production is not as important as the opportunity cost, the cost at which a country can produce one good in comparison with another. “A country has a comparative advantage in producing a good if the opportunity cost of producing that good in terms of other goods is lower in that country than it is in other countries” (Krugman and Obstfeld, 2006). Free trade can benefit two countries if each exports goods for which it has a comparative advantage (Warr, 1994).

As an example of a comparative advantage, Table 2 shows that higher labor productivity gives Country A an absolute advantage in both wine and cheese industries (Krugman and Obstfeld, 2006). The opportunity cost of cheese relative to wine in Country A is 1/2=0.5, while it is 6/3=2 in Country B. Consider the amounts of cheese and wine that sell for the same price, say a pound and a gallon, respectively. Country A can produce this amount of cheese using half as many person-hours as it takes to produce the corresponding amount of wine, so that Country A will earn more by producing cheese. Country B can produce a gallon of wine using half as many hours as it takes to produce a pound of cheese (3 versus 6), so it has a comparative advantage in producing wine. With this specialization, both countries will gain from free international trade.

Table 2. Hours of labor required to produce

Country	Cheese	Wine
A	1 hour per pound	2 hours per gallon
B	6 hours per pound	3 hours per gallon

An extension of Ricardo's model, which deals with a single factor of production (i.e., labor), the Heckscher and Ohlin model determines which good to produce by considering two of the following four factors: labor, land, capital, and natural resources (Krugman and Obstfeld, 2006). A country realizes a comparative advantage if the inputs required to produce a good are locally abundant, making it cheaper to produce than another good that requires inputs that are locally scarce . The Heckscher and Ohlin model is also called the "*2 by 2 by 2*" model because it involves two countries, two goods, and two production factors. For example, a country in which natural resources are scarce but labor and land are abundant –so that their costs are low- has a comparative advantage in producing grains, which require large amounts of labor and land but few natural resources. Companies that use factors that are locally abundant will produce at lower cost relative to the opportunity cost of producing other goods. Both Ricardian and Heckscher and Ohlin models are about the efficient allocation of resources among industries within a particular country (Warr, 1994).

Along with the development of the theory of comparative advantage, Balassa (1965) recently proposed the concept of the Revealed Comparative Advantage (RCA) index, which allows us to indentify the comparative advantages of a nation. We introduce the RCA following the theory of comparative advantage since we relate it to the U.S.'s trade shift from Mexico to China in the later section. The comparative advantage of country i can be quantified using the RCA index, RCA_{ij}, which is the ratio of two fractions: the export of good j from country i divided by the total exports from country i and the world export of good j divided by total world exports (Balassa, 1965).

An $RCA_{ij} > 1$ $(RCA_{ij} < 1)$ reveals that country i has a comparative advantage (disadvantage) relative to good j (Ferto and Hubbard, 2003). For example, RCAs have shown that Mexico enjoys comparative advantages over China, allowing it to exceed in exporting combustion engines, vehicle parts, meters and control systems, and medical instruments, while China has comparative advantages over Mexico relative to leather, manmade woven fabric, office machines, computer equipment, electrical transmission equipment, motorcycles, and furniture (Rosen, 2003).

4.2 Competitive advantage

While the theory of comparative advantage long dominated thought about classical international trade, it is now viewed as an incomplete explanation for the modern global business environment. Advances in information technology, in particular, have created new opportunities for the increasingly complex modern global economy. Reductions in the cost of transportation and communication are making location less important, encouraging companies to move operations to lower cost environments while political and economic stability, a well-trained labor force, and strong institutional foundations are emerging as the key drivers of competitiveness (World Economic Forum, 2006). Ricardo advanced his theory at a time when capital, labor, and technology could not move offshore freely. In recent times, however, they have moved relatively easily, even in industries involving sophisticated technology and highly skilled employees.

In the 1980s, Michael Porter introduced the theory of competitive advantage with the goal of better explaining the global business environment and international trade.

This theory attempts to identify the fundamental determinants of the competitiveness of an i*ndustry* or of a *nation* and how they interact as a system. Barney (1991) provided a widely-accepted definition of competitive advantage relative to a *company*. “A firm is said to have a competitive advantage when it is implementing a value creating strategy not simultaneously being implemented by any current or potential competitors.” Further, he states that a firm is said to have a *sustained* competitive advantage when it has a competitive advantage and its competitors are unable to duplicate the benefits of its value creating strategy. Li *et al*. (2006) described competitive advantage as “the extent to which an organization is able to create a defensible position over its competitors” and proposed five dimensions of competitive advantage: price/cost, quality, delivery dependability, product innovation, and time to market.

To our knowledge, which is based on review of previous work, models for the design of global supply chains have not incorporated the theories of international economics. However, several studies have sought to identify how a firm can enhance its competitive advantage. Nordin (2008) reviewed streams of literature related to how firms might enhance their competitiveness and ultimately (sustainable) competitive advantage, presenting four prominent schools of thought, two of which are the position (Porter, 1980) and the resource-based views (Barney, 1991). While the position school of Porter (1985) argues that there are three strategies – product differentiation, cost leadership, and focus - for achieving a competitive advantage, the resource-based view of Barney (1991) argues that a competitive advantage is endowed by the company’s resources that are valuable, rare, imperfectly imitable, and non-substitutable. In particular, intangible resources are often important sources of competitive advantage because they are difficult for competitors to duplicate. Such intangible resources include (1) intellectual property rights; (2) trade secrets; (3) contracts and licenses; (4) databases; (5) information in the public domain; (6) personal and organizational networks; (7) employee know-how; and (8) organizational culture, for example, the ability to react to challenges and cope with change (Hall, 1993). The resource-based view holds that is not possible to purchase a sustainable competitive advantage on the open market or to duplicate one easily.

In addition, other studies have dealt with how firms generate and sustain a competitive advantage through using innovative management skills. In particular, supply chain management practices (Li *et al*., 2006), patents (Triest and Vis, 2007), autonomous cooperation and control (Hulsmann *et al*. 2008), electronic transactions (Hausen, 2006), enterprise resource planning (Zhang *et al*. 2005), product designs (Iranmanesh and Thomson, 2008), and supplier (Li *et al*., 2007) and sourcing (Nordin, 2008) decisions have all been studied. Our research focuses on how an international enterprise can obtain and sustain competitive advantage by identifying and exploiting competitive advantages and competitiveness of nations or economic regions.

Porter (1998b) emphasized that the theory of competitive advantage reveals a source of wealth, arguing that the local factor inputs upon which a comparative advantage depends (e.g., labor, natural resources, land, and capital) have become less important in the global economy. While international economists widely believe that comparative advantage is a key determinant of international production and trade, Neary

(2003) argued that scholars in business schools, who are typically not economists, emphasize competitive –not comparative- advantage as a predictor of the economic fortunes of firms and nations.

4.3 Competitiveness

Along with the theory of competitive advantage, national competitiveness has been studied since the 1980's. The theory of national competitiveness evolved from the theory of competitive advantage, subsuming the factors with which the latter deals. Porter pioneered the use of economic analysis to investigate important issues relating to the competitiveness of a firm, industry, or nation (Snowdon and Stonehouse, 2006) (See also Murtha and Lenway (1994)). Originating from the Latin word *competer*, which means involvement in a business rivalry for markets, competitiveness is now used commonly to describe a firm's ability to be profitable in the global economy.

Competitiveness has been a controversial notion and few agree on a precise definition (Ezeala-Harrison, 2005), although numerous definitions have been proposed. We relate several to indicate the diversity of thought on this topic. Ambastha and Momaya (2004) defined competitiveness as "the ability of a firm to design, produce and or market products superior to those offered by competitors, considering price and non-price qualities" Ezeala-Harrison (2005) defined competitiveness in terms of two levels: firm-industry (i.e., micro) and national (i.e., macro).

The Competitiveness Institute (2007) defines competitiveness differently for companies, industries, and nations (http://www.competitiveness.org). "For the company, competitiveness is the ability to provide products and services as (or more) effectively and efficiently than relevant competitors. Measures of competitiveness include firm profitability, the firm's export quotient (exports or foreign sales divided by output), and regional or global market share. At the industry level, competitiveness is the ability of the nation's firms within the same industry to achieve sustained growth relative to foreign competitors without protection or subsidies and measures include profitability, the nation's trade balance in the industry, the balance of outbound and inbound FDI, and cost and quality. For the nation, competitiveness is the ability to achieve a high and rising standard of living as measured by the level and growth of the standard of living and of aggregate productivity, and the ability of the nation's firms to increase penetration of world markets through exports or FDI." IMD defines competitiveness as "Competitiveness of nations is a field of economic theory, which analyses the facts and policies that shape the ability of a nation to create and maintain an environment that sustains more value creation for its enterprises and more prosperity for its people" (IMD, 2006).

Porter explains the competitiveness of a nation using his Diamond Model as an analytical tool to measure the quality of the business environment in a given country relative to four interlinked factors: (1)firm strategy, structure and rivalry; (2)demand conditions; (3)related supporting industries; and (4)factor conditions. Porter identifies that firms in different countries have distinct systemic characteristics relative to firm strategies, structures, goals, managerial practices, and intensity of rivalry and states that these different characteristics promote the competitive advantage of a firm. When there are more discerning customers in a country, the firm faces more pressure to constantly improve their competitiveness via innovative products and high quality. The spatial proximity of the related supporting industries (i.e., clustering) facilitates the exchange of information and ideas and promotes continuous innovation (Porter, 1998b).

But, more importantly, Porter argued that the key factors of production - skilled labor, capital and infrastructure – are created, not inherited. Key factors of production involve extensive, continuing investment and lead to a sustained competitive advantage, while non-key factors such as unskilled labor and raw materials can be procured, so they do not. The Diamond Model has been evolved to analyze the competitiveness of firms, industries, and nations (Porter, 1998b).

4.4 Three streams of research

The comparative advantages of nations are changing as new technologies and global markets emerge. Further, the global economy violates the assumptions (e.g., that input factors are immobile) underlying the theory of comparative advantage and reinforces the theory of competitive advantage. Thurow (1994) stated "there is no longer such a thing as a capital-rich or capital-poor country. Modern technology has also pushed natural resources out of the competitive equation. Japan, with no coal or iron ore deposits, can have the best steel industry in the world." Porter and Linde (1995) argued that globalization is rendering the notion of comparative advantage obsolete and that the focus of traditional theories on a country's endowments (e.g., labor, natural resources, energy, and capital) do not explain current international trade.

The comparative advantages of a nation are not the same as its competitive advantages. Countries that have low labor costs may each have a comparative advantage, but many are caught in a cycle of poverty and slow development, so that this comparative advantage *itself* does not endow a competitive advantage. Thus, a comparative advantage does not automatically confer a competitive advantage, but it can be the basis on which a competitive advantage is built. Khemani (2005) concluded that competitiveness should be equated with productivity because it relates measures that firms, industries, and nations adopt to foster, maintain, and increase productivity on a sustainable basis. National competitiveness depends on the continual upgrading of human resources, attracting of capital, and discovering additional natural resources and/or using them innovatively.

Warr (1994) reasoned that comparative advantage guides an efficient allocation of resources in an open (i.e., without trade restriction) economy at the national level, while competitive advantage deals with the determinants of the commercial performance of individual firms, especially those operating within 'advanced' economies. Some studies argue that the theory of competitive advantage has been advanced as a fundamental challenge to the classical theory of comparative advantage, but the argument that the former should be used as a replacement for the latter is mistaken - the two theories should be properly viewed as complementary to each other, rather than as competing or conflicting (Warr, 1994).

Comparative advantages still exist but no longer support high productivity or give competitive advantages in most industries (Porter, 1998a). International enterprises need to shift from relying on inherited endowments (comparative advantages such as low-cost labor or natural resources) to competitive advantages that arise from efficient and distinctive products and processes. To this end, an international enterprise must first identify a nation that is competitive and then upgrade the way in which it competes from within the nation.

Thus, in addition to comparative advantage, an extensive analysis of competitive advantage and competitiveness should be employed to select a location within a country that will facilitate the success of the enterprise. Such a comprehensive approach can also enhance other strategic planning related to broader aspects of global supply chains. Figure 2 summaries the evolution of these three theories of international economics, which can be used to strategic OR/MS models.

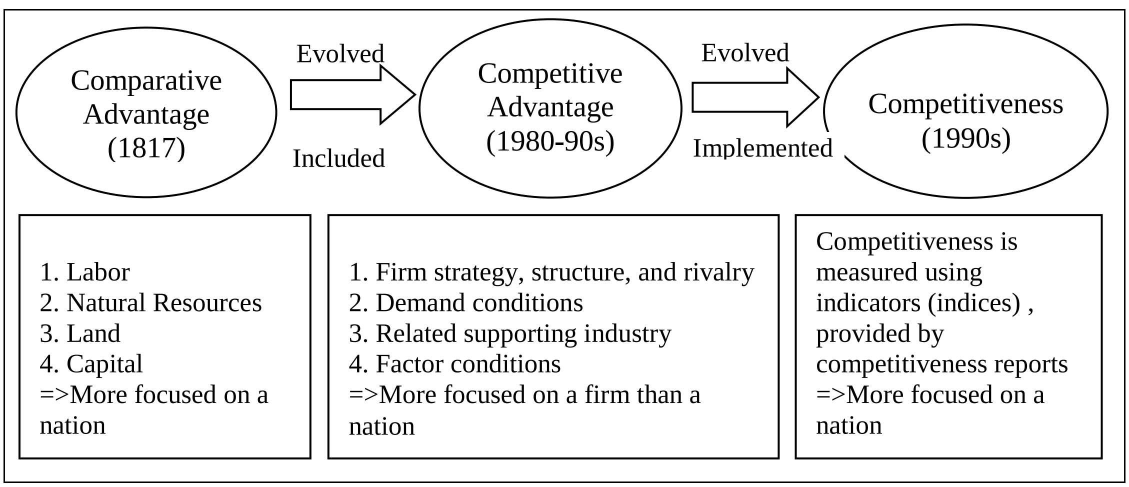

Figure 2. Relationship and differences of theories of international economics

CHAPTER V

COMPETITIVENESS REPORTS*

In the previous chapter, we explained the three theories of international economics, their relationships and their evolution. In this chapter, we discuss why we need annual competitiveness reports. First, from the perspective of international economics, we might use the reports to validate the theories of international economics or to evolve them. Second, we can use the reports to obtain quantitative measures (i.e., individual competitiveness indicators) that incorporate theories of international economics. In this chapter, we describe how comparative and competitive advantages and the competitiveness of a nation are measured by competitiveness indicators given by two competitiveness reports. In particular, we focus on describing annual competitiveness reports, which provide information that can potentially be used to enhance strategic planning. The last two subsections compare two annual competitiveness reports and discuss their limitations and issues.

Table 3 summarizes a selected set of reports (Fraser Institute, 2008; Heritage Foundation, 2009; IMD 2006; International Monetary Fund, 2007; National Science Foundation, 2007; The World Bank, 2007a, 2007b, 2007c; UNCTAD, 2007; World Economic Forum 2006). The GCR and WYC report indicators that measure the

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*Reprinted with permission from "On integrating theories of international economics in the strategic planning of global supply chains and facility location" by C. Lee and W. Wilhelm, 2010, *International Journal of Production Economics*, 124, 225-240, competitiveness of a nation, while the Index of Economic Freedom (published by Heritage Foundation) and Economic Freedom of the World (published by Fraser Institute) assess the degree to which the policies and institutions of nations are supportive of economic freedom. We assume that an international enterprise will locate facilities in countries that offer high levels of economic freedom; otherwise, it would incur undue risks. Globerman and Shapiro (2003) argued that without a minimum threshold of effective governance, which is an integral part of economic freedom, nations are unlikely to receive FDI for facility location.

Table 3. Annual reports

Report :Global Competitiveness Report (GCR) **Sponsor**: WEF **Focus**: Analysis of the competiveness of more than 120 countries (World Economic Forum 2006)
Report : World Competitiveness Yearbook(WCY) **Sponsor**: IMD **Focus**: Analysis of the competitiveness of 61 countries (IMD 2007)
Report :Index of Economic Freedom **Sponsor**: Heritage Foundation **Focus**: Systematic, empirical assessment of economic freedom of more than 183 countries (2009) with 10 components: business freedom, trade freedom, fiscal freedom, government size, monetary freedom, investment freedom, financial freedom, property rights, freedom from corruption, labor freedom
Report :Economic Freedom of the World **Sponsor**: Fraser Institute **Focus**: Assessment of economic freedom in 102 countries (2008) in five broad areas: size of government, legal structure and security of property rights, access to sound money, freedom to trade internationally, and regulation of credit, labor and business. * Note that half of survey data are supplied by WEF and IMD surveys
Report : Doing Business Database **Sponsor**: World Bank, International Finance Corporation **Focus**: Measures of business regulations and their enforcement in 175 economies Analysis of regulations that enhance or constrain investment, productivity, and growth Analysis of the time and cost for business startup, operation, trade, taxation, and closure
Report : World Development Indicators **Sponsor**: World Bank **Focus**: Over 800 indicators for about 150 economies and 14 country groups in more than 80 tables. Six chapters: world view, people, environment, economy, states and markets, and global Links

Table 3. Continued

Report : Enterprise Survey **Sponsor**: World Bank **Focus**: Business perceptions of investment climates in 97 countries, based on surveys of 60,000 firms
Report : Investment Compass **Sponsor**: U.N. Conference on Trade and Development **Focus:** Analysis of the investment environment through six groups of variables: resource assets, infrastructure, operating costs, economic performance and governance, taxation and incentives, and regulatory framework
Report : World Economic Outlook **Sponsor**: International Monetary Fund **Focus**: Analysis and projections of economic developments in selected country groups
Report : Science and Engineering Indicator **Sponsor**: U.S. National Science Foundation **Focus**: Measures of country competitiveness : science, engineering and labor skills; and R&D investment

While Table 3 lists a number of annual reports, we focus on the GCR and WYC because they are particularly relevant to the thesis of this research. They give comprehensive, up-to-date data that can be closely related to the strategic planning done by international enterprises. Even though competitiveness is difficult to quantify, these reports are among the most influential in contemporary economic publications (Kaplan, 2003).

The methodologies employed to generate these two reports have been updated frequently to reflect the changing international business environment. It is important to understand what indicators are used to measure the competitiveness of a nation, what those indicators mean, and how the two reports differ, so that a set of indicators pertaining to the competitiveness of nations can be used by an enterprise in making strategic plans, including locating facilities. This section comprises three subsections, which analyze the two reports and then compare them. Note that each report uses different terms (i.e., 9 pillars, Global and Business Competitiveness Indices, and 148 basic indicators for the GCR; 4 factors, 20 sub-factors, and 331 criteria for the WCY) and, thus, we use *pillar, index, and factor* to describe a group of individual indicators, depending on the report, and *competitiveness indicator* for an individual criterion (or measure) for both reports. Each report also gives a *composite index,* which is used to determine an overall ranking of each nation; each is calculated by forming a linear combination of individual indicators, assigning weights, and performing calculations according to a unique methodology determined by each report.

5.1. The GCR

The annual GCR assesses over 130 national economies, providing a detailed profile of each of them along with rankings relative to some 140 indicators (World Economic Forum, 2008). The data are derived both from statistical reports (published by World Bank, International Monetary Fund, UN, and World Trade Organization) and the Executive Opinion Survey (compiled annually by WEF using respondents in over 130 nations). The Executive Opinion Survey assesses the importance of a broad range of factors that are central to creating a healthy business environment in support of successful economic activity. Some indicators reported in GCR 2008-2009 were calculated using more than 12,000 survey responses (World Economic Forum, 2008).

The GCR provides two composite indices: the Global Competitiveness Index (GCI) and the Business Competitiveness Index (BCI). The GCI is intended to gauge the ability of a country's economy to achieve sustained economic growth over the medium-to-long term. It employs nine pillars that measure different aspects of national competitiveness (that is, the potential for economic growth). The nine pillars are based on more than 120 indicators (see Table 4, World Economic Forum, 2006), which provide a holistic overview of attributes that are critical to driving productivity and the competitiveness of enterprises located in the country. A nation itself does not produce goods or increase its GDP; rather, enterprises do. However, a nation can be a facilitator for the growth of companies located in it (World Economic Forum, 2006).

In addition, based on GDP per capita, the economy of a country can be categorized into one of three development stages: factor-, efficiency-, or innovation-driven (World Economic Forum, 2006). In the factor-driven stage, a country competes mainly on basic requirements: well-functioning institutions, appropriate infrastructure, stable macro-economic framework, and healthy (but not necessarily skilled) workforce. In the efficiency-driven stage, competitiveness is driven by efficiency enhancers: higher education and training, market efficiency, and ability to utilize existing technologies. In the innovation-driven stage, competitiveness is driven by business sophistication and innovation.

The BCI, a micro-economic index related to the short-term, complements the GCI, a medium-term, macro-economic index. The BCI evaluates the underlying micro-economic foundations of productivity in a country. Pooled data from the Executive Opinion Survey are used to conduct two principal-factor analyses: *sophistication of enterprise operations and strategy* and *quality of the national business environment* (World Economic Forum, 2006). Using regression analysis, the GCR has shown that differences in the BCI's of nations explain some 80 percent of the variation in GDP per capita (World Economic Forum, 2006; Ketels, 2006). Table 4 presents selected aspects of the GCI, the BCI, and a sample of Executive Opinion Survey questions. If a nation has high (positive) GCI and BCI values, it will tend to foster the productivity and competitiveness of companies located in it. It follows that enterprises should locate in nations that have high (positive) GCIs and BCIs.

Table 4. Examples of GCI, BCI, and Executive Opinion Survey used by the GCR

GCI	**1st Factor: Institutions.** Property rights, ethics and corruption, burden of government regulation, costs of crime and violence, organized crime **2nd Factor: Infrastructure.** Infrastructure quality, transportation infrastructure development, telephones **3rd Factor: Macroeconomy.** Government surplus/deficit, inflation, interest rate spread **4th Factor: Health and primary education.** Prevalence of and medium-term business impact of diseases, infant mortality, life expectancy, primary school enrolment **5th Factor: Higher education and training.** Secondary and tertiary enrollment ratio, quality of the educational system, especially math and science education, management schools, on-the-job training, specialized research and training **6th Factor: Market efficiency.** Distortions, competition, and size, extent and effect of taxation, procedures required to start a business, time required to start a business, intensity of local competition, foreign ownership restrictions, GDP – exports + imports, labor markets (flexibility and efficiency, hiring and firing practices, flexibility of wage determination, labor-employer relations, pay and productivity), financial markets (sophistication and openness, ease of access to loans, soundness of banks) **7th Factor: Technological readiness.** Firm-level use of technology, FDI and technology transfer; use of cellular telephones, internet users and personal computers (hard data) **8th Factor: Business sophistication.** Supporting industries, local supplier quantity/ quality, sophistication of firms' operations and strategy, extent of marketing, control of international distribution, nature of competitive advantage **9th Factor: Innovation.** Quality of scientific research institutions, company spending on R&D, university/industry research collaboration, government use of advanced technology, availability of scientists and engineers, intellectual property protection
BCI	**Company Sophistication.** Production process sophistication, extent of staff straining, willingness to delegate authority, capacity for innovation, degree of customer orientation, spending on R&D, prevalence of foreign technology licensing

Table 4. Continued

BCI	**Business Environment Quality.** Presence of demanding regulatory standards, Internet and cellular phone usage, intellectual property protection, stringency of environment regulations, local supplier quality, property rights, quality of electricity supply, quality of public schools, business cost of corruption, buyer sophistication, effectiveness of antitrust policy, university/industry R&D collaboration, ease of access to loans, judicial independence, port infrastructure, quality of management schools, U.S. patents granted, transportation infrastructure, availability of scientists and engineers
Executive Opinion Survey	Administrative requirements(e.g., permits) issued by the government (1=burdensome,…,7=not burdensome) Hiring and firing of workers is (1=impeded by regulations,…,7=flexibly determined by employers) Competitiveness of companies in a country (1=low cost of local natural resources,…,7=unique products and processes) Buyer sophistication: Buyers in country (1=unsophisticated, choose lowest Price,…, 7=knowledgeable, buy based on superior performance) Customer orientation: Firms in your country (1 = generally treat their customers badly, …, 7 = are highly responsive to customers and customer retention)

Some attributes of a country (e.g., sound fiscal and monetary policies, a trusted and efficient legal system, a stable set of democratic institutions) contribute to a healthy economy, providing the opportunity to create wealth; but, they do not create wealth. Rather, wealth is created at the micro-economic level, based on the sophistication of the operating practices and strategies of companies and the quality of the microeconomic business environments in which international enterprises are sited.

Table 5 gives GCI rankings of selected countries for each of the past seven years. The GCI is not determined by GDP or population, even though a larger GDP and/or population could indicate an attractive market. The GCR outlines the methodology it employs in the rating and ranking of countries but does not give a detailed description of it (Oral and Chabchoub, 1997).

Table 5. GCI rankings of selected countries (GCR 2001, 2002, 2003, 2004, 2005, 2006 Reports)

Region	Countries	GDP (US$B, 05)	Population (M, 06)	2000	2001	2002	2003	2004	2005	2006
NAFTA	The U.S.	12485.7	298.2	5	2	1	2	2	1	6
	Canada	1130.2	323.3	6	3	8	16	15	13	16
	Mexico	768.4	107.0	42	42	45	47	48	59	58
CAFTA-DR	Costa Rica	19.8	4.3	37	35	43	51	50	56	53
	El Salvador	16.9	6.9	49	58	57	48	53	60	61
	Guatemala	27.4	12.6	N/A	66	70	89	80	95	75
	Honduras	8.3	7.2	N/A	70	76	94	97	97	93
	Nicaragua	5.0	5.5	N/A	73	75	90	95	96	95
	Dominican Republic	29.2	8.9	N/A	50	52	62	72	91	83
Growing Economy	China	2224.8	1315.8	40	39	33	44	46	48	54
	India	1103.4	1103.4	48	57	48	56	55	45	43
EU	Denmark	259.7	5.4	14	14	10	4	5	3	4
	Finland	193.5	5.2	6	1	2	1	1	2	2
	France	2105.9	60.5	22	20	30	26	27	12	18
	Germany	2797.3	82.7	15	17	14	13	13	6	8
	Italy	1766.2	58.1	30	26	39	41	47	38	42
	Sweden	358.8	9	13	9	5	3	3	7	3
	United Kingdom	2201.5	59.7	9	12	11	15	11	9	10
Others	Switzerland	367.5	7.3	10	15	6	7	8	4	1
	Japan	4571.3	128.1	21	21	13	11	9	10	7

The U.S. enjoys an excellent business environment, provides efficient markets, and is a global center for technology development. However, its overall competitiveness is threatened by large macro-economic imbalances related to rising levels of indebtedness. The GCI of Mexico shows relatively high scores for health, primary education, market efficiency and selected components of technological readiness (e.g., FDI and technology transfer). China’s rapid growth rates, coupled with low inflation, one of the highest savings rates in the world, and manageable levels of public debt, have boosted its GCI (macro-economic) ranking to 6th place. However, a number of structural weaknesses within the nation must be addressed, including the largely state-controlled banking sector, low penetration rates for the latest technologies (e.g., mobile telephones, Internet, personal computers), secondary and tertiary school enrollment rates, and the quality of both public and private institutional environments (World Economic Forum, 2006).

5.2. The WCY

Published annually, two thirds of WCY is based on statistical data from national and international sources; and one third, on opinions obtained by surveys of over 3000 respondents (IMD, 2008). WCY evaluated the competitiveness of 61 national and regional economies in 2006 based on some 300 indicators (IMD, 2006) and 55 economies in 2008 (IMD, 2008). One objective of WCY is to provide all of the information necessary to determine the *comparative advantage*s of selected countries. (The IMD still uses the term, *comparative advantage*, but the WEF uses only *competitive advantage* and *competitiveness*, perhaps because Porter, who advocates the theory of competitive advantage, is one of the major contributors to the GCR). Globalization has created the opportunity for an enterprise to locate assets strategically to enhance its competitiveness (IMD, 2006).

Table 6 itemizes the four major factors of competitiveness used by WCY. The factors of labor, capital, and land that measure the comparative advantage of a nation are included in the business efficiency and infrastructure factors.

Table 6. Competitiveness indicators of the WCY

Categories	Description	No. of Indicators
Economic Performance	Macro-economic evaluation of the domestic economy	77
Government Efficiency	Extent to which government policies are conducive to competitiveness	73
Business Efficiency	Extent to which enterprises are performing in an innovative, profitable and responsible manner	69
Infrastructure	Extent to which basic, technological, scientific and human resources meet the needs of business	95

Table 7 presents WCY competitiveness rankings of selected countries over each of the last five years, showing how national competitiveness evolves. Four rows of rankings are given for each country; the methodology used to determine has been revised frequently so that each row resulted from a unique methodology. As an example related to several specific countries, Table 8 details the WCY 2006 evaluation of NAFTA countries. An enterprise can use such evaluations to identify countries that offer the factors it considers most important.

Table 7. WCY rankings of selected countries (IMD 2002, 2003, 2004, 2005, 2006 reports)

Region	Countries	1998	1999	2000	2001	2002	2003	2004	2005	2006
NAFTA	The U.S.	1	1 1	1 1 1	1 1 1	1 1 1 1	1 1 1	1 1	1	1
	Canada	8	10 2	8 2 8	9 2 9	8 2 7 7	3 6 6	3 4	5	7
	Mexico	34	35 14	33 14 33	36 15 36	41 19 43 43	24 53 53	56 56	56	56
Growing Economy	China	21	29 11	30 11 24	33 12 26	31 12 28 28	12 29 29	24 24	31	19
	India	38	42 19	39 18 41	41 19 42	42 17 41 41	20 50 50	34 34	39	29

Table 7. Continued

Region	Countries	1998	1999	2000	2001	2002	2003	2004	2005	2006
EU	Denmark	10	9 7	13 10 6	15 10 5	6 4 3 6	3 3 5	8 7	7	5
	Finland	6	5 5	4 3 6	3 4 5	2 2 3 3	1 3 3	3 8	8 6	10
	France	22	23 8	22 7 22	25 8 25	22 9 22 25	8 23 23	30 30	30	35
	Germany	15	12 4	11 4 13	12 4 13	15 4 17 5	5 20 6	21 4	23	22
	Italy	31	30 13	32 16 32	32 13 33	32 14 34 26	17 41 39	51 39	37	50
	Sweden	16	14 9	14 7 14	8 7 11	11 7 12 20	7 12 18	11 25	30	28
	United Kingdom	13	19 6	16 5 15	19 6 17	16 5 16 6	7 19 9	22 14	14	8
Others	Switzerland	9	7 4	7 4 7	10 6 8	7 3 5 5	5 9 9	14 14	8	8
	Japan	20	24 10	24 10 21	26 9 23	30 11 27 27	11 25 25	23 23	21	17
CAFTA-DR	* WCY does not provide data for Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Dominican Republic									

Table 8. WCY overview of competitiveness of selected countries (IMD, 2006)

Country	Strong Indicators	Weak Indicators
Canada	**Economic performance** Long-term unemployment Terms of trade index Direct investment flows inwards US$ **Government Efficiency** Start-up days, consumption tax rate Ease of doing business, the public service	**Economic performance** Exports of commercial services Real GDP growth per capita, tourism receipts Relocation of production **Government Efficiency** Corporate tax rate on profit, exchange rate stability and policy Effective personal income tax rate, real corporate taxes

Table 8. Continued

Country	Strong Indicators	Weak Indicators
Canada	**Business efficiency** Ethical practices, the national culture, stock market The image of abroad of your country Labor force **Infrastructure** Higher education achievement Human development index Electricity costs for industrial client	**Business efficiency** Compensation levels, remuneration in services professions Stock market index, banking sector assets Working hours **Infrastructure** Investment in telecommunications Mobile telephone subscribers, secondary education Patent productivity, high-tech exports
Mexico	**Economic performance** Long-term unemployment, youth unemployment Unemployment rate, cost-of-living index Direct investment flows inwards US$ **Government Efficiency** Total general government debt Consumption tax rate Employee's social security contribution rate **Business efficiency** Working hours, remuneration in services professions Compensation levels, stock market index Large corporations **Infrastructure** Mobile telephone, high-tech exports US$ Internet costs, computers in use	**Economic performance** Portfolio investment assets, exports of commercial services Resilience of the economy to economic cycles Relocation of production, GDP per capita **Government Efficiency** Parallel (black-market, unrecorded) economy, creation of firm Political parties, regulation intensity Personal security and private property **Business efficiency** Banking and financial services, banking sector assets Small and mid-size enterprises Adaptability of companies to market changes **Infrastructure** Dependency ration, total expenditure on R&D International telephone costs, pupil-teacher ration
U.S.	**Economic performance** Portfolio investment liabilities Direct investment stock inward and abroad Exports of commercial services US$ **Government Efficiency** Start-up days, ease of doing business Unemployment legislation, creation of firm Labor regulation (hiring/firing practices, etc) **Business efficiency** Venture capital, foreign high-skilled people Value of society, value traded on stock markets US$ Overall productivity **Infrastructure** Computers in use, high-tech exports Total health expenditure, computers per capita, Mobile telephone costs	**Economic performance** Trade to GDP ratio, exports of goods, tourism receipts Exports of commercial services Terms of trade index **Government Efficiency** Management of public finance Corporate tax rate on profit, subsidies Immigration laws, social cohesion **Business efficiency** Stock market index, remuneration in services professions Compensation levels Unit labor costs in the manufacturing sector **Infrastructure** Investment in telecommunications, health problems Youth interest in science Language skills, mobile telephone subscribers

5.3 Comparison of GCR and WCY

Table 9 highlights differences between the GCR and WCY. The WCY employs more statistical data than the GCR but covers only about half as many countries. The competitiveness indicators given by both reports include the factors of labor, capital, and land, which determine the comparative advantage of a nation. However, neither deals with natural resources, which are no longer considered to be an important determinant of the competitiveness of a nation. While the GCR and WCY both employ some of the same indicators, each deals with additional, unique indicators and uses unique measurement methodologies, so that the competitiveness indicators they report are complementary. Thus, an enterprise might use both reports as inputs to strategic planning models.

Table 9. Comparison of WCY and GCR

Categories	Global Competitiveness Report (World Economic Forum, 2008)	World Competitiveness Yearbook (IMD, 2008)
Initial Publication	1979	1989
Economies covered	134	55 (used to include 6 economic regions)
Proportion of Survey	2/3, Opinion Data 1/3, Hard Statistical Data	1/3, Opinion Data 2/3, Hard Statistical Data
Number Surveyed	12,297 respondents, 134 countries	3,960 executives, 55 countries
Major Indicators	12 Pillars, 148 indicators	4 major factors, 20, sub-factors 331 indicators
Published by	WEF	IMD

5.4 Issues related to competitiveness reports

Several misunderstandings concerning the relationship between competitiveness and the economic growth of a nation have been identified. First, competitiveness is not necessarily an indicator of national wealth, even though wealth can be the result of past competitiveness (IMD, 2005). A nation can be wealthy without being competitive; for example, wealth can result from the availability of natural resources (e.g., oil for Middle East countries, natural resources for Canada). Second, competitiveness is not necessarily an indicator of economic performance, which results from value added over the short-term and is commonly expressed as GDP growth (IMD, 2005). However, analysis of some reports (e.g., BCI, Economic Freedom) leads to the conclusion that their composite indices are positively correlated with GDP (or GDP growth) (Ketels, 2006; World Economic Forum, 2006). For example, measures of economic freedom are positively correlated with the GDP growth rate and level of per-capita GDP of a given country, creating a virtuous cycle that triggers further improvements in economic freedom (Fraser Institute, 2008; Heritage Foundation, 2009). Although there is some controversy about whether competitiveness results in GDP growth (Ochel and Rohn, 2006), Ezeala-Harrion (2005) proposed a two-way causal relationship between levels of a nation's competitiveness and economic (i.e., GDP) growth: competitiveness facilitates economic growth, which, in turn, enhances competitiveness.

Some would caution against relying upon survey data instead of quantitative, statistical indicators. Survey data could reflect national biases of respondents, overall changes in national business sentiment unrelated to underlying competitiveness, or very different assumptions in different countries about relevant international benchmarks. However, after editing and processing raw survey data, it has been shown that it is robust and consistent with national competitiveness (Ketels, 2006, World Economic Forum, 2008).

Competitiveness reports can rank nations differently, contradicting each other because each uses a single composite index that is based on its unique purpose and criteria and because there is no unified theoretical basis that is common to all of them (Ochel and Rohn, 2006). The composite index given by each report is calculated by assigning weights to individual indicators, standardizing, and summing them. We do not advocate incorporating composite indices in OR/MS models used to support strategic planning; rather, a subset of (individual) indicators selected for relevancy to a particular industry could potentially provide meaningful support for strategic planning.

In addition, the ranking of one country might change over time, introducing uncertainty regarding its comparative advantages and competitiveness. Volkswagen's unsuccessful acquisition of Spanish car maker SEAT is a dramatic example of the potential for improving strategic planning through using the theories of international economics. As Brandt stated (1993), Volkswagen aimed to profit from the comparative advantage that Spain offered relative to labor cost in the late 1980s and early 1990s. However, the acquisition turned out to be unsuccessful when Eastern Europe became competitive with Spain's labor-cost advantage (e.g., in 2001, monthly wages in the Czech Republic were 21 percent lower than in Spain) (Pampillon, 2005). Thus, Spain lost its comparative advantage over time. Since strategic planning may fix a supply chain and the locations of its facilities for a relatively long time, it is important to base them on long-range forecasts of competitiveness indicators.

Overall, the focus of our research is not to propose methodologies to evaluate report quality, to validate competitiveness reports, or to compare various reports. Instead, **the thesis of this research** is to advocate the study of individual competitiveness indicators to determine which ones are closely related to the success of a particular industry and then to incorporate them in OR/MS models used to support the strategic planning process. We note that annual competitiveness reports provide access to data, but are not tools in and of themselves.

CHAPTER VI

RELATIONSHIP OF COMPARATIVE ADVANTAGE AND COMPETITIVENESS TO STRATEGIC PLANNING*

This chapter describes how comparative advantage and competitiveness might be used to explain strategic planning made in the past. While there are no reports that such strategic planning was supported by OR/MS models that incorporated these theories, the examples in the chapter are offered **to support the thesis** of this research. One example (Section 6.1) is the shift in trade partners that the U.S. has made over the last decade as it has increased trade with China. The second example (Section 6.2) involves the relationship of competitiveness indicators to location selection in the automotive industry, showing a correlation that reflects the success of an international enterprise. The third example (Section 6.3) comprises a study that shows how competitiveness indicators can be employed, in practice, to analyze the performance of the logistics system that constitutes an integral part of a supply chain. The last example (Section 6.4) shows that competitiveness indicators can be used to explain clustering in the automobile industry.

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6.1 Shift of trade partner over time

Rosen (2003) described the evolution of the RCA ratios of China and Mexico over the past decade as the comparative advantage related to low labor cost has changed in China's favor. He argued that, even though overall trade between the U.S. and China has grown significantly, certain industries still rely upon the comparative advantages of Mexico afforded by NAFTA. Several researchers have described a shift of trade from NAFTA countries to other emerging economies. Mexico is generally regarded as one of the developing countries most affected by Chinese competition (Lall and Weiss, 2005). China has overtaken Mexico as the second largest source of U.S. imports. China was able to gain initial inroads, attracting labor-intensive and low-technology industries with the comparative advantage bestowed by low-cost labor, but its share of high-technology exports has increased significantly since 1990, suggesting that it is now competitive over a range of industries.

Latin American export sectors, with which China has competed for some time, include not only the well-known cases of relatively labor-intensive industries (e.g., clothing, textiles, leather, footwear, and furniture) but also capital-intensive ones (e.g., iron, steel, and aluminum) (Lall and Weiss, 2005; Jenkins *et al*., 2006). In particular, the textile and apparel sectors have caused the most concern to CAFTA-DR countries (e.g., Dominican Republic, El Salvador, Honduras, Nicaragua, and Guatemala), which are most threaten by China's increasing exports of textiles and apparel. Even though the new CAFTA-DR agreement provides some hope for member countries, the benefits it offers will not likely to be sufficient to offset the comparative advantage that China currently enjoy (Condo, 2004). The shift in trade partners that the U.S. has made over the last decade as it has increased trade with China can be explained by the theory of comparative advantage.

6.2 Location selection in the automotive industry

We explore factors typically used by the automobile industry to select locations and how past decisions can be explained by competitiveness indicators. Woodward (1992) analyzed Japanese-affiliated manufacturing locations in the U.S., using a regression analysis based on the 1980s industrial location literature; it employed several independent variables (local markets, unionization, taxation, state industrial promotion, availability manufacturing clustering, population density, interstate connections, wage rates, productivity, educational attainment, poverty rate), concluding that locations with strong markets and low unionization rates have been preferred for automotive manufacturing facilities. Most of these independent variables correspond to the indicators published in annual competitiveness reports.

Kim (2005) identified 16 indicators and showed they can explain the selection of manufacturing sites in the automobile industry. Moon (2005) employed Porter's Diamond Model to analyze locations selected by foreign automobile companies for manufacturing facilities in China. Table 10 relates the 16 factors used by Kim and the four factors used by Moon to explain location selections. Moon's Diamond model analysis led to the conclusion that Shanghai is the location that would allow an automobile company to be most competitive because of the automotive-industry cluster that has coalesced there. The indicators that Kim and Moon used correspond to those employed to determine comparative advantage, competitive advantage, and national competitiveness.

Table 10. Indicators important to location selection in the automobile industry

Author	Indicators Considered by Kim(16) and Moon(4)
Kim (2005)	Low labor cost, Availability of labor, Good labor relations/low unionization rate Availability of capital/low interest rate, Low transportation cost of input Low transportation cost of output, Transportation facilities (highways, airports) Good infrastructure (utility, communication), Proximity to assemblers/markets Land availability and cost, Availability of warehousing, Availability of business services Proximity to other parts manufacturers, Amenities (cultural and climatic) Local government incentives, Proximity to owner's residence
Moon (2005)	**Factor conditions** Labor cost: average wage of staff and workers in manufacturing sector Land cost: average selling price of houses for business use Resource quantity: output of steel Labor quality: number of institutions of higher education with science & engineering majors **Demand conditions** Demand quantity: total population Demand quality for a car: gross domestic product by region Demand quality for a car: per capita annual disposable income Demand quality for a car: number of private-owned passenger vehicles **Related & supporting industries** Total annual volume of water supply Length of paved roads Volume of freight handled in nearby ports Number of enterprises in heavy industry Average corporate tax rate **Strategy, structure & rivalry** Ratio of foreign-funded firms versus local firms (Equal administrative treatment) Amount of actually used foreign direct and other investment Number of firms

Some studies (Woodward, 1992; Kim, 2005) have formulated regression models and shown that past location decision in the automotive industry can be related to individual indicators, associated with comparative advantages, competitive advantages, competitiveness of the countries in which the enterprises are sited. In addition, regression analysis has led to the conclusion that some independent variables, which correspond to competitiveness indicators, are statistically significant. Thus, a positive correlation exists between individual competitiveness indicators of a nation and the success of an international enterprise sited in it. Some studies (Moon, 2005; Jin and Moon 2006) have shown that Porter's Diamond model, with minor modification, can be used in the strategic location selection process. The Diamond Model and FDI analysis can be combined to potentially enhance strategic models.

6.3 Logistics systems

We now discuss studies that have pioneered the use of competitiveness reports in analyzing the logistics system of a nation, which is important to location selection. Management of an international enterprise would prefer to locate a distribution center in a nation with advanced logistics systems. Bookbinder and Tan (2003) compared the logistics systems of Asia and Europe by employing a subset of the competitiveness indicators reported by the WCY. They used six factors (infrastructure, human resources, business environment, performance, information technology, and political environment), forming three tiers of categories that ranked logistics performance relative to 20 indicators. They analyzed selected indicators statistically, showing how a nation might plan investments to enhance its logistics system so that it can attract international enterprises.

Bhatnagar and Sohal (2005) proposed a framework that measured the performance of a supply chain that is impacted by (both quantitative and qualitative) location factors, uncertainty (e.g., supply, process, and demand uncertainty), and manufacturing practices (e.g., preventive maintenance, quality systems audit, total quality management, just-in-time). Even though existing literature on supply chain design tends to emphasize quantitative factors (e.g., e.g., transportation costs, exchange rates, labor costs, and taxes), they concluded through a regression analysis that a significant relationship exits between independent variables representing qualitative factors (e.g., labor (education and skill level, impact of union), government, infrastructure, business environment, proximity to markets, proximity to suppliers, and locations of key competitors) and the competitiveness of the supply chains within a nation as measured by quality, flexibility, inventory turnover and responsiveness. Such qualitative factors are readily available in the GCR and WCY competitiveness reports.

6.4 Clustering in the automobile industry

Clustering is commonly used in selecting a location. A cluster is a geographic grouping (in a nation or, perhaps, in a single town) of companies, suppliers, service providers, and associated institutions in a particular field (World Economic Forum, 2006). Clusters (e.g., consumer electronics in Japan or high-performance cars in Germany) form to exploit specialized knowledge, skills, infrastructure, and supporting industries.

Clustering affects competitiveness in three broad ways: by increasing the productivity of participating companies; by driving the direction and pace of innovation, hence, productivity growth; and by stimulating the formation of new businesses, expanding and strengthening the cluster (Porter, 1998a). Steinle and Schiele (2008) argued that firms can derive competitive advantages from their relationships to either horizontal alliance partners or vertical supply partners by clustering. For example, if an apparel firm is located where apparel subcontractors and related industries are geographically concentrated, the firm could produce faster and at lower costs using locally available resources than a firm located at a distance from the cluster. As a result, each individual company becomes competitive and the area collectively creates more profit (Jin, 2004).

The locations of automobile assembly facilities and suppliers along the U.S.-Mexico border and across Southern U.S states give good examples of clustering. While the automobile industry in the U.S. has been shrinking, it has been expanding in Mexico, where low-cost labor is readily available. According to a recent news release (Roig-Franzia, 2008), Ford plans to invest $3 billion to upgrade two existing plants in Mexico City, where it will build a new, fuel-efficient car. Mexico is a growing market for passenger cars. A large number of automobile suppliers are operating in Mexico close to the U.S. border, exploiting the country's comparative advantage of low labor costs (Phillips *et al*., 2004). Matson and Matson (2007) have also identified an automotive cluster in the southern U.S. (i.e., Tennessee and Alabama). Sigurdson (2004) have presented another good example of regional clusters for the automotive industry in three regions of China: BoHai Rim, Yantze River Delta, and Pearl River Delta Region. This type of automotive clustering can be explained using Porter's Diamond Model and related competitiveness indicators.

While Porter's Diamond model emphasizes clustering, some international enterprises may place less emphasis on regional concentration for certain types of facilities, depending on the competitiveness indicators associated with potential facility locations and its strategy for integration. Thus, enterprises in some industries have started to site facilities in disperse geographical locations. For example, some international enterprises disperse locations in diverse countries to protect their intellectual property such as proprietary designs and information. Such strategies can reduce the risk of intellectual property theft by dispersing R&D, production, and assembly activities in several countries (Gupta and Wang, 2007). The extent to which a nation protects intellectual property rights is an especially important factor in locating security-sensitive R&D facilities. Thus, after considering several competitiveness indicators that measure intellectual property protection (World Economic Forum, 2006) and the work force – be it composed of inexpensive, unskilled workers or highly trained scientists or engineers - an enterprise can decide whether to cluster or disperse R&D, production, and assembly facilities.

Overall, the last few decades have seen the simultaneous rise of both globalization and regionalization of industry activity, and many now seem to believe that the two trends may be complementary rather than contradictory modes of industrial and geographical organization (Kim, 2005). Thus, the quantity and quality of local suppliers, local competition, and advances in transportation and communication technologies, intellectual property protection, and work force are quantified by competitiveness indicators, which annual competitiveness reports make readily available. Such indicators can be incorporated in OR/MS models to prescribe decisions regarding clustering or dispersing.

CHAPTER VII

INCORPORATING COMPETITIVENESS INDICATORS TO ENHANCE STRATEGIC PLANNING*

Prior OR/MS models that prescribe strategic plans (i.e., global supply chain design or facility location) have not explicitly incorporated the theories of international economics. This chapter presents an example of how competitiveness indicators, taken from annual competitiveness reports, might have a strong influence on the success of an international enterprise, how relevant individual indicators can be identified, and how they might be included in the form of constraints, parameters, or decision variables in global supply chain design models. We illustrate the link between the strategic design of global supply chains and theories of international economics using an example.

Wilhelm *et al*. (2005) proposed a MIP to prescribe an optimal international production-assembly-distribution system with the objective of maximizing after-tax profits, focusing on the NAFTA business environment. The model addresses a wide variety set of issues related to international supply chain design in general as well as those related to the NAFTA environment in particular. This strategic planning model can potentially be enhanced to support planning by incorporating competitiveness indicators (see Table 4) as we now discuss.

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Cost parameters can be redefined to reflect economics theories, for example, employing competitiveness indicators. The average hourly wage might not be the sole determinant of overall labor cost. The flexibility of hiring or firing an individual worker, flexibility of wage determination, strength of labor unions, labor-employer relations, productivity, and availability of scientists and engineers - all may be important constituents of labor cost and can be based on competitiveness indicators.

Transportation costs and capacities are typically based on existing transportation infrastructures and government plans to expand them. However, several additional competitive indicators could be incorporated in these parameters to represent delays at border crossings due to security screening as well as expedited border crossings due to advanced information technology, which may also affect costs by reducing pilferage.

The taxes and duties that international enterprises must remit to foreign countries depend not only on publicly announced rates but also on other factors related to government policies and regulations. Some quantitative and qualitative competitiveness indicators that could be incorporated include incentives for FDI, efficiency of government bureaucracy, prevalence of trade barriers, and degree of protectionism.

Wilhelm *et al*. (2005) reported a what-if analysis to demonstrate how decision makers might apply their planning model as a decision support aid. One of their examples involves assessing centralized versus decentralized management. To address this issue, competitiveness indicators could be incorporated to incorporate relevant factors. For example, a well-developed communications and transportation infrastructure; an abundance of highly trained, skilled labor force; and a local government that affords intellectual property protection are favorable factors in deciding decentralized management.

Government policies that lead to inducements, regulations, trade barriers, foreign ownership restrictions, presence of demanding regulatory standards, government support of land usage, ease of remittance to home country, clarity and stability of regulations, and stringency of environmental regulations (see Table 4) significantly influence facility location. Such policies may give rise to additional constraints in the MIP to limit potential locations.

One important aspect of strategic planning is to locate distribution centers near customers. This decision is related not only to transportation cost and infrastructure, but also to the quantity and quality of demand (i.e., buyer sophistication and customer orientation; for details, see Table 4.). In part, the quantity of demand may be positively related to the current GDP and projected GDP growth of a nation. Demand for each product type may be also related to these quantity and quality indicators.

Considering that strategic planning must deal with a lengthy horizon (3-5 years or longer), competitiveness indicators could be forecast (see Fildes *et al*. (2008) for a recent review) and incorporated in OR/MS models that provide support for long-term decisions. Such models would prescribe plans for an enterprise to locate and *relocate* its plants in countries where evolving competitive advantages are associated most advantageously to its needs.

CHAPTER VIII

RESEARCH OPPORTUNITIES TO ENHANCE NAFTA LOGISTICS: SYNTHESIZING OPPORTUNITIES FOR COMPANIES AND SUPPLY CHAINS

This chapter comprises 6 sections. Section 8.1 provides a background, summarizing trade relationships among NAFTA members as well as important global relationships. Section 8.2 focuses on research that has enhanced global supply chain networks in general as well as specific ones utilized for NAFTA trade. In addition, this section suggests research opportunities by relating examples of the Mixed Integer Programming (MIP) models that have been formulated to prescribe supply chains under NAFTA. Sections 8.3–8.6 form a vision of research needs relative to five different arenas. Section 8.3 discusses opportunities to enhance NAFTA trade through dealing with national and international political issues and uncertainties, education and training, infrastructure expansion, information technology, and security. Section 8.4 describes research needs related to enhancing transportation infrastructure, focusing on NAFTA trade corridors. Section 8.5 discusses research that will allow enterprises to exploit the proximity of NAFTA member countries in implementing Generalized just-in-time (JIT). Section 8.6 describes crucial needs in agriculture, an industry that has received very little attention from the OR/MS community.

8.1 Background

The Maquiladora Program, initially called the Border Industrialization Program, began in 1965 to foster trade between the U.S. and Mexico. Comprised of low-cost, labor-intensive assembly plants that employed unskilled labor, it allowed U.S. companies to temporarily export parts, machinery, and equipment necessary to produce goods in Mexico (Vargas, 1998a, 1998b, 2000; Canas and Coronado, 2002). If the manufactured products were imported back into the U.S., the shipments into Mexico incurred no tariffs and the U.S. taxed only the value-added portion of the manufactured output, stimulating job growth in the Maquiladora but not encouraging development of suppliers in Mexico. The Maquiladora industry employs 10% of Mexico's employees - 1.2 million workers as of 2006 – and its exports represent almost 50% of Mexico's exports (Canas, 2006).

Initiated in 1994, NAFTA has allowed trade and investment flows in North America to increase dramatically. Total trade among the three NAFTA member countries has more than tripled, passing from $297 billion in 1993 to almost $930 billion in 2007 (Office of the U.S. Trade Representative, 2008). From 1993 to 2003, U.S. exports to Canada (Mexico) grew from $87.8 ($46.5) to $145.3 ($105.4) billion. About 88% of Mexico's exports go to the U.S., and 56% of its imports come from U.S. sources. The U.S. is Mexico's top trading partner and, at the same time, 14% of U.S. exports go to Mexico and 11% of its imports come from Mexico (Canas *et al.*, 2006). By 2004, about 82% of Canadian exports or about 33% of Canadian GDP was exported to the U.S (Baggs and Brander, 2006).

From 1994 to 2004, Mexican exports to Canada grew from $2.7 billion to $8.7 billion, an increase of almost 227%. The value of Canada's exports to its NAFTA partners increased by 104% for the ten years that followed NAFTA's implementation

(Office of the U.S. Trade Representative, 2008). U.S. employment rose 20.1% from 112.2 million in December 1993 to 134.8 million in February 2006, an increase of 22.6 million jobs. The average unemployment rate was 7.1% during the period 1982-1993 compared to 5.1% in the period 1994-2005 (Office of the U.S. Trade Representative, 2008). In summary, NAFTA has created the world's largest free trade area, connecting 439 million people who produce $15.3 trillion worth of goods and services annually. The removing of trade barriers and the opening of markets has led to economic growth and increasing prosperity in all three countries.

This research focuses on trade under NAFTA but it is difficult – and probably not desirable – to divorce it from the global economy in general and from trade under CAFTA-DR and bilateral agreements that have been instituted recently. For that reason, we briefly mention trends in these other arenas as well. With the rapid growth of the economies of China and India, Asia is becoming a highly attractive region for world investment. In 2003, more than 60% of the foreign direct investment (FDI) directed to developing nations went to Asia with China attracting more than half of that amount. In comparison, Latin American nations received 34.5% of the FDI that went to the developing world (IMD, 2004). In 2003, China exported more goods to the U.S. than Mexico for the first time. China and India are currently drawing a large portion of the FDI to which Mexico aspires.

The U.S. has pursued regional and bilateral FTAs with Central and South American countries. Implemented in 2005, CAFTA-DR encompasses the U.S., Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua, and the Dominican Republic.

The Wall Street Journal (O'Grady, 2007) reports that member countries have started to reap the benefits of CAFTA-DR with total trade growing in the region. The U.S. recently entered into bilateral FTAs with Jordan (2000), Singapore (2003), Chile (2004), Australia (2005), Morocco (2006), and Bahrain (2006). The U.S. completed negotiations for bilateral agreements with Colombia, Panama, and Korea and they are currently awaiting congressional approval (Office of the U.S. Trade Representative, 2008). Thus, the global business environment is continuously evolving, as nations and international enterprises jockey to reap benefits from regional and bilateral trade.

The business environment created by NAFTA involves important, unique issues (e.g., NAFTA terms, supplier locations, proximity, transportation, infrastructure, education and training, warehousing, distribution) as well as issues that are common to all international operations (e.g., local-content rules, border-crossing costs, transfer prices, income taxes, exchange rates) albeit with parameter values that depend upon NAFTA terms and country-specific laws. In particular, the unique issues lead to new opportunities for designing and operating supply chains and associated transportation systems, requiring new models and new model structures. For example, new networks of suppliers must be selected and integrated supply chains designed; the clustering of facilities in a particular industry has not been addressed by traditional facility location models; transportation corridors must be planned, especially to support North-South transport, and alternative means evaluated for financing them; models are needed to design new inland ports and to make existing ports more competitive; new methods are needed to achieve Generalized Just in Time to exploit proximity; and new approaches are needed to address the risks involved in agriculture, which represents a significant portion of trade under NAFTA.

Trade among NAFTA member countries is subject to a number of uncertainties over the next 20 years. For example, if the Panama Canal were expanded (as planned) to accommodate a new generation of larger container ships, how would the comparative advantages of NAFTA-member countries change? How will the implementation of CAFTA-DR and other bilateral FTAs affect the relative comparative advantages of NAFTA member countries? Will the political environments in South American countries allow a broader trade block to complement NAFTA, altering comparative advantages? China's comparative advantage of low labor cost has made it a global competitor but will it be successful in evolving more high-technology advantages in the future?

The Workshop on Enhancing NAFTA Logistics: Synthesizing Opportunities for Companies and their Supply Chains was held in Waterloo, Ontario, Canada on June 5-6, 2007, under the sponsorship of the Canadian Social Sciences and Humanities Research Council. Focusing on the OR/MS disciplines, the primary goal of the Workshop was to identify the research needed to enhance trade and the profitability of international enterprises under NAFTA. Researchers from academia, practitioners from industry, and individuals from governments participated, representing all three NAFTA member countries. A number of essential research needs were identified by Workshop participants and this research includes them along with others.

8.2 Previous research on international supply chain design

Since supply chain issues are related to most topics discussed in this research, we emphasize the importance of supply chain research and present associated research needs in brief. While a number of studies have addressed international supply chain design, few have focused on issues relevant to the NAFTA environment.

Several papers (Sarmiento and Nagi, 1999; Guenes and Pardalos, 2003; Vidal and Goetshalckx, 1997; Goetschalckx *et al*., 2002) and books (Simchi-Levi and Bramel, 1997; Simchi-Levi *et al*., 1999; Tayur *et al.*, 1999) describe the state-of-the-art relative to designing international production/distribution (P/D) systems. A substantial literature has addressed strategic decisions (Bitran and Tirupati, 1993; Goetschalckx *et al*., 1996); but, typically, each paper addresses just a subset of relevant factors, for example, P/D (Erenguc *et al*., 1999; Schmidt and Wilhelm, 2000), locating facilities and warehouses (Kouvelis *et al*., 2004; Owen and Daskin, 1998; Revelle and Laporte, 1996; Verter and Dincer, 1995), global sourcing (Vidal and Goetschalckx, 2002), and capacity expansion (Verter and Dincer, 1995, 1992).

Most studies have formulated (deterministic) MIPs. Some papers extend models of limited domestic P/D issues to the global environment (e.g., Bartmess and Cerny, 1993; Kouvelis and Rosenblatt, 1997). MIPs have been formulated to prescribe production, distribution, and investment decisions (Bhutta *et al*., 2003); to design global logistics networks in light of governmental inducements to attract international trade (e.g., taxation, subsidized financing, and local content rules) (Kouvelis and Rosenblatt, 1997); to coordinate procurement, manufacturing, and distribution in global supply chains (Cohen *et al*., 1989); and to investigate the sensitivity of a supply chain to exchange rates and supplier reliability (Vidal and Goetschlackx, 2002). In particular, Cohen *et al*. (1989) addressed financial considerations such as transfer prices and exchange rates. Vidal and Goetschalckx (2002) classified relevant factors as those that can be modeled accurately, those that can be modeled adequately by invoking assumptions, and those that are very difficult to model. The factors that can be modeled accurately include Bill of Material (BOM) constraints; capacities of suppliers, production facilities, transportation channels; and conservation of product flows. Factors that can be modeled adequately by invoking assumptions include customer demand satisfaction, which requires the assumption that demand is deterministic. Factors that are difficult to model include variations of tax and currency-exchange rates, and stochastic lead times and demands. Vidal and Goetschalckx (2001) addressed transfer prices and transportation charges, leading to a non-convex model for which they devised a heuristic.

A number of studies have addressed the interfaces between strategic and tactical decisions in global supply chains (Goetschalckx *et al*., 2002; Vidal and Goetschalckx, 2002) and several others have dealt with material flow control (Cohen and Moon, 1991; Erenguc *et al*., 1999), especially in P/D (Beamon, 1998; Mohamed, 1999; Vidal and Goetschalckx, 2001). Talluri and Baker (2002) proposed an approach in which they designed the supply chain network first and then specified tactical and operational decisions subsequently.

Other studies have addressed uncertainty explicitly in global supply chain design.

Again, the typical study has addressed a limited number of practical considerations, such as facility location (Hodder and Dincer, 1986; Hodder and Jucker, 1985) or exchange rates (Hodder and Jucker, 1985). However, several studies have addressed broader sets of issues (Alonso-Ayuso *et al*., 2003; Huchzermeier, 1991; Santoso *et al*., 2005), making some progress in dealing quantitatively with uncertainty. However, stochastic programming capabilities are still evolving to deal with large-scale systems so that deterministic models remain an important focus.

Researchers have pointed out research needs in the international arena. Verter and Dincer (1992) recommended that, instead of dealing with isolated considerations, models should integrate decisions that determine location, technology selection, and capacity acquisition. Vidal and Goetschalckx (1997) noted that research is needed on MIP models for the strategic design of global supply chain systems, arguing that most models do not include sourcing, inventory costs, and BOM constraints. They also noted that most research addresses a single component of the overall P/D system, such as purchasing, production, inventory, warehousing or transportation; thus they pointed out that research is required to address the integration of such individual components into the overall supply chain. More comprehensive global supply chain models that include BOM constraints and qualitative factors that are important in the global environment remain for future research to address.

Studying trade under NAFTA, Bookbinder and Fox (1998) dealt with designing intermodal routings in North America, presenting a method to prescribe the optimal intermodal routings for containerized transport from Canada to Mexico. They used a shortest path algorithm to calculate the route of least time and the route of minimum cost.

Most research relates to the design of generic international supply chains; few address NAFTA specifically. Wilhelm *et al*. (2005) provided decision support for the strategic design of a production-assembly-distribution system (i.e., supply chain). Their strategic design model, a MIP, holds the objective of maximizing after-tax profits. The MIP prescribes a set of facilities - including their locations, technologies, and capacities – and other strategic aspects of the supply chain, selecting suppliers; locating distribution centers; planning transportation modes; and allocating target levels for production, assembly, and distribution. It addresses typical international issues (e.g., local-content rules, border-crossing costs, transfer prices, income taxes, and exchange rates) as well as features that are unique to the NAFTA business environment (e.g., NAFTA terms, supplier location, proximity, transportation, warehousing). It incorporates design issues such as BOM restrictions as well as strategic aspects of transportation and distribution. The MIP deals with relevant financial considerations, prescribing transfer price and transportation-cost allocations, invoking safe harbor rules, modeling graduated income tax rates, and incorporating exchange rates. It prescribes inventory and backorder levels at each stage in the P/D process and integrates material flow through the entire supply chain (i.e., suppliers, production, assembly, distribution, transportation, customers). Finally, the paper gives examples to demonstrate how managers might use the model as a decision support aid.

A recent paper by Robinson and Bookbinder (2007) presents a MIP model to prescribe the optimal supply chain for Tectrol Inc., a Canadian manufacturer of power supplies. This paper shows how supply chain costs can be minimized using a real-world example based on the NAFTA environment in which lower Mexican wages may offset additional transportation costs and capital-intensive operations that are based in the U.S. or Canada. Their model minimizes total cost, while satisfying customer demand over a multi-period time horizon. It prescribes the optimal number and locations of manufacturing plants and distribution centers in North America under NAFTA terms. It also addresses transportation mode (i.e., rail or truck) selection in the supply chain context.

8.3 Enhancing NAFTA trade

This section discusses opportunities to enhance current NAFTA trade through research dealing with national and international political issues and uncertainties, education and training, infrastructure expansion, information technology, and security. We describe timely issues that can affect NAFTA trade either favorably or adversely. New OR/MS models are needed to deal with these topics.

Even though OR/MS models are not always used to deal with political issues, at least some could be analyzed, if not resolved, through research. For example, each government's evolving laws and regulations on the travel required for international trade (e.g., immigration laws and the requirement that U.S. citizens present their passports upon entry to the U.S.) may have a significant effect on NAFTA trade, affecting long-term strategic decisions of international enterprises. Investment is required to fuel infrastructure expansion, but it must be decided which party (e.g., local/federal government, industry, private investors) will fund development of ground transportation, coastal ports, inland ports, logistics parks, and free trade zones to facilitate NAFTA trade.

Labor, environmental, and safety standards under NAFTA have recently come to the forefront as important issues. NAFTA includes agreements on environmental and labor issues that emphasize cooperative efforts to resolve disputes between member countries. But, these agreements have not been enforced. During the recent U.S. presidential campaign, candidates have argued that strong labor, environmental, and safety provisions are needed under any FTA to protect workers as well as consumers. They emphasize that environmental standards should be enforced so that a company based in one country cannot gain an economic advantage by degrading the environment of another country. The OR/MS models that are used in strategic decision making should take these issues into account. By 2020, most container ports in North America will have to double or triple their capacities to meet the growing trade volume (Vickerman, 2006). At current productivity and growth levels, North American ports and their associated intermodal systems will be severely congested by 2020.

Ports and waterways that are currently under construction will both facilitate international trade in general and NAFTA trade in particular and bring rigorous competition to U.S. ports and transportation infrastructure. In September, 2007, a $5.2 billion project to expand the Panama Canal began and the project is expected to complete in 2014. The expansion will allow ships twice the size of those that can currently navigate the canal, drastically increasing the amount of goods that pass through it. Research is needed to identify how the comparative advantages of NAFTA-member countries will evolve after the canal expansion. Further, the expansion will affect the selection of transportation modes and the design of optimal routings in North American supply chains.

China is investing heavily in developing ports in Mexico to transport an unprecedented volume of containers into the U.S. Hutchinson Ports Holdings, a Chinese port operations firm, is investing millions to expand the ports that the company manages at Lazaro Cardenas and Manzanillo on Mexico's Pacific coast (Corsi, 2006). In addition, according to a recent news release, Mexico finalized a plan to develop Punta Colonet, Baja California over the next seven years as a west-coast Mexican port, an alternative to the U.S. ports in Los Angeles and Long Beach. Located about 150 miles south of Tijuana, Mexico, the projected port will serve as a destination for the 30 million containers headed to North America from China and Asia each year. The new port will provide competitive advantages by using less expensive Mexican labor and by operating at lower levels of congestion that will expedite transportation time, in comparison with American ports in Los Angeles and Long Beach (Corsi, 2008). The project, which will require some $9 billion in private capital to develop, will involve some 7,000 acres at Punta Colonet, an area about as large as the ports of Los Angeles and Long Beach combined. Hutchinson Ports Holdings of China is also planning to invest additional millions to develop facilities at the Punta Colonet port.

OR/MS research is needed to establish decision support tools for NAFTA logistics companies, including U.S. port operators, railroads, and trucking companies, so that they can optimize transportation after these new port capabilities are in place. Research is also needed to enhance U.S. port capabilities, making them more competitive. International enterprises need new models to select suppliers in Asia and optimally route shipments through ports so that transportation time and cost can be reduced.

The U.S. Congress recently approved several trade agreements (e.g., CAFTA-DR (2005), Australia FTA (2004), Chile FTA (2004), Singapore FTA (2003)) and others (e.g., Korea, Columbia, and Oman FTA) are currently awaiting approval. Countries that enter into FTAs with the U.S. may compete with NAFTA countries for certain U.S. markets.

Human resources are also important in North American trade under NAFTA. Hourly wages in India, China, and Mexico are $0.9, $0.67 and $2.75, respectively, so that Mexico no longer enjoys a comparative advantage relative to labor cost (U.S. Department of Labor, 2008). On the other hand, Mexico offers lower transportation cost and reduced transport time as competitive advantages. To effectively compete with other developing countries, Mexico will need to enhance the education and training of its labor forces. Evolving information technology (IT) can play a critical role in improving North American trade. Efficient and timely information flow utilizing high-speed internet and mobile telecommunications in supply chain management (SCM) is a key to the success of JIT production and to intermodal transportation.

From the perspective of Homeland Security, exploiting innovative IT and advanced technologies can reduce delay at border-crossings and enhance security at the same time. For example, using new IT systems and technologies, containerized goods from Asia can be moved to a SIP with minimum delay at a border crossing. Before departing Asia, shipments can be pre-screened and electronic notification can be sent in advance to Mexico and the U.S. Upon arrival of a shipment in Mexico, containers can pass through multiple X-ray and gamma ray screenings to identify containers that require further inspection. Container shipments can be tracked using intelligent transportation systems (ITS) that could include global positioning systems (GPS) and/or radiofrequency identification systems (RFID) and monitored by the ITS on their way to a SIP in the U. S (www.kcsmartport.com).

8.4 Transportation infrastructure for effective supply chain networking under NAFTA

In this section, we briefly review the recent rapid increase in international freight in North America. We also describe NAFTA trade corridors and their plans for expanding limited capacities to handle growing freight volumes. The need to prescribe plans to expand the transportation infrastructure to handle larger freight volumes gives rise to a number of OR/MS research opportunities. For example, OR/MS models should address how plans for expanding corridors and adding inland ports can be optimized and how these expansions will affect the optimal design of transportation routes and selection of transportation modes.

The volume of the freight moved by the U.S. transportation system has grown dramatically in recent decades and economists predict that U.S.-bound international containerized cargo will increase 350% by 2020 (www.nasco.com). Also, by 2020 total domestic and foreign U.S. freight traffic will increase 67%, general cargo freight will increase 113%, highway traffic will grow 73% to 19 billion tons, and rail traffic will grow 85% to 3.7 billion tons (Bingham, 2006). New and increased transportation capacity is required, particularly in urban areas where bottlenecks are most severe.

The implementation of NAFTA, the internationalization of supply chains, and the evolutions in transportation and information technologies have contributed to this increase in freight movement (Johnson and Sedor, 2004). According to the U.S. Department of Transportation's (USDOT) Bureau of Transportation Statistics, U.S. trade with Canada and Mexico has grown about 90% since NAFTA took effect. As a result, U.S. highway and rail networks, which were initially developed for the traditional east-west trade in the U.S., are now strained, especially at border crossings. In the future, trade with NAFTA and Latin American countries is expected to grow, along both east-west and north-south corridors throughout northern and southern regions. However, improvements in the U.S. transportation infrastructure have not kept up with the growth in freight exchanged between NAFTA member countries, Asia, and the EU. Research is needed to help North American countries deal with this growing trade volume by enhancing the efficiency of existing ports and ground transportation infrastructures and by planning necessary capacity expansions.

According to a recent article (The Wall Street Journal, 2008), rail companies are making large investments in their networks to add tracks, straighten curves, and expand tunnels for larger trains. Since 2000, railroad companies have spent $10 billion to expand tracks, build freight yards, and buy locomotives; they plan to invest $12 billion more to upgrade further. OR/MS models can be formulated to prescribe transportation modes to reduce transportation cost and time as well as to enhance the efficiency of congested coastal ports, roads, and rail systems. NAFTA trade corridors, combinations of highway and rail infrastructure in North America, have been a primary means for transporting ground freight. Following the implementation of NAFTA, special-interest coalitions have formed to promote specific trade corridors, to develop the infrastructures of these corridors, and to facilitate border crossing. These coalitions involve the private-sector, government (i.e., city, county, state) agencies, civil organizations, metropolitan areas, and rural communities. Figure 3 shows the five major trade corridors in North America: NASCO, CANAMEX, ROTCC, GREAT PLAINS, and CISCOR.

Figure 3: NAFTA corridors (Reprinted with permission of Warnock)

Founded in 1994, North America's Super Corridor Coalition (NASCO) is a nonprofit organization dedicated to increasing economic development while supporting multi-modal infrastructure improvements, technology / security innovations, and environmental initiatives and stimulating the dialogue between public and private sectors about critical, corridor-wide trade and transportation challenges (www.nascocorridor.com). The NASCO corridor is currently a primary trade and transportation infrastructure from Canada to Mexico; it includes the largest (Detroit, Michigan-Windsor, Canada) and second largest (Laredo, Texas-Nuevo Laredo, Mexico) border crossings in North America. The corridor also includes major intermodal inland ports and others under development.

The Canada America Mexico Corridor (CANAMEX) was established in 1995 to link Canada to Mexico through the U.S. Mountain States (www.canamex.org). The River of Trade Corridor Coalition (ROTCC) was created in 2004 to unite cities, counties, transportation authorities, freight movement entities, and businesses along a traditional NAFTA trade route to protect, maximize, and expand commerce and the economic vitality of the corridor while mitigating congestion and facilitating a cleaner environment, incorporating Pacific Ocean port gateways for international and NAFTA trade (www.rotcc.org). The Great Plains International Trade Corridor (GREAT PLAINS in Figure 3) connects metropolitan cities and regional trade centers from Canada to Mexico through the Great Plains to increase economic efficiency.

The Canadian Intelligent Super Corridor (CISCOR) is an east-west transportation infrastructure in Canada from Vancouver and Prince Rupert to Montreal and

Halifax. With a smart inland port (SIP) network, the Saskatchewan province serves as the central logistics and coordination hub, creating a Canadian east-west land bridge that connects with the three major North American north-south corridors, NASCO, CANAMEX, and ROTCC.

As evidenced by the growth in freight related to NAFTA trade, the transportation infrastructure in North America is on the brink of gridlock. With ever-increasing volumes of trade in North America, the existing road and rail infrastructure will not be able to handle the fast-growing burden effectively. Several OR/MS models (e.g., multi-commodity network design, production-assembly-distribution network design, and the transportation model) have been developed to prescribe optimal routes and transportation modes, considering current transportation infrastructure and trade volume (see Section 8.2). However, not many models have been proposed to deal with rapid increases in NAFTA trade volume. For example, a stochastic, multi-stage OR/MS model can be formulated to prescribe the best use of current transportation systems along with projected expansions of highways, rails, and ports in both short- and long-term.

Models can quantify the trade off between investing to refurbish highways, railroads and ports, versus investing to enhance security. The latter investments are necessary, post 9-11, even though they may tend to impede trade by slowing down the movement of goods and by competing for funding for the renewal of infrastructure. In contrast, even though the EU has expanded from 15 to 25 countries, border inspections have been relaxed substantially.

One of solutions proposed for alleviating congestion at ports and delay at border crossings is to establish inland ports and SIP's along major NAFTA corridors. *An Inland Port is a physical site located away from traditional land, air, and coastal borders with the vision to facilitate and process international trade through strategic investment in multi-modal transportation assets and by promoting value-added services as goods move through the supply chain* (Leitner and Harrison, 2001).

The North American Inland Port Network (NAIPN) is a tri-national sub-committee of NASCO that has been tasked with developing an active inland port network along the NASCO corridor, specifically to alleviate congestion at maritime ports and at NAFTA borders. By networking Inland Ports, NAIPN extends economic benefits throughout the Corridor.

A SIP is defined less on the physical aspects of one location and more on the intelligent logistics and coordination of a multitude of services. Made up of key transportation stakeholders, a SIP serves its regional economy, facilitating growth for both import and export trade logistics and providing national coordination and collaboration among ocean ports.

Despite its inland location 1,500 miles away from the Pacific Ocean and more than 900 miles from the Atlantic Ocean, Kansas City will be the first foreign (i.e., Mexican) customs inspection office in the U.S., permitting freight to clear U.S. customs without border delay. As a major intermodal hub with excellent air, rail, road, and river infrastructure, Kansa City will have global logistics capacity to consolidate and disperse goods from Canada and Mexico throughout the U.S. The Kansas City SIP will serve as an alternative port as trade growth begins to congest Pacific and Atlantic coastal ports and customs facilities in Texas. In addition, it might be possible to mitigate traffic congestion along the North-South NASCO corridor by detouring North-South traffic to an east-west corridor that links Pacific and Atlantic ports.

Free Trade Alliance-San Antonio, a non-profit corporation comprising most of San Antonio economic institutes, started to develop an inland port in San Antonio, taking advantage of its strategic location close to Mexico and on the NASCO. Some 50-60% of the trade between the U.S. and Mexico flows through San Antonio, which offers well-developed interstate highway, rail, and air infrastructure (Rosmalen and Vido, 2002). Union Pacific announced plans to build a $90 million, 300-acre intermodal rail terminal alongside I-35 in San Antonio, advancing the city's goal to establish itself as a NAFTA inland port (Corsi, 2007).

Important research questions remain in determining the optimal number of SIP(s), considering major corridors; road, rail, and air infrastructures; and distance to coastal ports. These questions can be addressed using OR/MS models. In the past, local and federal governments, along with private-sector investors, have invested to develop NAFTA corridors. Which parties should be key players in developing SIPs and assuring security? If SIPs were available and foreign (i.e., Mexican) trucking companies were permitted to cross the U.S. border, how many distribution centers would be needed and at which locations? How many new ports should be developed to deal with containerized freight volumes that will double or triple in the next decade?

Following the development of SIPs, international enterprises will need improved OR/MS models to effectively utilize them and accompanying infrastructure improvements. Global supply chain design models will have to reflect these enhancements to prescribe the optimal locations for plants and distribution centers and to select optimal transportation modes and suppliers.

Recently, the U.S. has implemented a contentious NAFTA term, approving Mexican trucks to travel within the U.S., even though only 100 trucking companies have been approved and only for a limited time period. Direct shipments using Mexican trucks within the U.S. will reduce transportation time and cost substantially since current drayage practices will no longer be needed.

Extended homeland security measures will be needed with Mexican customs in the Kansas City SIP and Mexican trucks on U.S. soil. Practices needed to assure security may serve to impede transportation flow. Government and private investments will have to be allocated optimally, apportioning funds to upgrade highways, railroads, and ports, yet enhance security.

Yet another research topic is to develop good options to track the movement of goods and long-haul vehicles (e.g., multiple X-ray and gamma ray screenings, intelligent transportation systems (ITS), GPS, RFID). Funding will have to be allocated effectively to expand transportation infrastructure and implement security systems to reduce border crossing delay.

8.5 Generalized JIT under NAFTA

In this section, we briefly review Generalized JIT, describing an example of its use by automotive companies in NAFTA countries. This section further describes research opportunities for the OR/MS community to exploit competitive advantages posed by NAFTA (e.g., geographical proximity and NAFTA terms) using Generalized JIT. Two primary needs are to reflect the full impact of proximity in supply chain design models and to integrate strategic models with tactical material flow management that utilizes Generalized JIT.

Nissan Motors, a Japanese company, operates a plant in Decherd, Tennessee, which produces engines and transmissions, as well as a plant in Mexico, which processes parts and performs assembly. Challenger Motor Freight, a major Canadian trucking company, has an American subsidiary that manages transportation for Nissan. Challenger transport transmissions to Mexico, returning with a backhaul of components; the output of one plant is the input to the other. This is not Just-in-Time as practiced by Toyota: suppliers are much closer in Japan. Rather, Nissan operations exemplify what might be called Generalized JIT. Toyota Just-in-Time (Joo and Wilhelm, 1993) features retained on the North American scale of distances include: (i) transportation at regular intervals; (ii) reliability of supply; and (iii) excellent communication between supplier, manufacturer, and transport company.

Opened in 2005, Toyota's first Mexican manufacturing plant in Baja California near Tijuna produces 180,000 truck beds and 30,000 Tacoma vehicles per year. Truck beds manufactured in Baja are transported to a final assembly plant -a joint venture of Toyota and General Motors- in Fremont, California (Toyota online news, 2005). Toyota opened another $1.28 billion plant in November, 2006 to assemble Tundra trucks in San Antonio, Texas and the plant is expected to develop a network of auto parts suppliers in the U.S. and Mexico (Houston Chronicle, 2003, 2006). A large number of automobile suppliers are operating in Mexico within a day's drive of San Antonio, taking advantage of the country's low labor costs (Phillips *et al*., 2004). San Antonio is located near the center of an automotive cluster, comprising 18 assembly plants and stretching from Mexico City to Atlanta. Most of the auto parts manufactured in Mexico are produced by the Maquiladora industry in the Mexican states that border Texas; they are well located to serve the Toyota Plant in San Antonio (Phillips *et al*., 2004).

In 2002, Toyota's Mexican plant purchased $600 million worth of auto parts from 20 Mexican suppliers and the company planned to expand its supplier networks in Mexico to support both San Antonio and Baja plants (Jefferson, 2003). Klier (2000) summarized that the quality of transportation infrastructure and capacity of delivery management systems assures predictable on-time delivery of auto parts and are key factors that will determine the success of JIT production in this NAFTA environment. For example, Ciudad Juarez, which is located between Tijuana and San Antonio, is home to a large number of auto parts suppliers and can be an important source for both Tijuana and San Antonio since it is located on a well-developed interstate highway (i.e., Interstate-10) and is accessible by rail.

Several studies show that Generalized JIT is used by most Maquiladoara along the U.S.-Mexico border. Cuevas *et al*.(2005) argued that most Maquiladora plants are located close to the U.S.-Mexico border since JIT production and distribution is an important factor for foreign investors in Mexico, even though other countries provide much lower-cost labor in manufacturing. Sullivan *et al*. (2000) argued that trucking is the most popular mode of transporting goods across the U.S.–Mexico border (72.7 percent of all trade in 1998) due to the use of JIT philosophies.

Freeland (1991) surveyed companies, classifying them into four groups: high-JIT benefits, low-JIT benefit, JIT in future, and no plans for JIT. The automotive, computer, electrical, and food processing industries are more involved in JIT than other U.S. industries, while aircraft, ship-building, medical supplies, pharmaceuticals, and steel fabrication are among the industries with no plans to employ JIT (Freeland, 1991). Developing and testing a model, Dong *et al*. (2001) concluded that JIT purchasing directly reduces costs for buyers and that suppliers will also benefit if they implement JIT manufacturing in conjunction with a JIT purchasing program. Matson and Matson (2007) identified supply chain issues important to the automobile industry in the southern USA (i.e., Tennessee and Alabama), using a survey of automobile suppliers. They analyzed the extent to which JIT has been implemented by the area's growing automobile industry and the characteristics of companies that use it. After identifying issues experienced by JIT suppliers, they proposed ways to resolve implementation issues.

OR/MS Research is needed to identify the industries most likely to benefit from Generalized JIT, to exploit geographical proximity by enhancing Generalized JIT, and to implement Generalized JIT effectively within the environment posed by NAFTA. We discuss several examples that demonstrate how the automotive industry has learned to benefit from Generalized JIT.

Mexico's comparative advantages lie in its labor costs, which are relatively lower than those in the U.S. and Canada, and its proximity to developed North American markets. In fact, Mexico's proximity to the U.S. market is one of its remaining hopes to compete with the rapidly growing competitive economy of China (Rosen, 2003). Thus, if Mexico's comparative advantage and proximity can be exploited, Generalized JIT will significantly contribute to reducing production and distribution costs in the automotive industry.

The automobile industry exploits JIT to reduce cost. According to a recent news release (Roig-Franzia, 2008), Ford plans to invest $3 billion to upgrade two existing plants in Mexico City, where it will build its new fuel-efficient car. The investment is considered the largest foreign investment ever made in Mexico and is expected to create about 4,500 jobs as well as an additional 30,000 supporting jobs in Mexico. While the automobile industry in the U.S. has been shrinking, it has expanded dramatically in Mexico where low-cost labor is readily available.

From the view point of international economics, the Gravity Model is one way to explain international trade between two countries. The Gravity Model predicts that the volume or value of trade between any two countries is proportional to the product of their two GDPs and inversely proportional to the distance between them (Krugman and Obstfeld, 2006). The Gravity Model reflects the fact that geographical proximity is a facilitating factor for trade between countries. Impediments to trade are distance, governmental barriers (e.g., trade restrictions, policies), and borders (e.g., tariffs, delays). A Free Trade Agreement reduces these impediments. For example, under NAFTA, the border between the U.S. and Canada is considered one of the most open borders in the world. Thus, the NAFTA member countries may exploit advantages of geographical proximity as they compete against other countries. Both geographical proximity and NAFTA terms can be exploited with the use of Generalized JIT.

Global supply chains must be designed to exploit the relative proximity of NAFTA member countries, implementing the Generalized JIT strategy efficiently. Even though terms of the Maquiladora program discouraged the development of suppliers in Mexico, NAFTA will change the environment over time, opening new opportunities for supply chains. Furthermore, countries that participate in CAFTA-DR and those in South America that have bilateral trade agreements with NAFTA members offer proximity to each other and to NAFTA members, opening even more opportunities in this arena.

NAFTA and CAFTA-DR member countries account for 92% of the total volume of apparel exports to the U.S. (Office of Textiles and Apparel, 2003). A shortened lead time, due to its proximity to the U.S. market, can be an important competitive advantage for NAFTA and CAFTA-DR countries relative to textile and apparel products manufactured in other countries (Condo, 2004). Condo added that textile and apparel plants cluster to exploit proximity, fostering the success of the industry. The relative proximity within NAFTA and CAFTA-DR can be exploited by OR/MS models formulated to design international supply chains. In particular, research can build on Porter's Diamond model to formulate improved OR/MS models to support strategic decisions.

8.6 Agriculture

Agricultural products constitute a significant portion of trade under NAFTA, including livestock (e.g., cattle, hogs, poultry), field crops (e.g., corn, cotton, rice, seeds, soy beans, wheat), and specialty crops. Specialty crops are defined in the Specialty Crops Competitiveness Act of 2004 (Public Law 108-465) as *fruits and vegetables, tree nuts, dried fruits and nursery crops*. A wide range of agricultural products are classified as specialty crops. For example, fruits include citrus fruits (e.g., oranges, lemons, limes, grapefruit), apples, pears, peaches, grapes and wines, berries (e.g., blueberries, strawberries, raspberries, blackberries), and dried fruits. Tree nuts include almonds, pecans, and walnuts; and nursery crops include ornamentals (i.e., potted plants) and floriculture.

The OR/MS community has largely neglected agriculture in spite of its importance to GDP, giving rise to a number of important research opportunities under NAFTA. Lowe and Preckel (2004), Weintraub and Romero (2006), Glen (1987), and Oriade and Dillon (1997) provide reviews for general farm planning and agricultural management but no prior study has focused on agribusiness under NAFTA. Papers on methodologies like risk management (e.g., Hardaker *et al*., 2004) and systems engineering (e.g., Ahuja *et al*., 2002) deal with general farm crops. Several OR/MS studies (Villalobos and Sanchez, 2007; Caixeto-Filho, 2006; Munhoz and Morabito, 2001; Cholette, 2007; Kolympiris *et al*., 2006; Leven and Segerstedt, 2004) provide planning tools and methods to design supply chains specifically for specialty crops. However, they do not consider the NAFTA environment. Villalobos and Ahumada

(2007) and Zhang and Wilhelm (2008) provide recent reviews that focus on specialty crops.

In fiscal year 2007, Canada and Mexico were the first and second largest export markets for U.S. agricultural products, respectively. Exports from the U.S. to these two markets were greater than the U.S.'s exports to the next six largest markets combined. The U.S. is the largest market for Canadian agricultural exports. Mexico was Canada's third largest market and third largest source of agricultural food products in 2005. To put agribusiness into perspective, Table 11 gives the value of agricultural trade from/to each pair of NAFTA countries (U.S. Department of Agriculture, 2008; Fleishman-Hillard Canada, 2006). Table 12 gives major agricultural products traded between NAFTA countries.

Table 11. Total agricultural trade between NAFTA countries in FY2007
(in billions, (*) indicates 2005 data)

From\To	Canada	Mexico	U.S.
Canada	-	$1(*)	$14.7
Mexico	$0.6(*)	-	$9.9
U.S.	$13.5	$12.3	-

Table 12. Major agricultural products traded between NAFTA countries in 2005

From\To	Canada	Mexico	U.S.
Canada	-	Canola (seeds and oil), beef, wheat, powdered milk, seeds, meat, grains, malt	Fruits, vegetables, wine and beer, meats
Mexico	Vegetables, fruit, nuts, coffee, beer, tea	-	beer, vegetables, fruit
U.S.	meats, live animals, bulk grains, oilseeds, vegetables	Grains, oilseeds, meat, and related products	-

Several trends are exerting significant influences on agribusiness. For example, the recent interest in producing ethanol from corn to reduce U.S. dependency on foreign sources of gasoline has caused growers to dedicate more acreage to producing corn. In turn, this has buoyed the prices of other field crops, since they must compete with corn for land and other scarce resources. The need for new silos to store corn is acute, spawning the need for decision support tools to plan investments in view of the risks involved.

Perhaps the most serious issue is that a severe scarcity of farm workers has developed and is expected to become even more disruptive over time. The U.S. has hired migrant farm workers from Mexico for several hundred years, even in formalized guest-worker programs (e.g., the Braceros Program (1942 – 1964)). This labor shortage is especially problematic for specialty crops, which account for about half of the value of all crops grown in the U.S. but requires three fourths of all farm labor. Even though specialty crops is the fastest growing agribusiness segment, some 20% of U.S. farm products were lost last year due to the lack of labor to harvest them. It has been estimated that California, the U.S.'s largest agricultural producer, lost up to 30% of its production in 2007 for the same reason. This scarcity has been attributed to the low jobless rate in the U.S. and to a reduction of immigrant labor, which has been caused by enhancement of border control and immigration laws. Immigrants are now more likely to find permanent, better paying jobs in the U.S. in other industries (e.g., construction) than to risk crossing the border periodically to pursue agricultural jobs over time. One response by U.S. growers – especially large-scale operations – has been to establish operations south of the border where labor is available. This trend will negatively impact the GDP of the U.S. and will increase the cost of agricultural products.

Specialty crops are grown in the few states (e.g., Washington, California, Arizona, Texas, Florida, New York, Pennsylvania, Michigan) that offer accommodating climates. The typical farm comprises relatively few acres, so that individual growers do not exert significant influence on market prices. Growers must deal with a number of risks, many of which are unique to the industry and even to a specific crop. For example, it takes several years of maturation for newly planted tress to bear fruit, so that investments must deal with a long, uncertain future. Production depends heavily on weather conditions, which are highly uncertain. Too much – or too little – rain or sunshine can have devastating effect. Each crop is subject to numerous diseases and pests, including ones that focus on specific crops. Irrigation and harvesting equipments are expensive. To maximize productivity, labor must be available in specific time windows to prune and to harvest. An early, unexpected frost can devastate production. Farm Bill 2007 recognizes these threats and includes special provisions for specialty crops.

Research needs for agriculture in general and specialty crops in particular encompass a wide variety of disciplines. For example, genetic engineering is needed to make plants more disease and pest resistant as well as more productive. Biologists and agricultural scientists can contribute by enhancing biological models to predict plant growth and productivity. Improved robotic systems are needed to prune and harvest, substituting for farm workers. Enhanced material handling systems are needed to pick, transport, sort, store, and distribute crops without damaging them. New techniques are needed to implement precision-agriculture, which seeks to maximize the productivity of each individual plant, growing in its own unique microclimate. Research is needed to develop sensors that can accurately and inexpensively measure sunlight exposure as well as food and water absorption for each plant so that appropriate amounts of food, water, and pesticide can be metered to it.

Not many OR\MS models have been proposed to support decisions related to specialty crops and most of those available have originated in various countries around the world, making this a fertile research area for NAFTA researchers. Models must be made extremely user friendly, however, since growers typically have little experience in using them. OR\MS models are needed to support both long-and short- term decisions. For example, long term decisions prescribe the mix of crops to be grown as well as the size and density of plants to be planted. Time-staged decisions must plan replacement (e.g., of portions of an apple orchard) over time to maximize long-term productivity. Short term decisions include timing annual thinning and pruning operations as well as harvesting and storage.

The design of supply chains is becoming more important as the global economy embraces agriculture. The U.S. is importing more crops from international sources and, in turn, exporting more to other countries. In particular, U.S. growers are establishing more farms in Mexico where labor is readily available. Lengthening supply chains in this way exacerbates issues of timeliness, packaging, cooling, and storage time for perishable farm products, making supply chain design crucial. In fact, food safety has become an acute problem, emphasizing the need for research to devise improved monitoring, inspection, testing, and tracking techniques.

Agriculture provides a fertile ground for all types of OR\MS methodologies. Risk management is crucial. For example, harvesting must balance risks associated with picking too early or too late in the growth cycle of a crop, picking when labor and/or equipment is likely to be available, and picking to avoid the damage that can potentially be done by an early frost. Simulation and biological models can be combined to enhance the capability to predict plant growth and, consequently, the optimal harvest time. Integer, stochastic and multi-objective programming models are needed to address appropriate operational problems as well as international supply chain design.

CHAPTER IX

INTRODUCTION TO THE DSCR MODEL

The configuration of a supply chain is determined by prescribing the location and capacity of each facility that comprises it as well as the links used for transportation. Such a configuration must be dynamically redesigned over time to cope with changes in the demand and/or cost structures, which reflect the evolving business environment. Demand for products in each market and costs to produce them at each possible location vary as economic factors change over time. Economic downturns and periods of rapid economic growth give rise to such changes and force an enterprise to reconfigure its supply chain to meet customer demands at the lowest possible cost (Melo *et al*., 2006). Another example of a phenomenon that gives rise to such changes is the product life cycle: demand increases after introduction and decreases as the end of the life cycle approaches.

To address changing business environments, we propose a dynamic supply chain reconfiguration (DSCR) model, which reflects the dynamic facility location problem with capacity expansions and contractions at each facility in a multi-period, multi-product, multi-echelon supply chain. Our DSCR model can provide management with the responsiveness and adaptability needed in the competitive modern business environment.

The objectives of this research are

- alternative comprehensive mathematical formulations for the DSCR problem, and

- tests that identify the computational characteristics of each model to determine if one offers superior solvability in comparison with the others.

To achieve the first objective, this dissertation presents an initial MIP model, a refined alternative model that relates binary decision variables according to a convenient structure, and two branch and price (B&P) schemes for the refined model.

Even though the dynamic facility location problem with facility openings and closings has been studied extensively, there has not been adequate attention to the dynamic facility location problem with capacity expansion and contraction over a planning horizon. In particular, little research has been directed to dynamic facility location within a multi-period, multi-product, multi-echelon supply chain network (i.e., the DSCR problem).

Figure 4 depicts the dynamic reconfiguration of a supply chain network comprising four echelons to represent suppliers, manufacturing plants, warehouses, and customers, respectively, over two time periods. The configuration of facilities can change from one time period to the next as new facilities are opened, existing facilities are expanded or contracted, and established facilities are closed. The black portion of each icon symbolizes facility capacity after opening, expanding, contracting, and closing in time periods (t) and (t+1). Each directed acyclic arc; i.e., an arrow in the figure, with both ends in one layer (i.e., in the same time period) represents a transportation link for products shipped between two operating facilities in time periods (t) and (t+1). Inventory (backordering) can be carried over from period t to t+1 (t+1 to t) at each facility. Our DSCR model prescribes material flow from a supplier to a processing plant and through a distribution center (DC) to a customer zone (CZ) for each product on a network that comprises nodes (i.e., locations) and arcs (i.e., transportation links) for each time period. Our model is distinguished from the dynamic facility location problem in that it deals with material flow through multiple echelons.

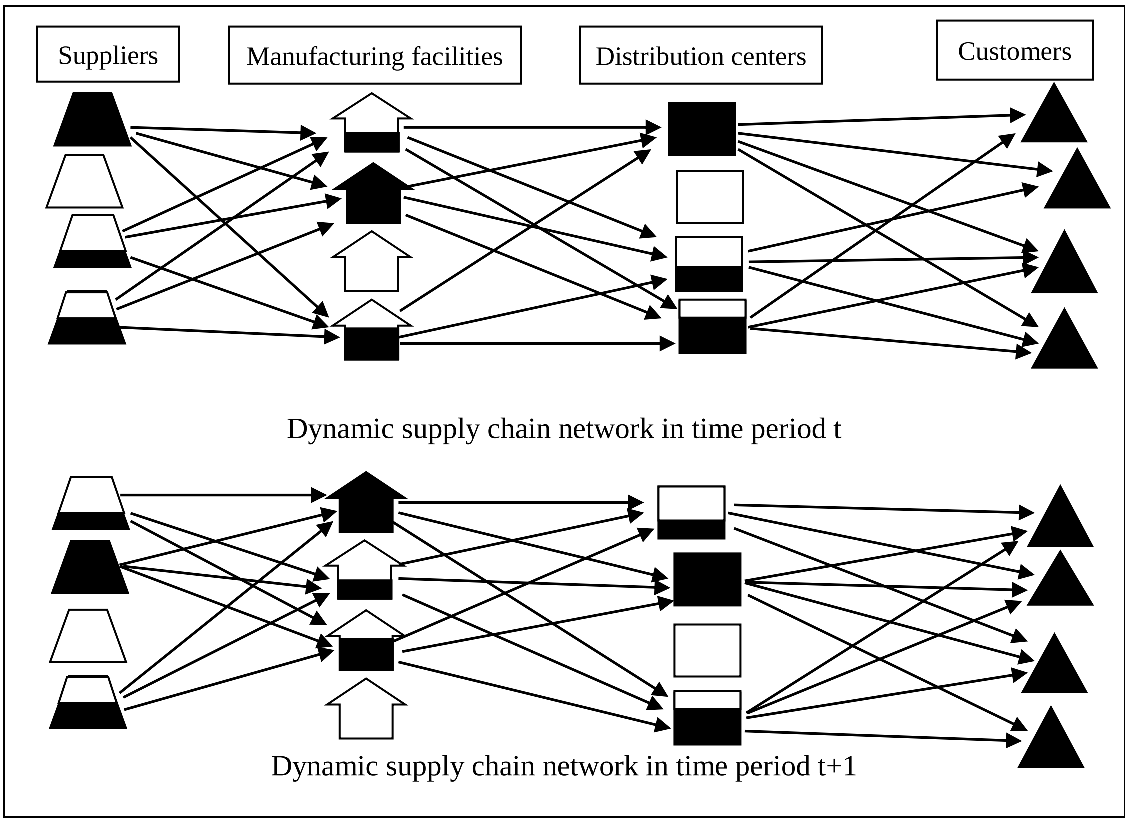


Figure 4. Dynamic supply chain network over planning horizon

The supply chain network we consider accommodates a different type of facility in each echelon (e.g., supplier, plant, DC, or customers). We assume that each echelon performs a unique function and that each product must be "processed" in each echelon. Each viable transportation link allows shipment from a facility in one echelon to another in the next echelon, but no links connect facilities within the same echelon. A viable transportation link is established between a pair of operating facilities and any product can be transported on it. Thus, the problem deals with a dynamic, multi-period, multi-product, multi-echelon supply chain network through which different products are delivered to satisfy the demands of CZs.

We model inventory carry over, backordering, and outsourcing in each time period over the planning horizon because they are typically essential to customer service. Single sourcing provides several significant advantages (e.g., cost, diminished opportunity for error, consistency) and, thus, a single DC must be prescribed to provide each CZ with all types of products. We restrict the number of reconfigurations over the entire planning horizon at each potential location by a budget limitation on total cost as well as limitations on the numbers of capacity expansions and/or contractions. A cost would be incurred to close or contract a facility that is underutilized, so we assess a cost for excess capacity to motivate capacity reduction.

We assume that a facility can be opened and closed at a specific location only once over the entire planning horizon (i.e., it cannot be reopened once closed) but that a facility can be expanded and/or contracted once each period after being opened. We assume that all openings, expansions, contractions, and closings occur at the start of the specified time period and take place instantaneously.

The remainder of the second part of the dissertation is organized in five chapters. Chapter X reviews relevant literature and presents a taxonomy that summarizes various dynamic facility location problems, focusing on prior work that is most closely related to this study. Chapter XI presents our alternative DSCR formulations and discusses them in some detail, addressing part of the first research objective. Chapter XII describes a selected set of B&P decomposition schemes for the refined DSCR formulation to complete the first research objective. Chapter XIII reports our computational evaluation, which accomplishes the second research objective. Finally, Chapter XIV offers conclusions and recommendations for future research.

CHAPTER X

LITERATURE REVIEW: THE DSCR MODEL

This chapter reviews related literature, presenting a current taxonomy of prior results. The DSCR problem is related to four classical OR problems: facility location, dynamic facility location, supply chain design, and production-distribution network design. The facility location problem addressed by the OR/MS community involves siting a set of facilities to serve a set of customer demands with the objective of minimizing total distance (or time or cost) incurred by all transports (Owen and Daskin, 1998). An extension, the dynamic (multi-period) location problem, has been proposed to meet demands and costs as they change over time (Melo *et al.*, 2009). Dynamic facility location models form a basis for building comprehensive supply chain network models.

A supply chain network comprises a number of facility types (e.g., suppliers, manufacturing plants, DCs, and warehouses) that perform operations ranging from acquiring raw materials, transforming materials into intermediate and finished products, and distributing finished products to customers (Hinojosa *et al.*, 2008; Melo *et al*. 2009). A specialization of the supply chain design problem is called the production-distribution network design problem (Klose and Drexl, 2005), which is also a special case of the network design problem in which the network is acyclic.

Due to the wide range of applications and its challenges to solution methods, the dynamic facility location problem with opening and closing has been studied widely since the first work of Ballou (1968), including both uncapacitated (Chardaire *et al.*, 1996; Galvão and Santibañez-Gonzalez, 1992; Kelly and Marucheck, 1984; Khumawala and Whybark, 1976; Roodman and Schwarz, 1975, 1977; Van Roy and Erlenkotter, 1982; Canel and Khumawala, 1997) and capacitated (Sweeney and Tathanm, 1976; Erlenkotter, 1981; Fong and Srinivasan, 1981a, 1981b, 1986; Jacobsen, 1977; Lee and Luss, 1987; Shulman, 1991; Melachrinoudis *et al*., 1995; Antunes and Peeters, 2001) cases. The dynamic supply chain network problem, which includes locating facilities, has been studied by Canel *et al*. (2001), Melachrinoudis and Min (1999, 2000), Melo *et al*. (2006), Hinojosa *et al*. (2000,2008), and Gue (2003).

The possibility of expanding capacity was considered by Aghezzaf (2005) and Ko and Evans (2007). Lowe *et al*. (2002) modeled the capacity-contraction case. A few studies (Melachrinoudis and Min, 2000; Melo *et al*., 2005, 2006; Vila *et al*., 2006; and Behmardi and Lee, 2008) considered both capacity expansion and contraction. Daskin *et al*. (2005), Klose and Drexel (2005), and Melo *et al*. (2009) provided a survey of the dynamic facility location problem.

In particular, a few papers are closely related to this research. Hinojosa *et al*. (2000) dealt with the multi-period, multi-product, two-echelon, capacitated location problem in which new facilities can be opened and existing facilities closed. They didn't consider inventory carry over, capacity expansion and contraction, or a budget limitation. Melo *et al*. (2006) considered the step-wise reallocation of capacities. They assumed (1) all existing facilities are operating at the start of the planning horizon; (2) if an existing facility is closed, it cannot be reopened; and (3) when a new facility is established, it will remain in operation until the end of the planning horizon.

Behmardi and Lee (2008) studied a dynamic, multi-product, capacitated facility location problem in which each facility can be opened and subsequently closed with no reopening allowed. Extending Hinojosa *et al*. (2000), Hinojosa *et al*. (2008) formulated a model for a dynamic, two-echelon, multi-product, capacitated facility location problem with inventory and outsourcing and developed a Lagrangian relaxation method to solve it. Thanh *et al*. (2008) proposed a MIP for the design of a multi-product, multi-echelon, production–distribution network, considering the opening, expanding, and closing of facilities as well as supplier selection. Inventories were held only in warehouses, not in plants. Toress-Soto (2009) studied the dynamic, capacitated facility location problem that determines the optimal time and location for opening facilities when demand and cost parameters are time-varying. His model minimizes costs of transportation and the opening, operating, closing, and reopening of facilities and was solved using Lagrangian relaxation and Benders' decomposition. As in Wesolowsky and Truscott (1975), he employed binary variables for (re)opening, closing, and operating a facility, but neither the Wesolowsky and Truscott (1975) nor the Toress-Soto (2009) model allowed for capacity expansion or contraction.

In most models that allow only facility opening and closing (e.g., Van Roy and Erlenkotter, 1982; Hinojosa *et al*., 2000, 2008; Melo *et al*., 2005, 2006; Behmardi and Lee, 2008; Thanh *et al*., 2008), the capacity of a facility cannot be increased or decreased over time. Facilities that are open at the start of the planning horizon can only be contracted or closed and, after closing, must remain closed until the end of planning horizon. Facilities that are not operating at the start of the planning horizon can only be opened and subsequently expanded; but an open facility must remain opened until the end of the planning horizon-it cannot be closed and its capacity cannot be contracted. In particular, this approach does not allow for a facility with excessive capacity to be closed or contracted during the planning horizon. Our model, which allows flexible capacity expansion and contraction alternatives, addresses these issues, contributing by filling this gap.

Regarding solution approaches, commercial mathematical programming software has often been used (Elson, 1972; Gue, 2003; Melachrinoudis and Min, 2000; Melachrinoudis *et al*., 2005; Melo *et al*., 2006). Branch and bound (B&B) (Barros, 1998; Barros and Labbe, 1994; Canel and Khumawala, 1997; Canel *et al*., 2001; Kaufman *et al.*, 1977; Khumawala and Whybark, 1976; Roodman and Schwarz, 1975, 1977; Tcha and Lee, 1984; Van Roy and Erlenkotter, 1982), Benders decomposition (Geoffrion and Graves, 1974; Kelly and Maruckeck, 1984) have been used as exact procedures, dynamic programming (Lee and Luss, 1987; Sweeney and Tatham, 1976; Shulman, 1991; Hormozi and Khumawala, 1996), and Lagrangian relaxation (Galvão and Santibañez-Gonzalez, 1992; Hinojosa *et al*., 2000, 2008; Prikul and Jayaraman, 1998) approaches have been used. Heuristics have been offered by Antunes and Peeters (2001), Chadaire *et al*. (1996), Dias *et al*. (2007a, 2007b), Fong and Srinivasan (1981a, 1981b), Roodman and Schwarz (1975, 1977), Wang *et al*. (2003). As Klose and Drexel (2005) indicated, the computational challenge presented by the dynamic facility location problem increases drastically with the size of the model, reducing the chances to solve large-scale, real-world instances.

Table 13 presents a taxonomy of existing dynamic facility location and supply chain design models that are related to our DSCR model. Following the format of Melo *et al*. (2005) and Thanh *et al*. (2008), the table classifies models with each column representing a model characteristic: type of planning horizon; type of objective function; number of commodities; number of echelons in the supply chain; consideration of opening, closing, and reopening; inclusion of capacity expansion and contraction; consideration of inventory; budget constraint; single sourcing requirement; formulation type; solution method; and application area (refer to the legend at the bottom of the table for details). As the table makes evident, no prior model takes into account all of the features that our DSCR model addresses.

Table 13. Taxonomy of existing literature related to DSCR
(Refer to legend of the table for headings)

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)
Our Model	D	C	M	M	O C R	C,E,D	Y	Y	S	MIP	B&P	Dynamic supply chain
Barros (1998), Barros and Labbé (1994)	S	P		1			N	N	S	MIP	B&B , LgR	One Plant/DC for CZ
Canel and Khumawala (2001)	D	P	1		O				M		HU	Dynamic international facilities location
Elson(1972)	S	C	M	2		C, E	N			MIP	C	Warehouse location problem
Fong and Srinivasan (1986)	D	C	1	2			N	N	M	MIP	HU	Dynamic capacity expansion

Table 13. Continued

<table>
<tr><th></th><th>(a)</th><th>(b)</th><th>(c)</th><th>(d)</th><th>(e)</th><th>(f)</th><th>(g)</th><th>(h)</th><th>(i)</th><th>(j)</th><th>(k)</th><th>(l)</th></tr>
<tr><td>Gue (2003)</td><td>D</td><td>C</td><td>M</td><td>1</td><td rowspan="21">OC</td><td rowspan="9">C</td><td>Y</td><td>N</td><td></td><td>MIP</td><td>C</td><td>Combat logistics system</td></tr>
<tr><td>Hinojosa et al.(2000)</td><td>D</td><td>C</td><td>M</td><td>2</td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>LgR</td><td>Both opening and closing of facilities. Once closed, no reopen allowed.</td></tr>
<tr><td>Hinojosa et al.(2008)</td><td>D</td><td>C</td><td>M</td><td>2</td><td>Y</td><td>N</td><td>M</td><td>MIP</td><td>LgR</td><td></td></tr>
<tr><td>Hormozi and Khumawala (1996)</td><td>D</td><td>C</td><td>1</td><td>1</td><td></td><td>N</td><td>M</td><td>MIP</td><td>B&B ,DP</td><td>Multiperiod facility location</td></tr>
<tr><td>Melachrinoudis et al.(1995)</td><td>D</td><td>M</td><td></td><td>1</td><td></td><td></td><td>M</td><td>MIP</td><td>C</td><td>Dynamic location of landfills</td></tr>
<tr><td>Melo et al.(2005, CIO Working Paper)</td><td>D</td><td>C</td><td>1</td><td>1</td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>BD</td><td>Dynamic capacitated location</td></tr>
<tr><td>Roodman and Schwarz (1975)</td><td>D</td><td>C</td><td>1</td><td>1</td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>B&B</td><td>Facility phase-out strategy</td></tr>
<tr><td>Sweeney and Tatham (1976)</td><td>D</td><td>C</td><td>1</td><td>2</td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>DP</td><td>Multiple warehouse location</td></tr>
<tr><td>Wesolowsky and Truscott (1975)</td><td>D</td><td>C</td><td>1</td><td>1</td><td>N</td><td>N</td><td>S</td><td>MIP</td><td>DP</td><td>Dynamic uncapacitated facility location problem</td></tr>
<tr><td>Ko and Evans(2005)</td><td>D</td><td>C</td><td>M</td><td>2</td><td>C, E</td><td>N</td><td>N</td><td>M</td><td>MIP NLP</td><td>HU</td><td>Forward and reverse logistics network for 3PLs</td></tr>
<tr><td>Lee and Luss (1987)</td><td>D</td><td>C</td><td></td><td>1</td><td>E</td><td>Y</td><td>N</td><td></td><td>MIP</td><td>DP</td><td>Capacity expansion problem</td></tr>
<tr><td>Melachrinoudis and Min (2000)</td><td>D</td><td>M</td><td></td><td>2</td><td>E,D</td><td></td><td>Y</td><td></td><td>MIP</td><td>C</td><td rowspan="2">Plant/DC location</td></tr>
<tr><td>Antunes and Peeters (2001)</td><td>D</td><td>P</td><td></td><td>1</td><td rowspan="3">C, E,D</td><td></td><td>Y</td><td>M</td><td>MIP</td><td>SA</td></tr>
<tr><td>Behmardi and Lee (2008)</td><td>D</td><td>C</td><td>M</td><td>2</td><td>Y</td><td>N</td><td>N</td><td>MIP</td><td>CPLEX</td><td>Dynamic supply chain</td></tr>
<tr><td>Melo et al.(2006)</td><td>D</td><td>C</td><td>M</td><td>M</td><td>Y</td><td>Y</td><td>M</td><td>MIP</td><td>C</td><td>Dynamic supply chain network</td></tr>
<tr><td>Chardaire et al. (1996)</td><td>D</td><td>C</td><td>1</td><td>1</td><td rowspan="3">U</td><td>N</td><td>N</td><td>M</td><td>MQP</td><td>SA, LgR</td><td>Dynamic facility location</td></tr>
<tr><td>Kelly and Marucheck (1984)</td><td>D</td><td>C</td><td>1</td><td>2</td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>BD</td><td>Dynamic warehouse location</td></tr>
<tr><td>Van Roy and Erlenkotter (1982)</td><td>D</td><td>C</td><td></td><td>2</td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>B&B Dual ascent</td><td>Dynamic uncapacitated facility location problem</td></tr>
<tr><td>Kaufman et al. (1977)</td><td>S</td><td>C</td><td></td><td>2</td><td rowspan="3"></td><td>N</td><td>N</td><td>M</td><td>MIP</td><td>B&B</td><td>Plant/DC location</td></tr>
<tr><td>Khumawala and Whybark (1976)</td><td>D</td><td>C</td><td>1</td><td>2</td><td>N</td><td>N</td><td>S</td><td>Example</td><td>HU</td><td>Dynamic warehouse location</td></tr>
<tr><td>Roodman and Schwarz (1977)</td><td>D</td><td>C</td><td></td><td>1</td><td>N</td><td>N</td><td></td><td>MIP</td><td>B&B</td><td>Phase-In/phase-out problem</td></tr>
</table>

Table 13. Continued

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)
Dias *et al*. (2007a, 2007b)	D	C	1	M	O C R	C	N	N	S	MIP	B&B , HU	Dynamic facility location
Canel *et al*.(2001)	D	C	M	2			N	N	N	MIP	B&B, DP	Multi-period facility location
Vila *et al*.(2006)	D	P	M	M			Y	N	M	MIP	C	Lumber industry
Ballou (1968)	D	C		2			N	N	M	DP	DP	Warehousing location
Wang *et al*. (2003)	S	C		1				Y	S	MIP	HU	Opening/closing of bank at same time
Erlenkotter (1981)	D	C	1	2		C	N	N	M	MIP	C	Dynamic location problem
Geoffrion and Graves(1974)	S	C	M	2			N	N	S	MIP	BD	Warehouse location problem
Schilling (1980)	S	P	1	1				N		MIP	HU	Public sector facilities/ Maximal covering problem
Shulman (1991)	D	C		1		C, E	N		M	MIP	LgR	Dynamic Capacitated Plant Location Problem
Thanh *et al*.(2008)	D	C	M	M			Y	N		MIP	C(Express-MIP)	Random instance (no reopen)
Tcha and Lee (1984)	S	P	1	M		U	N	N	M	MIP	B&B, HU	Multi-level uncapacitated facility location
Canel and Khumawala (1997)	D	C		2						MIP	B&B	Dynamic international facilities location

Legend:
(a) Planning horizon: S: Static model, D: Dynamic model with multiple time periods
(b) Objective: C: Minimize cost, P: Maximize profit, M: Multiple objectives
(c) Number of commodities: M: Multicommodities, S: Single commodity
(d) Number of facility echelon: M: Multi level
(e) Opening, reopening type: O: Opening; C:Closing; R: Reopening
(f) Capacity constraints for each: C: Capacitated, E: Capacity expansion, D: Capacity contraction, U: Uncapacitated
(g) Consideration of inventory: Y: Yes, N: No
(h) Consideration of inventory: Y: yes, N: No
(i) S: Single sourcing, M: Multiple sourcing
(j) Formulation type: MIP, DP (Dynamic programming), NLP (Non-LP), MILP, MQP: Mixed Quadratic Programming
(k) Solution approach: commercial mathematical programming software (C), B&B, Bender's decomposition (BD), dynamic programming (DP), Lagrangian relaxation (LgR), heuristics(HU), primal-dual heuristics (PD), simulated annealing (SA), and a combination of methods (CO)
(l) Applied area: application area

CHAPTER XI

MODEL FORMULATION

This chapter presents alternative formulations of DSCR. We first present an initial MIP formulation of DSCR, which we call DSCR-T. Then, we present an alternative refined formulation of DSCR, which we call DSCR-N, that relates binary variables according to a convenient structure. The initial MIP model results from using traditional formulation logic to relate binary decision variables to prescribe openings, expansions, contractions, and closings, while the refined DSCR formulation utilizes a specialized network to relate binary decision variables.

11.1 Initial MIP formulation of DSCR

This chapter presents our initial MIP formulation for DSCR. We first describe our notation, including indices, index sets, parameters, and decision variables. (The appendix summarizes this notation in a table for reader convenience). We consider four echelons in our DSCR formulation: suppliers, manufacturing plants, DCs, and CZs. We use several index sets to state the model in succinct form and the term *facility* for convenience to indicate a supplier, production, DCs, and a CZ. One facility is considered at each location $\ell \in L$; thus, we use index $\ell \in L$ to denote both of the facility at location ℓ as well as location ℓ for presentation simplicity. Each echelon in the supply chain comprises a unique facility type, which must process each product.

The set L contains four index subsets of locations: suppliers, $L_S \subset L$; production plants, $L_P \subset L$; DCs, $L_{DC} \subset L$; and CZs, L_{CZ}. Each supplier and each CZ are fixed in the "open" state and cannot be expanded or contracted. Each CZ experiences demand for each product $p \in P$. A manufacturing plant (DC) facility can be opened at each location $\ell \in L_P \subset L(\ell \in L_{DC} \subset L)$. We define a subset $L_{PDC} = L_P \cup L_{DC}$, in which facilities can be expanded and contracted. Note that $L_S \cup L_P \cup L_{DC} \cup L_{CZ} = L$ and $L_e \cap L_{e'} = \emptyset$, where $e, e' \in E, e \neq e'$ and $E = \{1, 2, 3, 4\}$, representing, $\{S, P, DC, CZ\}$.

The DSCR model must configure and reconfigure the supply chain over the index set of time periods T by opening, operating, expanding and contracting capacities, and closing facilities at the index set of alternative locations L_{PDC}. The capacity of operating (i.e., open) facility $\ell \in L$ can be expanded (contracted) at the beginning of any time period (after operating for at least one period) by selecting any alterative $j \in J_\ell$ ($i \in I_\ell$) where J_ℓ (I_ℓ) is an index set of expansion (contraction) alternatives at location $\ell \in L$.

The model incorporates a number of cost parameters; each is discounted to a present worth value. Fixed costs include $G^O_{k\ell t}$ $\left(G^C_{\ell t}\right)$ to open (close) a facility with capacity alternative k at location ℓ at the start of period t and cost $G^M_{\ell t}$ to operate a facility at location ℓ in period t once the facility is opened and is not yet closed by period t. Capacity expansion (contraction) alternative j (i) at location ℓ at the start of period t incurs fixed cost $G^E_{j\ell t}$ ($G^D_{i\ell}$).

Variable costs include $U^p_{\ell\ell' t}$ to ship each unit of product p from location ℓ to location ℓ' in period t, $H^p_{\ell t}$ ($Q^p_{\ell t}$) to hold each unit of product p in inventory (backorder) at facility ℓ at the end of period t, and $R^p_{\ell t}$ to purchase each unit of product p from an outside supplier (i.e., outsourcing). Another variable cost $F_{\ell t}$ is charged for each unit of excess (i.e., unused) capacity at location ℓ during period t, motivating decisions to reduce unused capacity or close the facility. If unused capacity would incurs cost, it would be neither contracted nor closed, since each action incurs a fixed cost.

The formulation employs four index sets to model the capacity of facility $\ell \in L$: $K_{k\ell}$, capacity alternative associated with the opening of facility ℓ where $k \in K_\ell$ is an index for capacity alternatives at location ℓ; $\overline{K}_{j\ell t}$, the capacity increment associated with expansion alternative j in period t; and $\underline{K}_{i\ell t}$, capacity decrement associated with contraction alternative i in period t. We allow different values for capacity expansions, $\overline{K}_{j\ell t}$, and contractions, $\underline{K}_{i\ell t}$, to promote flexibility and responsiveness.

The demand $b_{\ell t}^{p}$ for product $p \in P$ at facility (i.e., CZ) $\ell \in L_{CZ}$ during period t must be satisfied by production in the current period, by drawing from inventory, by incurring backorders, and/or by outsourcing. δ_ℓ^p denotes the workload required to process one unit of product p at facility $\ell \in L$. The maximum material flow on transportation link $\ell\ell'$ in period t is limited by the upper bound capacity $\mathrm{V}_{\ell\ell'\mathrm{t}}$, where $\ell \in L_e$ and $\ell' \in L_{e+1}$.

The available budget for all fixed costs over the entire planning horizon at location $\ell \in L$ is specified by B_ℓ. The maximum number of all expansions (contractions) (maximum combined numbers of expansions and contractions) for facility ℓ over the planning horizon is limited to N_ℓ^E (N_ℓ^D) (N_ℓ^T).

DSCR involves six types of binary variables. $O_{k\ell t} = 1$ if the facility with capacity alternative k at location ℓ is opened (i.e., action of opening) at the start of period t and $C_{\ell \mathrm{t}} = 1$ if facility ℓ is closed (i.e., action of closing) at the start of period t

(i.e., at the end of period $t-1$). $E_{j\ell t}=1$ ($D_{i\ell t}=1$) if the facility at location $\ell \in L_{PDC}$ incorporates expansion (contraction) alterative j (i) at the start of period t. We assume that opening, expanding, contracting, and closing each take place instantaneously. $M_{\ell t}=1$ if facility ℓ is operating in period t (i.e., to process or distribute products). Opening at the start of period t ($O_{k\ell t}=1$) means *operating* ($M_{\ell t}=1$) in the same time period t and in each subsequent period until closing. Closing at the start of period t means *not operating* ($\mathrm{M}_{\ell \mathrm{t}}=0$) in period t and in any subsequent period. $\mathrm{S}_{\ell\ell'\mathrm{t}}=1$ if the transportation link from location ℓ to location ℓ' is available for use (i.e., facilities at both ℓ and ℓ' are operating in period t). Each of these binary variables must have value 0 if the stated condition to be 1 is not satisfied.

Continuous variables prescribe material flow, inventory carry over, backorder, and outsourcing amounts. Material flow variable $x^{p}_{\ell\ell' t}$ prescribes the amount of product p shipped from location ℓ to location ℓ' in period t; inventory carry over variable $y^{p}_{\ell t}$ prescribes the amount of product p held in inventory at facility ℓ to be used in period $t+1$; backorder variable $v^{p}_{\ell t}$ prescribes the amount of product p backordered to be used in period $t-1$; and outsourcing variable $r^{p}_{\ell t}$ prescribes the amount of product p that is purchased from an outside supplier at facility ℓ to be used in period t. Depending on the types of facilities at locations ℓ and ℓ', the amount of flow of product p, $x^{p}_{\ell\ell' t}$, can be interpreted as an amount that is purchased from a supplier, processed, shipped on a link, or distributed from a DC to a CZ. We assume that initial (i.e., at time 0) and final (i.e., at time |T|) inventories are zero and initial (i.e., at time 1) and final (i.e., at time $|\mathrm{T}+1|$) backorders are also zero.

We now present our DSCR model, a MIP:

MIP Formulation of Problem : $(DSCR-T)$

$$Z^* = \min \sum_{t\in T}\sum_{\ell\in L_{PDC}}\left[\sum_{k\in K_\ell} G^O_{k\ell t} O_{k\ell t} + G^M_{\ell t} M_{\ell t} + G^C_{\ell t} C_{\ell t}\right]$$
$$+ \sum_{t\in T}\sum_{\ell\in L_{PDC}}\left[\sum_{j\in J_\ell} G^E_{j\ell t} E_{j\ell t} + \sum_{i\in I_\ell} G^D_{i\ell t} D_{i\ell t} + F_{\ell t}\,\widehat{K}_{\ell t}\right]$$
$$+ \sum_{t\in T}\sum_{\ell\in L}\sum_{p\in P}\left[H^p_{\ell t} y^p_{\ell t} + Q^p_{\ell t} v^p_{\ell t} + R^p_{\ell t} r^p_{\ell t} + \sum_{\ell'\in \bar{L},\ell'\neq\ell} U^p_{\ell\ell' t} x^p_{\ell\ell' t}\right] \quad (1)$$

Objective (1) is to minimize total cost. Fixed costs include charges for opening $G^O_{k\ell t}$, operating $G^M_{\ell t}$, and closing $G^C_{\ell t}$ facility ℓ and expanding $G^E_{j\ell t}$ and contracting $G^D_{i\ell t}$ capacity while open. Parameter $F_{\ell t}$ penalizes excessive capacity that is not required for processing. Without this term in the objective function, there is no cost-related inducement to eliminate excessive capacity (i.e., by contraction or closing), which causes idleness, entailing unnecessary costs. This is reasonable since an excessive labor force or unused, expensive equipment only adds only to cost, not productivity. Note that facility does not have to be closed at the end of the planning horizon. Variable costs accrue for holding inventories $H^p_{\ell t}$, incurring backorders $Q^p_{\ell t}$, outsourcing $R^p_{\ell t}$, and transporting products $U^p_{\ell\ell' t}$.

s.t. $\sum_{k\in K_\ell} O_{k\ell t} + C_{\ell t} + \sum_{j\in J_\ell} E_{j\ell t} + \sum_{i\in I_\ell} D_{i\ell t} \le 1 \qquad \ell\in L_{PDC}, t\in T \qquad (2)$

$\sum_{s=1}^{T}\sum_{k\in K_\ell} O_{k\ell s} \le 1 \qquad \ell\in L_{PDC} \qquad (3)$

$\sum_{s=1}^{t} C_{\ell s} \le \sum_{s=1}^{t-1}\sum_{k\in K_\ell} O_{k\ell s} \qquad \ell\in L_{PDC}, t\in T\backslash\{1\} \qquad (4)$

$M_{\ell t} = \sum_{s=1}^{t}\left(\sum_{k\in K_\ell} O_{k\ell s} - C_{\ell s}\right) \qquad \ell\in L_{PDC}, t\in T \qquad (5)$

$\sum_{j\in J_\ell} E_{j\ell t} \le M_{\ell t} \qquad \ell\in L_{PDC}, t\in T \qquad (6)$

$$\sum_{i\in I_\ell} D_{i\ell t} \le M_{\ell t} \qquad \ell \in L_{PDC}, t \in T \qquad (7)$$

$$\sum_{t\in T}\left[\sum_{k\in K_\ell} G^O_{k\ell t} O_{k\ell t} + G^C_{\ell t} C_{\ell t} + G^M_{\ell t} M_{\ell t} + \sum_{j\in J_\ell} G^E_{j\ell t} E_{j\ell t} + \sum_{i\in I_\ell} G^D_{i\ell t} D_{i\ell t}\right]$$

$$\le B_\ell \quad \ell \in L_{PDC} \qquad (8)$$

$$\sum_{t\in T} \sum_{j\in J_\ell} E_{j\ell t} \le N^E_\ell \qquad \ell \in L_{PDC} \qquad (9)$$

$$\sum_{t\in T} \sum_{i\in I_\ell} D_{i\ell t} \le N^D_\ell \qquad \ell \in L_{PDC} \qquad (10)$$

$$\sum_{t\in T} \sum_{j\in J_\ell} E_{j\ell t} + \sum_{t\in T} \sum_{i\in I_\ell} D_{i\ell t} \le N^T_\ell \qquad \ell \in L_{PDC} \qquad (11)$$

$$\sum_{\ell'\in L_{e+1}} x^p_{\ell\ell' t} - \sum_{\ell''\in L_{e-1}} x^p_{\ell''\ell t} + y^p_{\ell,t-1} - y^p_{\ell t} + v^p_{\ell,t+1} - v^p_{\ell t} + r^p_{\ell t} = b^p_{\ell t}$$

$$p \in P, \ell \in L, \ell' \ne \ell, t \in T \qquad (12)$$

$$S_{\ell\ell' t} \le M_{\ell t} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ \ell' \ne \ell, t \in T \qquad (13)$$

$$S_{\ell\ell' t} \le M_{\ell' t} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ \ell' \ne \ell, t \in T \qquad (14)$$

$$\sum_{\ell\in L_{DC}} S_{\ell\ell' t} = 1, \qquad \ell' \in L_{cz}, t \in T \qquad (15)$$

$$\sum_{p\in P} \ x^p_{\ell\ell' t} \le V_{\ell\ell' t} S_{\ell\ell' t} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ \ell' \ne \ell, t \in T \qquad (16)$$

$$\sum_{\ell'\in L_{e+1},\, \ell'\ne\ell} \ \sum_{p\in P} \delta^p_\ell x^p_{\ell\ell' t} \le \left[\sum_{k\in K_\ell} K_{k\ell} + \sum_{j\in J_\ell} \overline{K}_{j\ell s}\right] M_{\ell t},$$

$$\ell \in L_{PDC}, t \in T \qquad (17)$$

$$\sum_{\ell'\in L_{e+1},\, \ell'\ne\ell} \ \sum_{p\in P} \delta^p_\ell x^p_{\ell\ell' t} \le \ \sum_{s=1}^{t} [\sum_{k\in K_\ell} K_{k\ell} O_{k\ell s} + \sum_{j\in J_\ell} \overline{K}_{j\ell s} E_{j\ell s} \ -$$

$$\sum_{i\in I_\ell} \underline{K}_{i\ell s} D_{i\ell s}], \qquad \ell \in L_{PDC}, t \in T \qquad (18)$$

$$\widehat{K}_{\ell t} \ge \ \sum_{s=1}^{t} [\sum_{k\in K_\ell} K_{k\ell} O_{k\ell s} + \sum_{j\in J_\ell} \overline{K}_{j\ell s} E_{j\ell s} \ - \sum_{i\in I_\ell} \underline{K}_{i\ell s} D_{i\ell s}]$$

$$- \sum_{\ell'\in L_{e+1},\, \ell'\ne\ell} \ \sum_{p\in P} \delta^p_\ell x^p_{\ell\ell' t} - \left[K_{k\ell} + \sum_{j\in J_\ell} \overline{K}_{j\ell s}\right](1 - M_{\ell t}) \ ,$$

$$\ell \in L_{PDC}, t \in T \qquad (19)$$

$$C_{\ell t} = 0, E_{j\ell t} \ = 0, D_{i\ell t} = 0, \qquad \ell \in L_{PDC}, j \in J_\ell, i \in I_\ell, t = 1 \qquad (20)$$

$$y^{p}_{\ell,t=0} = y^{p}_{\ell,t=|T|} = 0 \qquad p \in P, \ell \in L_{PDC} \qquad (21)$$

$$v^{p}_{\ell,t=1} = v^{p}_{\ell,t=|T|+1} = 0 \qquad p \in P, \ell \in L_{PDC} \qquad (22)$$

$$E_{j\ell t}, D_{i\ell t}, O_{k\ell t}, C_{\ell t}, M_{\ell t} \in \{0,1\} \quad j \in J_{\ell},\ i \in I_{\ell}, k \in K_{\ell}, \ell \in L_{PDC},\ t \in T \quad (23)$$

$$S_{\ell\ell' t} \in \{0,1\} \qquad \ell \in L_e, \ell' \in L_{e+1},\ \ell' \neq \ell, t \in T \qquad (24)$$

$$x^{p}_{\ell\ell' t} \geq 0 \qquad p \in P,\ \ell \in L_e, \ell' \in L_{e+1},\ \ell' \neq \ell, t \in T \qquad (25)$$

$$y^{p}_{\ell t} \geq 0, v^{p}_{\ell,t} \geq 0, r^{p}_{\ell t} \geq 0 \qquad p \in P,\ \ell \in L_{PDC}, t \in T \qquad (26)$$

$$\widehat{K}_{\ell t} \geq 0 \qquad \ell \in L_{PDC}, t \in T \qquad (27)$$

Inequalities (2) ensure that at most one decision is prescribed during time period t to open or close facility ℓ, or expand or contract its capacity, preventing two or more such decisions in the same period. Inequalities (3) allow at most one opening at location ℓ over the planning horizon. Constraints (4) allow facility ℓ to be closed in period t only if it was opened in a previous period. Equalities (5) specify that facility ℓ is operating in period t ($M_{\ell t} = 1$) if it has been opened, but not closed, by that time. Facility ℓ is operating from the time period it is opened until the period it is closed. Inequalities (6) ((7)) ensure that at most one expansion (contraction) alternative can be prescribed at location ℓ in period t if that facility is operating.

Budget constraints (8) limit the amount of capital that can be invested in the fixed costs at location ℓ over the entire planning horizon for opening, expanding and contracting capacity, and closing the facility. This is plausible in that each potential location might have a limited budget allocation according to the overall long-term plan of the enterprise. Inequalities (9) ((10)) limit the maximum number of capacity expansions (contractions) allowed over the planning horizon at location ℓ to $N_\ell^E (N_\ell^D)$. The number of expansions *and* contractions is also limited by the budget and to N_ℓ^T by constraints (11).

Flow conservation constraints (12) ensure that demands in all CZs are met each period. Demand for end-products occurs only in CZs. Nodes representing suppliers are sources of flow and thus have positive $b_{\ell t}^p$ values, while nodes representing CZs are flow sinks and have negative $b_{\ell t}^p$ values. Nodes in intermediate echelons represent production plants or DCs that process (or store) a product and can be viewed as transshipment nodes, each with $b_{\ell t}^p = 0$. It is realistic to assume that manufacturing plants and DCs can hold stock from a previous period, receive flow from an outside supplier, and receive backorders from a subsequent period. For each product p, the summation of flow out to downstream nodes, inventory of p from period t -1, outsourcing of p in period t, and input backorders of p from t+1 minus the summation of flow in from each intermediate node from upstream facilities, inventory of p at the end of period t, and backorders of p at the end of period t sum to $b_{\ell t}^p$. Each supplier is assumed to have unlimited capacity.

Inequalities (13) ((14)) assure that the transportation link from ℓ to ℓ' can be used only if facilities at locations ℓ and ℓ' are both operating. Any product can be shipped on an established transportation link from ℓ to ℓ' during period t when that link is established. Single sourcing constraints (15) require that only one DC supplies customer zone $\ell' \in L_{cz}$ with all types of products, which is a common practice in industry. Constraints (16) allow product p to flow from location ℓ to ℓ' only in time periods during which the transportation link from ℓ to ℓ' is established.

Inequalities (17)-(18) assure that the total flow from facility ℓ during time period t cannot exceed its capacity (i.e., after any expansions and/or contractions). Without constraints (17), even closed facilities can be used by a transportation link since the RHS of constraint (18) accumulates capacity from opening, expansions, and contractions at location ℓ and does not eliminate it upon closing. Constraints (17) turn off the capacity of a facility once it has been closed. Inequalities (19) and (27) define $\widehat{K}_{\ell t}$ the capacity of facility ℓ that is not used, that is, excess capacity.

Equalities (20) enforce the fact that a facility at location ℓ cannot be closed, expanded, or contracted in period $t = 1$ since it cannot be opened prior to that period. Equalities (21) and (22) invoke the assumption that the on-hand inventory and backordered amount for each product at the start and end of the planning horizon are zero. Restrictions (23) and (24) impose nonnegativity and binary requirements and (25) and (26) invoke nonnegativity conditions for material flow, inventory variables, backordering, and outsourcing variables, respectively. Restrictions (27) invoke nonnegativity conditions for excess capacity variables.

We discuss our DSCR model in more detail. Instead of constraints (4) and (5), Wesolowsky and Truscott (1975) employed constraints (28) in their dynamic facility location problem to define a relation between opening, operating, and closing variables:

$$\mathrm{C}_{\ell \mathrm{t}} - \sum_{k \in K_\ell} O_{k\ell t} = \mathrm{M}_{\ell,\mathrm{t}-1} - \mathrm{M}_{\ell \mathrm{t}}, \ell \in L, t \in T. \qquad (28)$$

Although Wesolowsky and Truscott (1975) did not mention it explicitly, $\mathrm{M}_{\ell,\mathrm{t}=0}$ must be fixed to zero for each location at which a facility is not operating in time period 0 before opening it at the beginning of time period 1. Without this boundary condition of

$\mathrm{M}_{\ell,\mathrm{t}=0} = 0$, a facility is allowed to operate even though it has not been opened. Our DSCR model assumes that all potential facilities are not yet opened at the beginning of the planning horizon. If a facility is to operate (i.e., $\mathrm{M}_{\ell\mathrm{t}} = 1$), it must first be opened (i.e., $\sum_{k\in K_\ell} O_{k\ell t} = 1$); thus, if we employ constraints (28) instead of (4) and (5), we would need to include constraints, $M_{\ell,t=0} = 0$. If a facility were operating before the beginning of the planning horizon, the boundary condition of $\mathrm{M}_{\ell,\mathrm{t}=0} = 1$ would be required. Our preliminary computational tests showed that our DSCR model solves faster using constraints (4) and (5) than with (28).

Another approach for prescribing facility opening and closing is to define two location index sets: one set for facilities that can be opened and expanded, and the other set existing facilities that can be contracted and closed (e.g., Van Roy and Erlenkotter, 1982; Melo *et al*., 2006; Hinojosa *et al*., 2000, 2008; Thanh *et al*., 2008). In contrast to our model, this approach does not allow the same facility to expanded and contracted over the planning horizon once opened (and before closure).

The RHS of inequality (18), if denoted by $\widetilde{K}_{\ell t}$, is the amount of capacity that is accumulated at location ℓ by opening, expanding, and contracting up through period t:

$$\widetilde{K}_{\ell t} = \sum_{s=1}^{t}\left[\sum_{k\in K_\ell} K_{k\ell} O_{k\ell s} + \sum_{j\in J_\ell} \overline{K}_{j\ell s} E_{j\ell s} - \sum_{i\in I_\ell} \underline{K}_{i\ell s} D_{i\ell s}\right] \qquad \ell \in L, t \in T. \quad (29)$$

We note that, even though a facility is closed, (18) continues to define its accumulated capacity the same from the period it is closed to the end of the planning horizon; thus, constraints (17) are needed to “turn off” the accumulated capacity of a closed facility. The LHS of inequality (17) and (18) is the amount of capacity of facility ℓ that is used during time period t and, for convenience, may be denoted as $\overline{\overline{K}}_{\ell t}$,

$$\bar{\bar{K}}_{\ell t} = \sum_{p \in P} \sum_{\ell \neq \ell', \ell' \in \bar{L}} \delta_{\ell}^{p} x_{\ell \ell' t}^{p} \; \ell \in L, t \in T. \tag{30}$$

and where $\bar{\bar{K}}_{\ell t} \leq \widetilde{K}_{\ell t}$. We do not include capacity variables $\widetilde{K}_{\ell t}$ and $\bar{\bar{K}}_{\ell t}$ explicitly in the DSCR model but we do use them in the computational evaluation chapter later to provide the reader intuition about how capacity increases and decreases over time.

11.2 Alternative MIP formulation of DSCR

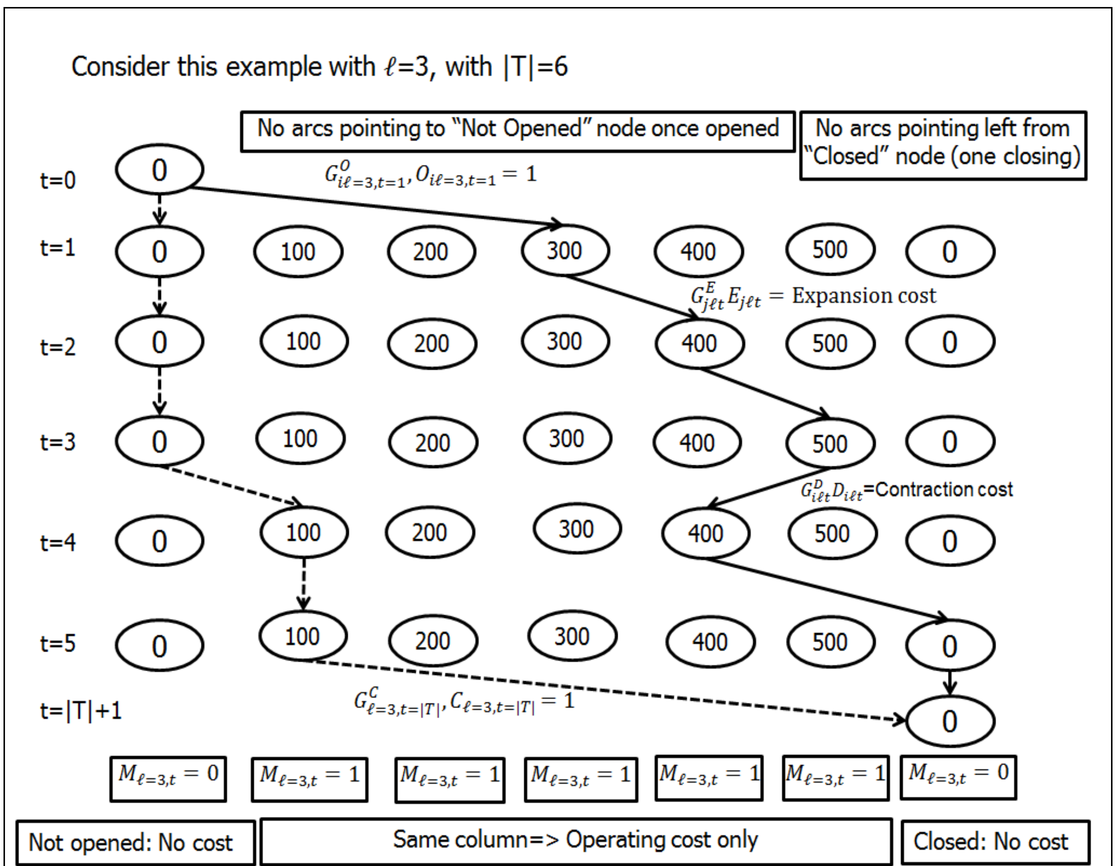
We now present an alternative MIP formulation for the DSCR problem, which we call DSCR-N. We use notation defined earlier and also introduce some additional symbols. We use K_{ℓ} to denote the index set of alternative capacities that might be provided at location ℓ and let $n = |K_{\ell}|$. The amount of capacity provided by alternative $k \in K_{\ell}$ is given by $\bar{U}_k$. Given that capacity alternative $j \in K_{\ell}$ is used in time period t, the index set of feasible capacity-expansion alternatives that can be used in period $t+1$ is denoted by $\vec{K}_{j\ell t}$, which includes the special case $j \in \vec{K}_{j\ell t}$, indicating that capacity alternative j is used in period t as well as in period $t+1$ with no expansion or contraction. Similarly, given that capacity alternative j is used in time period t, the index set of feasible capacity-contraction alternatives is denoted by $\overleftarrow{K}_{j\ell t}$; each $k \in \overleftarrow{K}_{j\ell t}$ denotes a feasible, reduced capacity $\bar{U}_k$ that is available for use in period $t+1$. Let $\bar{U}_k^{max}$ denote the maximum capacity of any alternative at location ℓ, which equals to $\bar{U}_n$.

Expansion (contraction) is defined by a positive (negative) capacity increment in DSCR-T; however, in the reformulation, the net capacity after expansion and contraction is defined by the capacity alternative in time period $t+1$. We define binary decision variable $z_{jk\ell t} = 1$ if the facility at location $\ell \in L$ utilizes capacity alternative j in period t and expands or contracts to use capacity alternative k in period $t + 1$. Instead of using five binary variables (i.e., $O_{\ell t}$, $M_{\ell t}$, $E_{j\ell t}$, $D_{i\ell t}$, and $C_{\ell t}$) for location ℓ in period t, depending on the combination of j and t, we use variable $z_{jk\ell t}$ to represent opening, operating, expanding, contracting, and closing over time at location ℓ. Note that variable $z_{jk\ell t}$ is defined only for L_P and L_{DC} since each suppliers and each CZ are fixed in the "open" state and cannot be expanded or contracted.

Corresponding costs are applied to $z_{jk\ell t}$, depending on the combination of capacity alternatives j and k and time period t. For example, capacity expansion with $j < k$ (contraction with $j > k$) at location ℓ in period $t + 1$ incurs fixed cost $G_{jk\ell t}^{E}$ ($G_{jk\ell t}^{D}$). We define costs parameters $G_{jk\ell t}^{ME}$ and $G_{jk\ell t}^{MD}$ as $G_{jk\ell t}^{ME} = G_{jk\ell t}^{E} + G_{j\ell t}^{M}$ and $G_{jk\ell t}^{MD} = G_{jk\ell t}^{D} + G_{j\ell t}^{M}$, respectively. Other constraints and variables are the same as in DSCR-T.

Before presenting DSCR-N formulation, we present an example of the capacity alternative network for location ℓ, which employs binary variable $z_{jk\ell t}$ instead of $O_{k\ell t}, M_{\ell t}$, $E_{j\ell t}$, $D_{i\ell t}$, and $C_{\ell t}$ (see Figure 5). The figure depicts the directed, acyclic network $G(\bar{N},\ \bar{A})$ in which $\bar{N}$ is the index set of nodes of capacity alternatives and $\bar{A}$ is the index set of (directed) arcs that connect feasible capacity alternatives relative to constraints (2)-(7). As a result, the structure of network $G(\bar{N},\ \bar{A})$ satisfies constraints (2)-(7) of DSCR-T for location ℓ over the entire planning horizon; thus, the DSCR-N reformulation does not explicitly include (2)-(7); rather, it introduces a "flow conservation" constraint for variable $z_{jk\ell t}$ to prescribe a single optimal capacity alternative path for location ℓ.

$\bar{N}$ includes a (dummy) start node in level $t = 0$ and a (dummy) end node in level $\tau = |T| + 1$, where T is the index set of time periods in the planning horizon. Level t represents time period t. Nodes in the first (last) column represent the decision to not open (close) facility ℓ in time period t. Each column of nodes represents an alternative capacity that can be prescribed for facility ℓ.



SP 1(ℓ) network with ℓ=3, with T=6

Figure 5. An example network of a RCSPP in SP1

Each arc $a = (j,k) \in \bar{A}$ points from capacity alternative node j in level t to a capacity alternative node k in level $t+1$. The network incorporates five types of arcs, each with a corresponding type of cost for opening, operating, expanding, contracting, and closing, respectively. The cost associated with each is applied to each of the corresponding arcs (i.e., expanding arcs, contracting arcs, and arcs maintaining the same capacity). An optimal path from the start node defines a capacity alternative for each time period and may involve opening, operating, expanding and contracting capacity, and closing the facility (e.g., see the two possible paths composed of arcs represented by solid and dash lines in Figure 5).

We now present the objective function in a form that highlights each of the individual costs that may be incurred.

$$Z^* = \min \sum_{t\in T} \sum_{\ell\in L_{PDC}} \sum_{k\in \vec{K}_{j\ell t}} (G^{O}_{k\ell t} + G^{M}_{k\ell t}) z_{j=0,k\ell t} + \sum_{\ell\in L} \sum_{k\in K_\ell} G^{O}_{k\ell t} z_{j=0,k\ell t=0}$$

$$+ \sum_{t\in T} \sum_{\ell\in L_{PDC}} \sum_{j\in K_\ell\setminus\{0\}} G^{C}_{\ell t} z_{j,k=n+1,\ell t}$$

$$+ \sum_{t\in T} \sum_{\ell\in L_{PDC}} \sum_{j\in K_\ell} \left(\sum_{k\in \vec{K}_{j\ell t}} G^{ME}_{jk\ell t} z_{jk\ell t} + \sum_{k\in \overleftarrow{K}_{j\ell t}} G^{MD}_{jk\ell t} z_{jk\ell t}\right)$$

$$+ \sum_{t\in T} \sum_{\ell\in L_e} F_{\ell t} \Big[\sum_{k\in \vec{K}_{j\ell t}} \overline{U}_j z_{j=0,k\ell t} + \sum_{j\in K_\ell} \sum_{k\in \vec{K}_{j\ell t}\cup \overleftarrow{K}_{j\ell t}} \overline{U}_j z_{jk\ell t} -$$

$$\sum_{\ell'\in L_{e+1}, \ell'\neq \ell} \sum_{p\in P} \delta^{p}_{\ell} x^{p}_{\ell\ell' t}\Big]$$

$$+ \sum_{t\in T} \sum_{\ell\in L_e} \sum_{p\in P} \Big[H^{p}_{\ell t} y^{p}_{\ell t} + Q^{p}_{\ell t} v^{p}_{\ell t} + R^{p}_{\ell t} r^{p}_{\ell t} + \sum_{\ell'\in L_{e+1}, \ell'\neq \ell} U^{p}_{\ell\ell' t} x^{p}_{\ell\ell' t}\Big] \qquad (31)$$

We now present our DSCR-N reformulation: (DSCR-N)

$$Z^* = \min \sum_{t\in T} \sum_{\ell\in L_{PDC}} \sum_{k\in \vec{K}_{j\ell t}} (F_{\ell t}\overline{U}_j + G^{O}_{k\ell t} + G^{M}_{k\ell t}) z_{j=0,k\ell t}$$

$$+ \sum_{\ell\in L} \sum_{k\in K_\ell} G^{O}_{k\ell t} z_{j=0,k\ell t=0}$$

$$+ \sum_{t\in T} \sum_{\ell\in L_{PDC}} \sum_{j\in K_\ell\setminus\{0\}} G^{C}_{\ell t} z_{j,k=n+1,\ell t}$$

$$+ \sum_{t\in T} \sum_{\ell \in L_{PDC}} \sum_{j\in K_\ell} [\sum_{k\in \vec{K}_{j\ell t}} \left(F_{\ell t}\overline{U}_j + G^{ME}_{jk\ell t}\right) z_{jk\ell t} + \sum_{k\in \overleftarrow{K}_{j\ell t}} \left(F_{\ell t}\overline{U}_j + G^{MD}_{jk\ell t}\right) z_{jk\ell t}]$$

$$+ \sum_{t\in T} \sum_{\ell\in L_e} \sum_{p\in P} [H^p_{\ell t} y^p_{\ell t} + Q^p_{\ell t} v^p_{\ell t} + R^p_{\ell t} r^p_{\ell t} + \sum_{\ell' \in L_{e+1}, \ell' \neq \ell} (U^p_{\ell \ell' t} - F_{\ell t} F_{\ell t}) x^p_{\ell \ell' t}] \quad (32)$$

s.t.

$$\sum_{j\in K_\ell} z_{kj\ell t} - \sum_{j\in K_\ell} z_{jk\ell, t-1} = \rho_{k\ell t} \qquad k \in K_\ell, \ell \in L_{PDC}, t \in T \qquad (33)$$

$$\sum_{t\in T\cup\{0\}} \sum_{j\in K_\ell} \sum_{k\in K_{j\ell t}} \psi_{jk\ell t} z_{jk\ell t} \le B_\ell \qquad \ell \in L_{PDC} \qquad (34)$$

$$\sum_{t\in T} \sum_{j\in K_\ell \setminus \{0,n+1\}} \sum_{k\in \vec{K}_{j\ell t} \setminus \{j\}} z_{jk\ell t} \le N^E_\ell \qquad \ell \in L_{PDC} \qquad (35)$$

$$\sum_{t\in T} \sum_{j\in K_\ell \setminus \{0,n+1\}} \sum_{\in \overleftarrow{K}_{j\ell t} \setminus \{j\}} z_{jk\ell t} \le N^D_\ell \qquad \ell \in L_{PDC} \qquad (36)$$

$$\sum_{t\in T} \sum_{j\in K_\ell \setminus \{0,n+1\}} \sum_{k\in \{\vec{K}_{j\ell t} \cup \overleftarrow{K}_{j\ell t}\} \setminus \{j\}} z_{jk\ell t} \le N^T_\ell \qquad \ell \in L_{PDC} \qquad (37)$$

$$\sum_{\ell' \in L_{e+1}} x^p_{\ell \ell' t} - \sum_{\ell'' \in L_{e-1}} x^p_{\ell'' \ell t} + y^p_{\ell, t-1} - y^p_{\ell t} + v^p_{\ell, t+1} - v^p_{\ell t} + r^p_{\ell t} = b^p_{\ell t}$$

$$p \in P, \ell \in L, \ell' \neq \ell, t \in T \qquad (38)$$

$$S_{\ell \ell' t} \le \sum_{j\in K_\ell \setminus \{0,n+1\}} \sum_{k\in K_{j\ell t}} z_{jk\ell t} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ell' \neq \ell, t \in T \qquad (39)$$

$$S_{\ell \ell' t} \le \sum_{j\in K_{\ell'} \setminus \{0,n+1\}} \sum_{k\in K_{j\ell' t}} z_{jk\ell' t} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ell' \neq \ell, t \in T \qquad (40)$$

$$\sum_{\ell \in L_{DC}} S_{\ell \ell' t} = 1 \qquad \ell' \in L_{cz}, t \in T \qquad (41)$$

$$\sum_{p\in P} x^p_{\ell \ell' t} \le V_{\ell \ell' t} S_{\ell \ell' t} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ell' \neq \ell, t \in T \qquad (42)$$

$$\sum_{\ell' \in L_{e+1}, \ell' \neq \ell} \sum_{p\in P} \delta^p_\ell x^p_{\ell \ell' t} \le \sum_{j=0, k\in \vec{K}_{0\ell t}} \overline{U}_j z_{jk\ell t} + \overline{U}_j z_{j=n+1, k=n+1, \ell t}$$

$$+ \sum_{j\in K_\ell \setminus \{0,n+1\}} \sum_{k\in K_\ell} \overline{U}_j z_{jk\ell t}, \qquad \ell \in L_{PDC}, t \in T \qquad (43)$$

$$z_{jk\ell t} \in \{0,1\} \qquad j,k \in K_\ell, \ell \in L_{PDC}, t \in T \cup \{0\} \qquad (44)$$

$$S_{\ell \ell' t} \in \{0,1\} \qquad \ell \in L_e, \ell' \in L_{e+1}, \ell' \neq \ell, t \in T \qquad (45)$$

$$y^p_{\ell, t=0} = y^p_{\ell, t=|T|} = 0 \qquad p \in P, \ell \in L_{PDC} \qquad (46)$$

$$v^p_{\ell, t=1} = v^p_{\ell, t=|T|+1} = 0 \qquad p \in P, \ell \in L_{PDC} \qquad (47)$$

$$x^p_{\ell \ell' t} \ge 0 \qquad p \in P, \ \ell \in L_e, \ell' \in L_{e+1}, \ell' \neq \ell, t \in T \qquad (48)$$

$$y_{\ell t}^{p} \geq 0, v_{\ell,t}^{p} \geq 0, r_{\ell t}^{p} \geq 0 \qquad p \in P,\ \ell \in L_{PDC}, t \in T \qquad (49)$$

Objective (32) is the same as (1) in the DSCR-T, which minimizes total costs. Flow conservation constraint (33) ensures that opening, expansions, contractions, and closing occur consistently over the planning horizon, essentially invoking (2)-(7). These constraints formulate the shortest-cost capacity alternative path as a network flow problem in which one unit of flow originates at the start node, travels through the network, and terminates at the end node. This requires a flow balance at each node, so that the summation of the flow out of node k minus the flow into it equals $\rho_{k\ell t}$, where $\rho_{k=0,\ell,t=0} = +1$, $\rho_{k=n+1,\ell,t=\tau} = -1$, and $\rho_i = 0$ for $i \in \bar{N} \backslash \{start\ node \cup end\ node\}$.

Inequalities (34) limit the amount of capital that can be invested in the fixed costs at location ℓ over the entire planning horizon for opening, expanding and contracting capacity, and closing the facility at location ℓ. $\psi_{jk\ell t}$ is specific to each combination of j and k: (i) j=0, k>=1 (opening & operating), $G_{k\ell t}^{O}$; (ii) j>1, and k>j (expansion & operating), $G_{jk\ell t}^{ME}$; (iii) j>1 and k<j (contraction & operating), $G_{jk\ell t}^{MD}$ (iv) j>1, k=j (operating without capacity change), $G_{k\ell t}^{M}$; (v) j>1, k=n+1 (closing cost), $G_{k\ell t}^{C}$; (vi) j=0, j=0, cost 0; (vii) j=n+1, j=n+1, cost 0. The RHSs of (39) and (40) are either zero or one, contributing to a tighter polytope that forms the feasible region for the linear relaxation of DSCR-N.

Other constraints are the same as in DSCR-T. Chapter XIII compares the sizes of these two models (i.e., numbers of constraints and continuous and binary variables) and the run time each requires.

CHAPTER XII

BRANCH AND PRICE (B&P) APPROACH

This chapter discusses an overview of column generation (CG), Dantzig-Wolfe Decomposition (DWD), and branch and price (B&P) approach. It also presents two B&P reformulation schemes for our refined DSCR-N model.

12.1 Overview of CG, DWD, and B&P approach

Real-world instances of our MIP model can be very large. Thus, to solve DSCR, we propose a B&P approach of the type that has proven to be a good approach for solving large-scale instances with special structure. Before presenting our B&P approach, we briefly review related concepts and solution methods.

Column generation (CG) has been one of the most successful approaches for solving large-scale linear programs (Wilhelm, 2001). The large-scale programs typically comprise a huge number of columns, which can be decomposed into the master problem (MP) and subproblems (SP(s)). Rather than enumerating all columns explicitly in the MP, CG deals with them implicitly by generating columns from associated SPs and incorporating them in a restricted master problem (RMP) as needed.

Wilhelm (2001) classified CG into three types, all of which involve an MP to be optimized and some type of SP(s) to generate columns. Type I CG uses an auxiliary problem (AP) to identify a promising set of columns, defining a MP that optimizes over these explicitly defined columns. The MP accepts these columns and does not interact further with the AP. Clearly, this CG does not guarantee optimality since it may not identify the set of optimal columns. Unlike Type I CG, Type II CG allows for RMP and SP to interact with each other to generate improving columns for the next iteration.

Type III CG, which is based on DWD (Dantzig and Wolfe, 1960), employs one or more SPs that interact with the RMP. At each iteration, values of dual variables from the RMP update the objective function coefficients in each SP and SPs are solved to generate an improving column, if possible. DWD, which is a form of CG (Jones *et al*., 1993; Barnhart *et al*., 1995; Wilhelm, 2001; Holmberg and Yuan, 2003; Liang and Wilhelm, 2010), represents each SP polytope by forming a convex combination of the columns (i.e., extreme-point solutions) of SP(s) while Type II CG enters improving columns into the RMP basis directly, without forming such convex combinations.

DWD, which is a price-directed decomposition method (Barnhart *et al*., 1995; Wilhelm, 2001), can be used to optimize an MIP by solving the linear relaxation of the RMP at each node in the B&B search tree to obtain a bound on the optimal integer program solution value (Wilhelm 2001; Liang and Wilhelm, 2010). The B&P approach, which uses DWD, reformulates the given MIP model as a MP and one or more SPs and CG is then used to deal with the large number of variables that constitute the reformulated model. To obtain an integer optimal solution, B&B uses RMP to provide a bound on the optimal integer solution value at ach node in the search tree.

The primary motivation for the development of the B&P approach is the advantage that the reformulation provides, decomposing a large problem into smaller SPs and then combining (partial) solutions from them to form a co-ordinated solution to the overall problem (Wilhelm, 2001). DWD and B&P have become some of the most successful approaches to dealing with large-scale linear (e.g., Gilmore and Gomory, 1961), integer (e.g., Desaulniers *et al*., 2001), and mixed integer linear programming (Wilhelm, 2001).

Appelgren (1969) presented the earliest use of B&P, solving a ship-scheduling problem. Desrosiers *et al*. (1984) applied B&P successfully to the vehicle routing problem; subsequently, it has been used to advantage in many applications, including integer multi-commodity flow (Alvelos and Valerio de Carvalho, 2007; Barnhart *et al*., 1995), cutting stock (Ben Amor and Valerio de Carvalho, 2005; Valerio de Carvalho, 2005), and crew scheduling (Desaulniers *et al*., 2001) problems. Recently, Klose and Gortz (2007) and Ceselli *et al*. (2009) applied B&P to the capacitated facility location problem. Surveys on CG and B&P include those of Wilhelm (2001), Lubbecke and Desrosiers (2002) and Desaulniers *et al*. (2005).

12.2 B&P reformulation schemes

A primary concern in designing an effective B&P reformulation is to obtain well-structured SPs that can be solved effectively. To address this concern, we propose two B&P reformulation schemes (see Table 14) for our DSCR-N model; both relegate constraints (39)-(43) and (45) and binary variables $S_{\ell\ell' t}$ to MP. The first scheme employs two types of subproblems (SPs): SP Type 1 (SP1) comprises constraints (33)-(37) and (44) and associated binary variables, $z_{jk\ell t}$, and SP Type 2 (SP2) comprises flow conservation constraints (38), boundary conditions (46) and (47), nonnegativity restrictions (48)-(49), and flow variables $x^p_{\ell\ell' t}$, $y^p_{\ell t}$, $v^p_{\ell t}$, $r^p_{\ell t}$. SP1 and SP2 each have a block diagonal structure that can be decomposed into a set of SPs, each with convenient structure. Each SP of type 1 prescribes the opening and closing of a facility at location $\ell \in L$ as well as capacity expansions and contractions and can be solved effectively as a resource-constrained shortest path problem (RCSPP). Each SP of type 2 represents the flow of materials through the supply chain for one product $p \in P$. Such a minimum cost network flow problem can be solved in polynomial time but, because it has the Integrality Property (Wilhelm, 2001), it cannot tighten the bound provided by B&P in comparison to that provided by the linear relaxation of the original problem (32)-(49). The B&P second scheme includes SP2 constraints and variables in the MP and retains only SP1.

Table 14. B&P schemes 1 and 2

Constraints and variables in scheme		B&P reformulation scheme 1	B&P reformulation scheme 2
Constraints	MP	(39)-(43), (45)	(38)-(43), (45)-(49)
	SP	SP 1: (33)-(37), (44) SP 2: (38), (46)-(49)	SP 1: (33)-(37), (44)
	Binary Variable	* Integer solutions of binary variables obtained in SP1 at each location	
Variables	MP	$S_{\ell\ell' t}$	$S_{\ell\ell' t}, x^p_{\ell\ell' t}, y^p_{\ell t}, v^p_{\ell t}, r^p_{\ell t}$
	SP	SP 1: $z_{jk\ell t}$ SP 2: $x^p_{\ell\ell' t}, y^p_{\ell t}, v^p_{\ell t}, r^p_{\ell t}$	$z_{jk\ell t}$
SP Type		SP 1, $\ell \in L$ SP 2, $p \in P$	SP 1, $\ell \in L$

We now present our B&P reformulations in compact from to highlight structures. Defining n_1, n_2, n_3, and n_4-vectors, $\boldsymbol{s}$, $\boldsymbol{z}$, $\boldsymbol{x}$, and $\boldsymbol{y}$ for binary variables for arcs, 5 types of binary variables for node (i.e., facility), continuous variables for a flow amount on an arc, and continuous variables for inventory, backordering, and outsourcing at a facility, respectively as shown in Table 15. We also group a set of interrelated constraints relative to the binary and continuous variables.

Table 15. Compact representation of DSCR-N

Variables and constraints	DSCR-N	DSCR-Compact
Variables	$s_{\ell\ell' t}$	$\boldsymbol{s} = ({s_{\ell\ell' t}}^T)^T,\ n_1 = \lvert\boldsymbol{s}\rvert$
	$z_{jk\ell t}$	$\boldsymbol{z} = ({z_{jk\ell t}}^T)^T,\ n_2 = \lvert\boldsymbol{z}\rvert$
	$x^p_{\ell\ell' t}$	$\boldsymbol{x} = ({x^p_{\ell\ell' t}}^T)^T,\ n_3 = \lvert\boldsymbol{x}\rvert$
	$y^p_{\ell t}, v^p_{\ell t}, r^p_{\ell t}$	$\boldsymbol{y} = ({y^p_{\ell t}}^T, {v^p_{\ell t}}^T, {r^p_{\ell t}}^T)^T, n_4 = \lvert\boldsymbol{y}\rvert$
Constraints	(33)	(51) $\boldsymbol{A_1} \in \mathbb{Q}^{m_1 \times n_2}$, $\boldsymbol{d_1} \in \{0,1\}^{m_1}$
	(34)-(37)	(52) $\boldsymbol{A_2} \in \mathbb{Q}^{m_2 \times n_2}$, $\boldsymbol{d_2} \in \mathbb{Q}^{m_2}$
	(38)	(53) $\boldsymbol{A_3} \in \mathbb{Q}^{m_3 \times n_3}$, $\boldsymbol{A_4} \in \mathbb{Q}^{m_3 \times n_4}$, $\boldsymbol{b} \in \mathbb{Q}^{m_3}$
	(39)-(40)	(54) $\boldsymbol{A_5} \in \mathbb{Q}^{m_4 \times n_3}$, $\boldsymbol{A_6} \in \mathbb{Q}^{m_4 \times n_2}$
	(41)	(55) $\boldsymbol{A_7} \in \mathbb{Q}^{m_5 \times n_1}$
	(42)	(56) $\boldsymbol{A_8} \in \mathbb{Q}^{m_6 \times n_1}$, $\boldsymbol{A_9} \in \mathbb{Q}^{m_6 \times n_3}$
	(43)	(57) $\boldsymbol{A_{10}} \in \mathbb{Q}^{m_7 \times n_2}$, $\boldsymbol{A_{11}} \in \mathbb{Q}^{m_7 \times n_3}$

A_i's are matrices of rational constraint coefficients where m_1, m_2, m_3, m_4,m_5, m_6 and m_7 are the number of constraints (51), (52), (53), (54), (55), (56) and (57), respectively. $\boldsymbol{d_1} \in \{0,1\}^{m_1}$, $\boldsymbol{d_2} \in \mathbb{Q}^{m_2}$ and $\boldsymbol{b} \in \mathbb{Q}^{m_3}$ are rational, right-hand-side (RHS) coefficients of (51), (52), and (53), respectively; and $\mathbf{0}$ and $\mathbf{1}$ are zero and 1 vectors with corresponding dimensions, respectively.

Now, we present our DSCR-Compact model in matrix notation:

$$(DSCR - Compact)\text{: min} \quad \boldsymbol{c}_z^T\boldsymbol{z}^\ell + \boldsymbol{c}_x^T\boldsymbol{x}^{\boldsymbol{p}} + \boldsymbol{c}_y^T\boldsymbol{y}^{\boldsymbol{p}} \tag{50}$$

$$\text{s.t.} \quad \boldsymbol{A_1}\boldsymbol{z}^\ell = \boldsymbol{d_1} \quad \text{for (33), SP1} \tag{51}$$

$$\boldsymbol{A_2}\boldsymbol{z}^\ell \le \boldsymbol{d_2} \quad \text{for (34)-(37), SP1} \tag{52}$$

$$\boldsymbol{A_3}\boldsymbol{x}^{\boldsymbol{p}} + \boldsymbol{A_4}\boldsymbol{y}^{\boldsymbol{p}} = \boldsymbol{b} \quad \text{for (38), SP2} \tag{53}$$

$$\boldsymbol{A_5}\boldsymbol{s} + \boldsymbol{A_6}\boldsymbol{z}^\ell \le \mathbf{0} \quad \text{for (39)-(40), MP} \tag{54}$$

$$\boldsymbol{A_7}\boldsymbol{s} = \mathbf{1} \quad \text{for (41), MP} \tag{55}$$

$$\boldsymbol{A_8}\boldsymbol{s} + \boldsymbol{A_9}\boldsymbol{x}^{\boldsymbol{p}} \le \mathbf{0} \quad \text{for (42), MP} \tag{56}$$

$$\boldsymbol{A_{10}}\boldsymbol{z}^\ell + \boldsymbol{A_{11}}\boldsymbol{x}^{\boldsymbol{p}} \le \mathbf{0} \quad \text{for (43), MP} \tag{57}$$

$$\boldsymbol{s} \in \{0,1\}^{n_1} \tag{58}$$

$$\boldsymbol{z}^\ell \in \{0,1\}^{n_2} \tag{59}$$

$$\boldsymbol{x}^{\boldsymbol{p}} \in \mathbb{R}_+^{n_3} \tag{60}$$

$$\boldsymbol{y}^{\boldsymbol{p}} \in \mathbb{R}_+^{n_4} \tag{61}$$

Here, $\boldsymbol{s} \in \{0,1\}^{n_1}$ represents a n_1-vector of binary variables for transportation links between facilities, while $\boldsymbol{z}^\ell \in \{0,1\}^{n_2}$ represents a n_2-vector of binary variables for opening, operating, expanding, contracting, and closing facility ℓ. $\boldsymbol{c_z} \in \mathbb{Q}^{n_2}$, $\boldsymbol{c_x} \in \mathbb{Q}^{n_3}$, and$\boldsymbol{c_y} \in \mathbb{Q}^{n_4}$ are n_2, n_3, and n_4-vectors, respectively, of rational objective function cost coefficients.

B&P reformulation scheme 1 has two types of SPs. Following DWD, we reformulate $(DSCR - Z)$ by decomposing $(DSCR - Compact)$, which places (51), (52) and (59) in SP1 and (53), (60) and (61) in SP2, respectively. Now, we present (RMP).

$$(RMP)\text{: min} \quad \sum_{k \in \Lambda_\ell} (\boldsymbol{c}_z^\ell \boldsymbol{z}_k^\ell) \lambda_{\ell k} + \sum_{k \in \Delta_p} (\boldsymbol{c}_x^p \boldsymbol{x}_k^p + \boldsymbol{c}_y^{\boldsymbol{p}} \boldsymbol{y}_k^p)\, \delta_{pk} \tag{62}$$

$$\text{s.t.} \quad \boldsymbol{A_5 s} + \sum_{k \in \Lambda_\ell} (\boldsymbol{A_6 z}_k^\ell) \lambda_{\ell k} \leq \boldsymbol{0} \tag{63}$$

$$\boldsymbol{A_7 s} = \boldsymbol{1} \tag{64}$$

$$\boldsymbol{A_8 s} + \sum_{k \in \Delta_p} (\boldsymbol{A_9 x}_k^p)\, \delta_{pk} \leq \boldsymbol{0} \tag{65}$$

$$\sum_{k \in \Lambda_\ell} (\boldsymbol{A_{10} z}_k^\ell) \lambda_{\ell k} + \sum_{k \in \Delta_p} (\boldsymbol{A_{11} x}_k^p)\, \delta_{pk} \leq \boldsymbol{0} \tag{66}$$

$$\sum_{k \in \Lambda_\ell} \lambda_{\ell k} = 1 \qquad \ell \in L \tag{67}$$

$$\sum_{k \in \Delta_p} \delta_{pk} = 1 \qquad p \in P \tag{68}$$

$$\lambda_{\ell k}, \delta_{pk} \geq 0 \tag{69}$$

$$\boldsymbol{s} \in \{0,1\}^{n_1} \tag{70}$$

$$\sum_{k \in \Lambda_\ell} (\boldsymbol{z}_k^\ell) \lambda_{\ell k} \in \{0,1\}^{n_2} \tag{71}$$

$$\sum_{k \in \Delta_p} (\boldsymbol{x}_k^p)\, \delta_{pk} \in \mathbb{R}^{n_3} \tag{72}$$

$$\sum_{k \in \Delta_p} (\boldsymbol{y}_k^p)\, \delta_{pk} \in \mathbb{R}^{n_4} \tag{73}$$

Here, Λ_ℓ (Δ_p) represents the index set of extreme points of SP polytope ℓ (p) of SP 1 (SP 2). Binary restrictions (53) and (41) correspond. Following traditional practice, we relax (52) and (53) and solve the linear relaxation of RMP to obtain a bound for each node in the B&B search tree. Once the solution for $\lambda_{\ell k}$ and δ_{pk} is obtained in (RMP), the solution relative to original binary variables and flow variables can be computed using $\boldsymbol{z}^{\ell} = \sum_{k\in\Lambda_\ell}(\boldsymbol{z}_k^{\ell})\lambda_{\ell k}$, $\boldsymbol{x^p} = \sum_{k\in\Delta_p}(\boldsymbol{x}_k^{p})\,\delta_{pk}$, and $\boldsymbol{y^p} = \sum_{k\in\Delta_p}(\boldsymbol{y}_k^{p})\,\delta_{pk}$, respectively.

Letting $\boldsymbol{\omega} \in \mathbb{R}^{m_4+m_5+m_6+m_7}$, $\boldsymbol{\alpha}_\ell \in \mathbb{R}^{|L|}$, and$\boldsymbol{\alpha}_p \in \mathbb{R}^{|P|}$ correspond to dual variable values associated with constraints (62)-(66), (67) and (68), respectively, where m_4,m_5, m_6 and m_7 are the numbers of constraints (54), (55), (56), and (57), respectively. We now give the general forms of SP1 and SP2.

$$SP\ 1\ (\ell): \quad \boldsymbol{Z}_{\boldsymbol{1}\ell}^{*} = \max\ (\boldsymbol{\omega}^{\boldsymbol{T}}\boldsymbol{A}_\ell - \boldsymbol{c}_z^{\ell})\boldsymbol{z}^{\ell} + \boldsymbol{\alpha}_\ell \tag{74}$$

$$\text{s.t.} \quad \boldsymbol{A_1 z}^{\ell} = \boldsymbol{d_1} \tag{75}$$

$$\boldsymbol{A_2 z}^{\ell} \leq \boldsymbol{d_2} \tag{76}$$

$$\boldsymbol{z}^{\ell} \in \{0,1\}^{n_2} \tag{77}$$

Here, $\boldsymbol{A}_\ell$ represents a sub-matrix of constraint coefficients of $(DSCR - Compact)$ associated with binary variables $\boldsymbol{z}^{\ell}$ for ℓ (i.e., $\boldsymbol{A}_\ell = [\boldsymbol{A}_6;\ \boldsymbol{0};\ \boldsymbol{0};\ \boldsymbol{A}_{10}]$).

$$SP\ 2\ (p): \quad \overline{\boldsymbol{Z}}_{\boldsymbol{2p}}^{*} = \max\ \left(\boldsymbol{\omega}^{\boldsymbol{T}}\boldsymbol{A_p} - \boldsymbol{c}_x^{T}\right)\boldsymbol{x^p} + \left(-\boldsymbol{c}_y^{T}\right)\boldsymbol{y^p} + \boldsymbol{\alpha_p} \tag{78}$$

$$\text{s.t.} \quad \boldsymbol{A_3 x^p} + \boldsymbol{A_4 y^p} = \boldsymbol{b} \tag{79}$$

$$\boldsymbol{x^p} \in \mathbb{R}_{+}^{n_3} \tag{80}$$

$$\boldsymbol{y^p} \in \mathbb{R}_{+}^{n_4} \tag{81}$$

Here, $\boldsymbol{A}_p$ represents a sub-matrix of constraint coefficients of $(DSCR - Compact)$ of the continuous variable set of $\boldsymbol{x^p}$ for p, i.e., $\boldsymbol{A}_p = [\boldsymbol{0};\ \boldsymbol{0};\ \boldsymbol{A_9};\ \boldsymbol{A_{11}}]$.

At each iteration, new values of the dual variables, ($\boldsymbol{\omega} \in \mathbb{R}^{m_4+m_5+m_6+m_7}$, $\boldsymbol{\alpha}_\ell \in \mathbb{R}^{|L|}$, and $\boldsymbol{\alpha}_p \in \mathbb{R}^{|P|}$) are passed from RMP to $SP1$ and $SP2$. Then, SPs are solved with updated objective function coefficients. We include all improving columns identified by solving all SPs in RMP, which is then re-optimized. An improving column from SP1 must satisfy ("$z_j - c_j$" > 0) $\boldsymbol{Z}_{\boldsymbol{1}\ell}^{*} = (\boldsymbol{\omega}^{\boldsymbol{T}}\boldsymbol{A}_{\ell} - \boldsymbol{c}_{w}^{\ell})\boldsymbol{z}^{\ell} + \boldsymbol{\alpha}_{\ell} > 0$ and one from SP2 must satisfy ("$z_j - c_j$" > 0) $\overline{\boldsymbol{Z}}_{\boldsymbol{2p}}^{*} = \left(\boldsymbol{\omega}^{\boldsymbol{T}}\boldsymbol{A}_{\boldsymbol{p}} - \boldsymbol{c}_{x}^{T}\right)\boldsymbol{x}^{\boldsymbol{p}} + \left(-\boldsymbol{c}_{y}^{T}\right)\boldsymbol{y}^{\boldsymbol{p}} + \boldsymbol{\alpha}_{\boldsymbol{p}} > 0$ to enter into RMP. Then, variables $\lambda_{\ell k}$ and/or δ_{pk}, which are associated with these newly generated, improving columns, become candidates to be incorporated in the revised RMP basis. If $\boldsymbol{Z}_{\boldsymbol{1}\ell}^{*} \leq 0, \ell \in L$ and $\overline{\boldsymbol{Z}}_{\boldsymbol{2p}}^{*} \leq 0, p \in P$, the current RMP solution is optimal and its objective function value specifies the bound sought at the current B&B node.

12. 3 Solution algorithms for SP1 and SP2

SP 1 is a resource constrained shortest path problem (RCSPP), a variant of the classical shortest path problem (SPP). RCSPP is to find a shortest path (i.e., the path with the least total arc cost) from the start node to the end node with a total consumption of each type of resource (e.g., time, distance, capacity, money, workload, and reliability requirement (Zhu and Wilhelm, 2007)) that observes a given upper bound on each. Several methods have been proposed to convert a RCSPP into a SP, which can be solved at each CG iteration (e.g., Desrochers and Soumis, 1989; Mingozzi *et al.*, 1999; Holmberg and Yuan, 2003; Wilhelm *et al.*, 2003; Wilhelm *et al.*, 2006; Wilhelm *et al.*, 2007; Zhu and Wilhelm, 2007).

Figure 5 presents an example SP 1 network for each location. We solve a CSSPP on the network that models SP1 for a given ℓ to generate improving columns. The reduced cost associated with an operating decision can be added to the reduced cost associated with each of the corresponding z_a variables (i.e., expanding arcs, contracting arcs, and arcs maintaining the same capacity). An optimal path from the start node to the end node along capacity nodes in Figure 5 that represents opening, operating, expanding and contracting capacity, and closing facility ℓ over the planning horizon is prescribed for each location (e.g., see the path composed of arcs represented by solid and dash lines in Figure 5).

We now present SP 1,

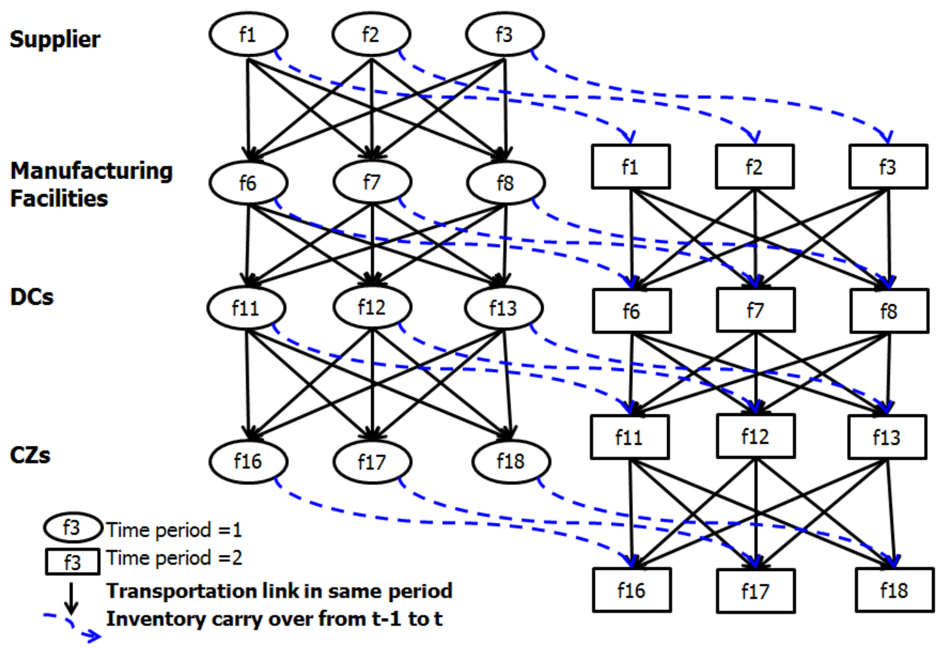
$$SP1(\ell): \boldsymbol{Z}^{*}_{\mathbf{1}\ell} = \max \text{``}z_j - c_j\text{''} = \sum_{(j,k,\ell,t)\in\bar{A}} \psi_{(j,k,\ell,t)} z_{jk\ell t} + \boldsymbol{\alpha}_{\ell} \quad (82)$$

s.t. (33)-(37), (44)

The objective function (82) maximizes the sum of "$z_j - c_j$"; (Bazaraa *et al*., 2005), i.e., minus one times the reduced cost of each prescribed arc (we use expressions *maximize* "$z_j - c_j$" instead of *maximize negative reduced cost).* Objective function coefficient "$\mathrm{z_j - c_j}$", which is associated with arcs in the expanded network, is updated each time at each iteration by incorporating new values of dual variables from RMP. While (82), (33) and (44) define a shortest path problem (SPP), which has the Integrality Property (Wilhelm, 2001), (82), (33)-(37), and (44) define a RCSPP, which does not have the Integrality Property, allowing our B&B approach to provide tighter bounds that improve the effectiveness of our solution approach.

The CSPP is NP-hard (Handler and Zang, 1980). We use the algorithm of Zhu and Wilhelm (2007) to solve SP1. It uses a pseudo-polynomial time dynamic programming algorithm to construct a directed, acyclic expanded network on which the RCSPP is solved as a SPP, which satisfies given constraints (2)-(7), at each iteration using a polynomial time algorithm (Ahuja *et al*., 1993).

We present an example of SP2(p) that includes all possible arcs. Figure 6 uses dashed arcs to represent inventory carry over from period t to period $t+1$; for simplicity, arcs for backordering and outsourcing are not included. SP2(p) for each product $p \in P$ is solved with all possible arcs within each time period representing transportation links and between different time periods representing inventory carry over and backorders. RMP dual variable values ultimately induce flow only on links that are established by SP 1. If the SP 2(p) solution generates an improving column, it may be entered into the basis of RMP.



SP2 (p=1) with $|p|$=3, with |L|=12, |T|=2, |EC|=4

Figure 6. An example network of SP2

A few challenges occur when implementing CG in the context of B&B. The analyst must specify (i) branching rules, (ii) methods to fix each branching variable to its upper or lower bound, (iii) techniques to reoptimize nodes in the B&B tree, and (iv) methods to construct the initial RMP basis. Our B&P scheme branches on $\boldsymbol{s}$ variables in RMP as well as $\boldsymbol{z}$ variables in SP1**.** (i) We select the most fractional variable (an element of $\boldsymbol{s}$ or $\boldsymbol{z}$**)** as the branching variable. (ii) To fix a binary variable, we adjust the upper or lower bound respectively in each resulting child node. (iii) After fixing a fractional binary variable, we use columns generated from SPs to optimize RMP at each of the two child nodes created by the corresponding branching. (iv) We start by generating a set of columns to form an initial basic feasible solution for RMP by setting dual variable values to zero and passing them to SPs.

Slack and artificial variables are employed appropriately for constraints (63)-(65). A large cost is assigned to the artificial variables in the objective function in big-M method. After improving columns are generated from SP1 and SP2 at each iteration, they are stored so that they are available for use by RMP.

CHAPTER XIII

COMPUTATIONAL EVALUATION

We design computational experiments to fulfill our objective of identifying the computational characteristics of each model to determine if one offers superior solvability in comparison with the others. To obtain computational results, we program our DSCR-T and -N formulations in *AMPL 9.0*® and use the *IBM ILOG CPLEX12.1*® branch-and-bound solver. We implement our two B&P schemes using *MATLAB® 7.9.0 (R2009b)* and *C++* in combination with *IBM ILOG CPLEX12.1*® *CPLEX Callable Library*. We invoke a time limit of one hour (i.e., 3600 seconds) to solve each instance. All computational experiments are performed on a PC with *Intel Core 2 Quad*® CPU @ 3.0 GHz with 8.00 GB RAM, and 64-bit *Windows*® OS System.

In preliminary tests, we determined the combinations of *IBM ILOG CPLEX12.1*® solution strategies that best solves our problem (e.g., node selection, branching strategy, MIP cut option, and simplex optimizer option). Different CPLEX B&B strategies result in different run times for the DSCR-T and -N models. Our preliminary tests showed that the best strategy for node selection is the best-bound node selection and that for branching variable selection is the pseudo cost option. The CPLEX network simplex optimizer outperformed its primal simplex, dual simplex, and barrier optimizers for the DSCR-N model as well as for solving SP2 in B&P Scheme 1 and the master problem in B&P Scheme 2. This chapter comprises five subsections, which describe our design of experiments, test results, analysis of results, tests of the RCSPP algorithm for SP1, and demonstration of model use with two demand scenarios.

13.1 Design of experiments

The design of experiments employs two levels for each of five factors (see Table 16): the number of demand scenarios (Scenarios 1 & 2), the number of potential locations for facilities (8 & 10), the number of product types (2 & 4), the number of capacity expansion alternatives and, similarly, capacity contractions at each location (2 & 4), and the number of time periods in the planning horizon (5 &10). The demand for Scenario 1(2) increases (decreases) in the early periods and decreases (increases) in subsequent periods (See Figure 7), representing a product life cycle (an economic downturn followed by recovery). We test each of the $2^5 = 32$ cases (i.e., factor-level combinations) by randomly generating an instance. We use a unique set of random number seeds to generate each instance, one for each parameter generated.

Table 16. Levels for each of six factors

	Demand scenario	# of Locations $\lvert L\rvert$	# of Products $\lvert P\rvert$	# of Expansion & contraction alternatives each period $\lvert E\rvert$&$\lvert C\rvert$	# of Time periods $\lvert T\rvert$	# of Echelons $\lvert EC\rvert$
Level 1 Level 2	Scenario 1 Scenario 2	8 12	2 4	2 4	5 10	4

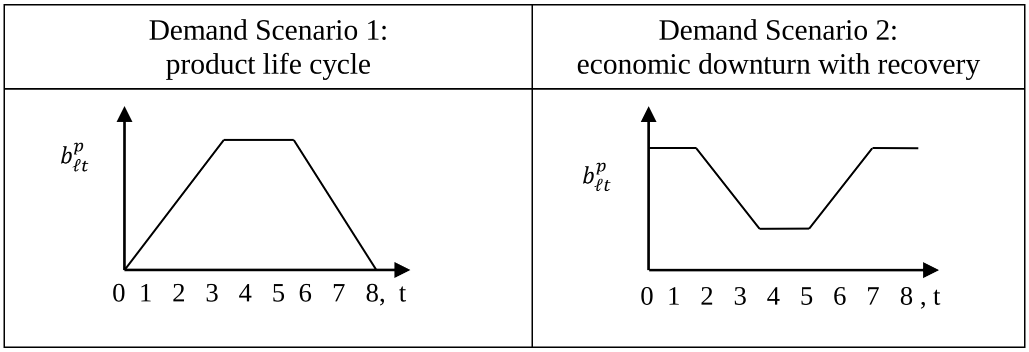


Figure 7. Scenarios with different demand over time

We denote the number of echelons by $|EC|$ and distribute the $|L|$ locations equally in all echelons so that each echelon has $|L|/|EC|$ locations. Our tests focus on the four-echelon case (so that $|EC|$ =4), a commonly studied structure that includes suppliers, manufacturing plants, distribution centers, and customer zones.

Our DSCR-T (DSCR-N) model contains multiples of $|L| \cdot |P| \cdot |T|$ constraints, $|E| \cdot |L| \cdot |T|$ binary variables ($|E| \cdot |K_\ell| \cdot |L| \cdot |T|$ binary variables), and $|\mathrm{L}|^2 |P| \cdot |T|$ continuous variables. Instance size grows with the cardinality of sets, $E, K_\ell, L, P,$ and T. We generate each parameter randomly from a continuous uniform distribution with a unique random seed; Table 17 specifies the bounds for each distribution.

Table 17. Bounds for distribution of each parameter (DU: Discrete uniform)

Parameters	U[LB, UB]	Parameters	U[LB, UB]
$G^O_{k\ell t}$	U[600, 900]	$H^p_{\ell t}$	U[50, 90]
$G^C_{\ell t}$	U[50, 90]	$Q^p_{\ell t}$	U[60, 100]
$G^M_{\ell t}$	U[100, 200]	$R^p_{\ell t}$	U[70, 100]
$G^E_{j\ell t}$	U[50, 60]	$F_{\ell t}$	U[200, 300]
$G^D_{i\ell t}$	U[40, 50]	$V_{\ell\ell' t}$	DU[1000, 4000]
$U^p_{\ell\ell' t}$	U[60, 90]	δ^p_ℓ	DU[1, 3]

Each cost is discounted to its present-worth value. Capacity alternatives for expansions and contractions are related to the initial capacity upon opening so that contractions cannot eliminate initial capacity, which could essentially close a facility using less costly contractions. While our model demonstrates several constraints that serve to limit capacity expansions and contractions at each location, including a budget limitation, B_ℓ; the maximum number of capacity expansion, N_ℓ^E; the maximum number of capacity contractions, N_ℓ^D; and the maximum number of expansions and/or contractions, N_ℓ^T, our tests use only the N_ℓ^T constraints so that results can be more easily interpreted intuitively. After several preliminary tests, we select the most appropriate value of N_ℓ^T for use in our tests.

13.2 Test results

Table 18 gives test results for DSCR-T, each row recording results for one of the $2^4 = 16$ test cases with CPLEX cuts while Table 19 provides test results for DSCR-T without CPLEX cuts. Columns in Table 18 are organized in four groups, the first group describes the case, giving the level of each factor ($|L|,\ |P|,\ |E|,\ |T|$), the second group gives instance size (# of continuous variables, # of binary variables, # of constraints), the third group details the cuts generated by CPLEX (GUB cover cuts, flow cuts, mixed integer rounding, flow path cuts, cover cuts, implied bound cuts, zero-half cuts, multicommidity cuts, Gomory fractional cuts, clique cuts, total cuts generated), and the fourth gives computational results for CPLEX (run time, MIP optimal objective value, number of B&B nodes, LP optimal objective value (i.e., root-node solution), and %

GAP). The % GAP is defined as %GAP=100(Z_{IP}^{*}-Z_{LP}^{*})/ Z_{IP}^{*}, in which Z_{IP}^{*} is the value of the optimal solution to the integer problem and Z_{LP}^{*} is the value of the optimal solution to its linear relaxation (i.e., the value of the optimal solution at the root node in the B&B search tree). Table 19 reports the same groups of test results, except the third group, since the test does not include the use of CPLEX cuts.

Tables 20 and 21 give results for the DSCR-N model with and without CPLEX cuts, respectively, and corresponding to Tables 18 and 19, respectively. Both DSCR-T and –N models allow the same number of capacity alternatives to be used over time to allow legitimate comparison of tests results. We generate parameter values randomly but make sure that all models solve the same randomly generated instances so they solve identical problems.

Tables 22 and 23 report test results for B&P schemes 1 and 2, respectively, giving optimal root node solution value, optimal objective function value, run time, the numbers of B&B nodes generated and groups of results for each sub-problem type (i.e., SP1 and SP2) (time to construct an expanded network, run time of SPs, number of SPs solved, number of columns entered in B&P). We use the network simplex optimizer to solve SP2 since our preliminary tests show that it is faster than other simplex optimizers (e.g., primal simplex, dual simplex, and barrier).

Table 18. Test results of DSCR-T with CPLEX12.1 MIP cuts
(* case takes longer than run time limit of 3600 secs to prescribe an optimal solution)

Case	|L|, Number of locations	|P|, Number of products	|E|, |C|, number of expansion / contraction alternatives	|T|, Number of time periods	Number of continuous var.	Number of binary var.	Number of constraints	GUB cover cuts	Flow cuts	Mixed integer rounding	Flow path cuts	Cover cuts	Implied bound cuts	Zero-half cuts	Multicommodity flow cuts	Gomory Fractional cuts	Clique cuts	Total cuts generated	Run time : Total (Sec.)	MIP Optimal Obj in CPLEX12.1	Nodes of B&B in CPLEX121	LP Optimal value	%GAP=100(IP-LP)/IP
1	8	2	2	5	236	200	434	4	154	16	17	10	29	14	0	17	6	267	1.73	452556	1335	278713.73	38.41
2	8	2	2	10	456	400	844	3	318	47	18	257	59	8	0	34	11	755	405.21	867377	555110	556052.23	35.89
3	8	2	4	5	236	280	434	3	162	29	11	186	37	10	4	15	6	463	3.10	452556	6983	278640.11	38.43
4	8	2	4	10	456	560	844	8	344	74	24	2949	47	15	4	35	10	3510	3600.02	*	972156	555906.58	*
5	8	4	2	5	452	200	530	7	218	0	17	3	52	8	0	4	5	314	0.95	671349	523	556588.65	17.09
6	8	4	2	10	872	400	1020	4	516	31	44	108	80	5	0	19	9	816	54.15	1333699	29730	1128491.22	15.39
7	8	4	4	5	452	280	530	3	228	41	12	180	50	7	2	10	8	541	7.49	671331	9734	556446.05	17.11
8	8	4	4	10	872	560	1020	7	618	62	31	3480	80	10	3	27	2	4320	3600.02	*	831366	1128097.85	*
9	10	2	2	5	360	315	667	3	279	16	39	36	69	32	0	12	15	501	10.41	457506	8575	265095.75	42.06
10	10	2	2	10	700	630	1302	5	600	55	92	937	108	16	0	32	21	1866	3600.02	*	1085013	531138.82	38.54
11	10	2	4	5	360	435	667	22	300	53	43	803	95	32	8	25	13	1394	217.23	457506	160998	265040.41	42.07
12	10	2	4	10	700	870	1302	18	540	79	54	3855	118	20	8	23	17	4732	3600.07	*	614208	531003.29	*
13	10	4	2	5	690	315	787	11	461	16	43	23	107	26	0	14	21	722	12.42	674619	3227	537958.14	20.26
14	10	4	2	10	1340	630	1522	9	988	52	85	369	174	20	0	30	14	1741	3313.98	1307046	424423	1071452.73	18.02
15	10	4	4	5	690	435	787	6	417	57	27	425	124	16	4	10	13	1099	76.25	674619	36526	537782.72	20.28
16	10	4	4	10	1340	870	1522	10	905	58	62	2754	214	21	1	38	10	4073	3600.03	*	369025	1071088.05	*

Table 19. Test results of DSCR-T without CPLEX12.1 MIP cuts
(* case takes longer than run time limit of 3600 secs to prescribe an optimal solution)

Case	|L|, Number of locations	|P|, Number of products	|E|, |C|, number of expansion / contraction alternatives	|T|, Number of time periods	Number of continuous var.	Number of binary var.	Number of constraints	Run time : Total (Sec.)	MIP Optimal Obj in CPLEX12.1	Nodes of B&B in CPLEX121	LP Optimal value	%GAP=100(IP-LP)/IP
1	8	2	2	5	236	200	434	1.05	452556	2088	278713.73	38.41
2	8	2	2	10	456	400	844	1886.04	865656	9248200	556052.23	35.77
3	8	2	4	5	236	280	434	2.71	452556	17577	278640.11	38.43
4	8	2	4	10	456	560	844	3600.02	*	17075516	555906.58	*
5	8	4	2	5	452	200	530	0.86	671349	1107	556588.65	17.09
6	8	4	2	10	872	400	1020	118.5	1333699	412743	1128491.22	15.39
7	8	4	4	5	452	280	530	2.71	671331	12509	556446.05	17.11
8	8	4	4	10	872	560	1020	3145.28	1323330	11162330	1128097.85	14.75
9	10	2	2	5	360	315	667	4.35	457506	17866	265095.75	42.06
10	10	2	2	10	700	630	1302	3600.02	*	9693068	531138.82	*
11	10	2	4	5	360	435	667	164.17	457506	1003541	265040.41	42.07
12	10	2	4	10	700	870	1302	3600.02	*	10850917	531003.29	*
13	10	4	2	5	690	315	787	3.62	674564	9730	537958.14	20.25
14	10	4	2	10	1340	630	1522	3600.02	*	13472810	1071452.73	*
15	10	4	4	5	690	435	787	21.59	674619	91443	537782.72	20.28
16	10	4	4	10	1340	870	1522	3600.04	*	6955482	1071088.05	*

Table 20. Test results of DSCR-N with CPLEX12.1 MIP cuts

Case	|L|, Number of locations	|P|, Number of products	|E|, |C|, number of expansion / contraction alternatives	|T|, Number of time periods	Number of continuous var.	Number of binary var.	Number of constraints	Flow cuts	Mixed integer rounding	Flow path cuts	Cover cuts	Implied bound cuts	Zero-half cuts	Multicommodity flow cuts	Gomory Fractional cuts	Clique cuts	Total cuts generated	Run time : Total (Sec.)	MIP Optimal Obj in CPLEX12.1	Nodes of B&B in CPLEX121	LP Optimal value	%GAP=100(IP-LP)/IP
1	8	2	2	5	184	412	342	91	3	18	5	38		6	13	4	178	0.33	452526	154	278322.99	38.50
2	8	2	2	10	384	872	692	216	29	34	5	31	3	12	26	4	360	3.35	867405	564	556812.27	35.81
3	8	2	4	5	184	520	346	0	22	15	4	24	5	8	13	4	95	1.25	452526	633	278977.69	38.35
4	8	2	4	10	384	1100	696	273	32	45	20	30	4	3	41	4	452	4.62	867405	922	555809.45	35.92
5	8	4	2	5	368	412	422	300	51	46	11	95	10	0	12	1	526	3.14	671319	869	556725.62	17.07
6	8	4	2	10	768	872	852	492	63	66	33	205	7	0	24	4	894	48.63	1333690	12221	1129450.13	15.31
7	8	4	4	5	368	520	426	0	66	35	7	103	3	0	12	1	227	3.18	671319	874	556610.98	17.09
8	8	4	4	10	768	1100	856	500	50	66	32	138	7	0	23	4	820	25.57	1324714	7138	1128973.05	14.78
9	10	2	2	5	290	633	533	247	16	71	13	79	3	6	11	0	446	4.04	457447	1483	265003.55	42.07
10	10	2	2	10	600	1338	1078	486	16	150	47	159	3	12	11	0	884	102.59	8641180	26163	535363.38	93.80
11	10	2	4	5	290	795	539	238	25	82	19	86	5	11	10	0	476	4.38	457477	1476	266157.23	41.82
12	10	2	4	10	600	1680	1084	513	15	155	76	157	1	8	25	0	950	115.64	8637970	29855	5339545.40	38.19
13	10	4	2	5	580	633	633	377	9	76	22	196	5	0	12	0	697	12.65	674570	2728	538326.18	20.20
14	10	4	2	10	1200	1338	1278	880	25	191	66	280	12	0	38	0	1492	388.83	1306957	41756	1073500.04	17.86
15	10	4	4	5	580	795	639	502	92	94	12	216	9	0	12	0	937	12.89	674570	2987	538439.28	20.18
16	10	4	4	10	1200	1680	1284	840	10	175	126	329	8	0	34	0	1522	1416.91	1298294	196638	1072569.59	17.39

Table 21. Test results of DSCR-N without CPLEX12.1 MIP cuts
(* case takes longer than run time limit of 3600 secs to prescribe an optimal solution)

Case	|L|, Number of locations	|P|, Number of products	|E|, |C|, number of expansion / contraction alternatives	|T|, Number of time periods	Number of continuous var.	Number of binary var.	Number of constraints	Run time : Total (Sec.)	MIP Optimal Obj in CPLEX12.1	Nodes of B&B in CPLEX121	LP Optimal value	%GAP=100(IP-LP)/IP
1	8	2	2	5	184	412	342	0.72	452526	1241	278322.99	38.50
2	8	2	2	10	384	872	692	6.51	867405	12050	556812.27	35.81
3	8	2	4	5	184	520	346	0.90	452526	2332	278977.68	38.35
4	8	2	4	10	384	1100	696	18.13	867405	42460	555809.45	35.92
5	8	4	2	5	368	412	422	1.01	671319	1475	556725.62	17.07
6	8	4	2	10	768	872	852	107.42	1333690	181267	1129450.13	15.31
7	8	4	4	5	368	520	426	1.33	671319	3198	556610.98	17.09
8	8	4	4	10	768	1100	856	342.83	1324714	870523	1128973.05	14.78
9	10	2	2	5	290	633	533	2.60	457477	4613	265003.55	42.07
10	10	2	2	10	600	1338	1078	142.38	8641180	166354	535363.38	93.80
11	10	2	4	5	290	795	539	7.07	457477	16031	266157.23	41.82
12	10	2	4	10	600	1680	1084	156.48	8637970	212541	5339545.40	38.19
13	10	4	2	5	580	633	633	5.74	674570	8032	538326.18	20.20
14	10	4	2	10	1200	1338	1278	3095.61	1306957	2734734	1073500.04	17.86
15	10	4	4	5	580	795	639	7.27	674570	11935	538439.28	20.18
16	10	4	4	10	1200	1680	1284	3600.02	*	2269335	1072569.59	*

Table 22. Test results of B&P schemes 1

Test Instance	|L|, Number of locations	|P|, Number of products	|E|, |C|, number of expansion / contraction alternatives	|T|, Number of time periods	|EC|, number of echelons	Root node solution value	Obj Val in B&P	Run time in B&P	B&B Nodes in B&P	SP1			SP2		
										Run time of SPs	Number of SPs solved	Number of Cols entered in B&P	Run time of SPs	Number of SPs solved	Number of Cols entered in B&P
1	6	2	2	2	2	45355	543220	78.79	139	17.55	278	278	15.81	278	138
2	6	3	3	2	3	67485	703480	76.34	131	16.91	262	262	14.52	262	130
3	6	3	3	3	3	1004400	1058500	156.83	271	34.71	542	542	31.15	542	270
4	6	4	3	3	3	1441300	1514300	338.44	587	77.54	2348	1174	68.65	1174	587

Table 23. Test results of B&P schemes 2

Test Instance	|L|, Number of locations	|P|, Number of products	|E|, |C|, number of expansion / contraction alternatives	|T|, Number of time periods	|EC|, number of echelons	Root node solution value	Obj Val in B&P	Run time in B&P	B&B Nodes in B&P	SP1		
										Run time of SP1 SPs	Number of SP1 solved	Number of SP1 Cols entered in B&P
1	6	2	2	2	2	45355	543220	106.74	245	25.59	433	428
2	6	3	3	2	3	67485	703480	176.83	403	38.20	662	638
3	6	3	3	3	3	1004400	1058500	1211.21	2565	256.99	4434	4242
4	6	4	3	3	3	1441300	1514300	928.52	2013	190.21	3381	3128

13.3 Analysis of results

This subsection analyzes results, focusing on performance of the models relative to run time and the number of B&B nodes to assess the solvability of each model. We also analyze run time sensitivity of key parameters.

13.3.1 Performance comparison

As reported in Table 18, a number of cuts is automatically generated to solve instances of the DSCR-T problem at each B&B node. Tables 18 and 19 report that 5 cases, each with |T|=10, of DSCR-T with/without CPLEX cuts, respectively, takes longer than the run time limit to prescribe optimal solutions. The DSCR-T model does not show significant difference in run time between the two options of with and without cuts.

Tables 20 and 21 report that the DSCR-N with/without CPLEX cuts solves each case in time less than 3600 seconds with one exception (|T|=10 in the without CPLEX cuts option shown in Table 21). The tables also report that the DSCR-N model solves faster with CPLEX cuts than without CPLEX cuts. The average run time is 52.20 seconds with cuts and 278.23 seconds without cuts, respectively, after removing the time that exceeds 3600 seconds. Run time of the DSCR-N model, in part, depends on the number of capacity alternatives, which determines the number of $z_{jk\ell t}$ variables in SP1.

The test results of Tables 18-21 show the DSCR-N model solves faster than the DSCR-T model, even though it has more binary decision variables (i.e., average of 918.75 for DSCR-N and 461.25 for DSCR-T in Tables 18 and 20). The root node bounds and %GAP of solved instances within the time limit for both DSCR-T and –N model are not significantly different. As the size of a problem instance increases, run time for DSCR-T increases significantly, compared to that of DSCR-N. Our test results show that DSCR-N provides superior solvability compared to DSCR-T relative to both run time and the number of B&B nodes.

13.3.2 Run time sensitivity

We now analyze the impacts of key parameters ($|E|$, $|L|$, $|P|$, and $|T|$) on run time. We use the test results for DSCR-N with CPLEX cuts (Table 20) since it solves all cases within the predetermined solution time limit. Table 24 summarizes average run time for each factor level.

We observe that increasing the number of locations has a significant impact on run time. We conjecture that this is due to the fact that the number of additional locations increases the numbers of both variables and constraints. An increase in the number of products also leads to increased run time since the number of continuous variables and constraints increases in proportion to $|P|$. Increasing the numbers of expansion and contraction alternatives does not seem to significantly impact run time compared to other factors. Note that even though the numbers of alternatives for capacity expansions and contractions increase, the number of constraints remains the same.

Table 24. Sensitivity of factors on run time of DSCR-N with cuts

	$\|L\|$	Average Run time	$\|P\|$	Average Run time	$\|E\|$& $\|C\|$	Average Run time	$\|T\|$	Average Run time
Level 1	8	11.26	2	29.53	2	70.45	5	5.23
Level 2	10	257.24	4	238.98	4	198.06	10	263.27

The number of time periods has the most significant impact on run time. Increasing the number of time periods increases instance size (i.e., the number of binary and continuous variables as well as constraints), resulting in significant computational challenges. Based on test results, the numbers of time periods and locations have the most significant impacts on run time. This result is intuitive in that increases in the numbers of locations and time periods are directly related to increases in the number of binary and continuous variables as well as constraints.

13.4 Tests of the RCSPP algorithm for SP1

This subsection studies the impact of parameter N_ℓ^T on the run time required to solve SP1. We also demonstrate that this approach is well suited to be incorporated in the proposed B&P schemes.

Preliminary tests associated with solving SP1 (see Table 25), a RCSPP, show that parameter N_ℓ^T has an interesting impact on the run time required to solve the shortest path problem on the expanded network. As N_ℓ^T increases, more capacity changes can be made over time at location ℓ. As N_ℓ^T reduces, bounds are tightened and the run time required to solve the B&P problem reduces.

Test results in Table 25 for an instance with $|T|=15$ and $|K_\ell| = 15$ show that the RCSPP algorithm solves instances of large size (i.e., a large number of nodes and arcs) rapidly. The maximum number of capacity changes that can be made is $(|T|-1)$ since we do not expand or contract in time period one (an expansion or contraction could be implemented in period $|T|$). The total cost to prescribe capacity changes over time (i.e., the optimal shortest path at location ℓ) gets smaller as more paths are made feasible by a larger value of N_ℓ^T(see the last column of Table 25). Note that the cost on each arc is generated from Uniform [1,100].

Table 25. Run time (sec.) for # of expansion and contraction

Case No	|T|	# of capacity alternatives	|E|, |C|	Allowed Exp / Con limit	# of Node, Initial Network	# of Arc, Initial Network	# of Node, Expanded Network	# of Arc, Expanded Network	Time for Expansion (sec.)	Run time for Shortest Path (sec. * e-1)	Cost for path
1	15	15	3	1	207	1226	129	320	0.020	0.00012	464
2	15	15	3	2	207	1226	316	1156	0.040	0.00034	405
3	15	15	3	3	207	1226	549	2510	0.090	0.00072	337
4	15	15	3	4	207	1226	831	4209	0.130	0.00152	276
5	15	15	3	5	207	1226	1182	6490	0.220	0.00168	276
6	15	15	3	6	207	1226	1937	11675	0.320	0.00330	267
7	15	15	3	7	207	1226	4189	28029	0.730	0.00618	244
8	15	15	3	8	207	1226	12182	86732	2.970	0.03574	225
9	15	15	3	9	207	1226	11768	84023	3.190	0.03612	205
10	15	15	3	10	207	1226	2640	18527	0.480	0.00488	192
11	15	15	3	11	207	1226	628	4028	0.110	0.00100	190
12	15	15	3	12	207	1226	481	3046	0.090	0.00090	190
13	15	15	3	13	207	1226	357	2228	0.060	0.00058	190
14	15	15	3	14	207	1226	207	1226	0.030	0.00038	190
15	15	15	3	15	207	1226	207	1226	0.040	0.00036	190

Using the test results reported in Table 25, Figure 8 plots the number of nodes and arcs of the expanded network and cost of the shortest path as functions of N_ℓ^T. It is interesting to note that the size of the expanded network (see also Table 25) increases and then decreases as the value of parameter N_ℓ^T increases.

That the size of the expanded network does not continue to increase with N_ℓ^T has a ready, intuitive explanation. To construct the expanded network, we consider each time period in the SP1 network from t=0 to t=|T|+1 and nodes within each time period from left to right, following a topological ordering (Zhu and Wilhelm, 2007). To extend the paths that lead to a node in the expanded network, each arc emanating from the associated node in the SP network is augmented to reach the next time period of the expanded network. Only augmented paths with cumulative resource requirements that do not exceed N_ℓ^T are feasible. After identifying feasible extensions to nodes in the next time period of the expanded network, we identify each subset of these nodes that has the same cumulative resource requirements and merge them into a single node. This combination manages the growth of the expanded network (see Figure 8) and leads to the pseudo-polynomial time complexity of the expansion method. A special case occurs for $N_\ell^T =$|T|; there is no need to construct an expanded network since all paths from the start to the end node are feasible.

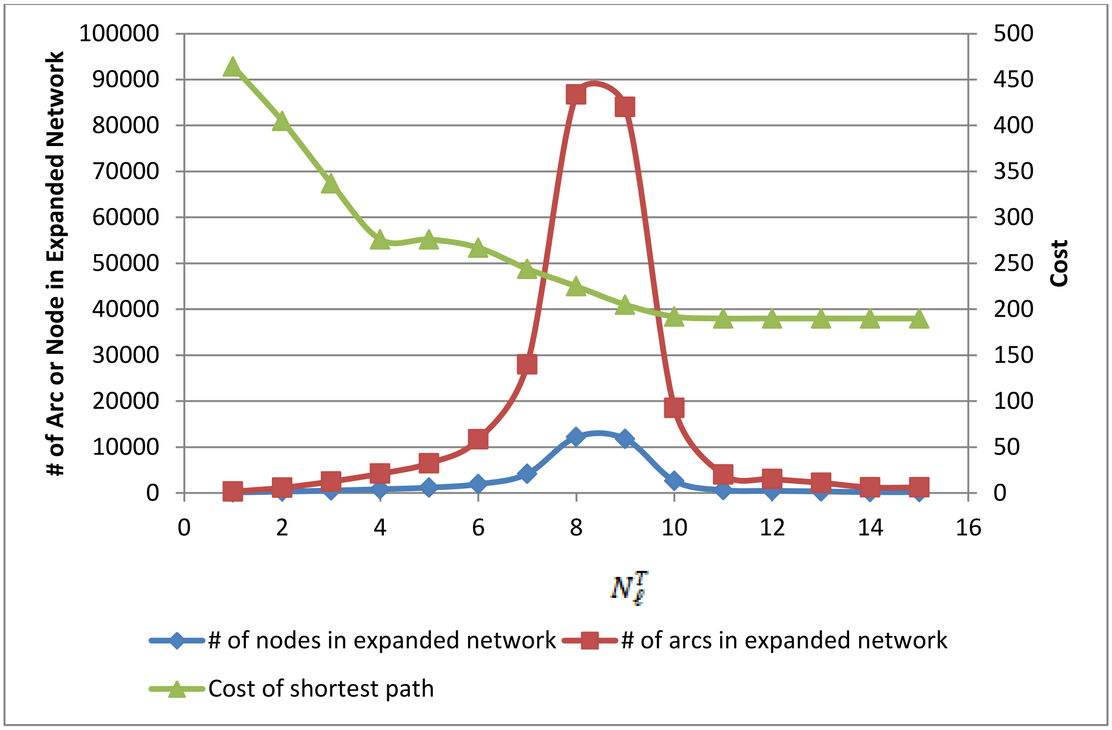


Figure 8. Size of expanded network and cost of shortest path vs N_ℓ^T

Figure 9 plots the value of parameter N_ℓ^T and run time required by the RCSPP algorithm to prescribe an optimal shortest path. We note that run time increases, then decreases as N_ℓ^T increases, correlating with the size of the expanded network in terms of the number of nodes and arcs. Run time increases up to mid-range values (i.e., N_ℓ^T =8 or 9) as N_ℓ^T continues to increase and run time reduces, paralleling the changes in the size of the expanded network. Since all run times are quite low, even for larger instances, this algorithm appears to be well suited to be incorporated in our B&P approach.

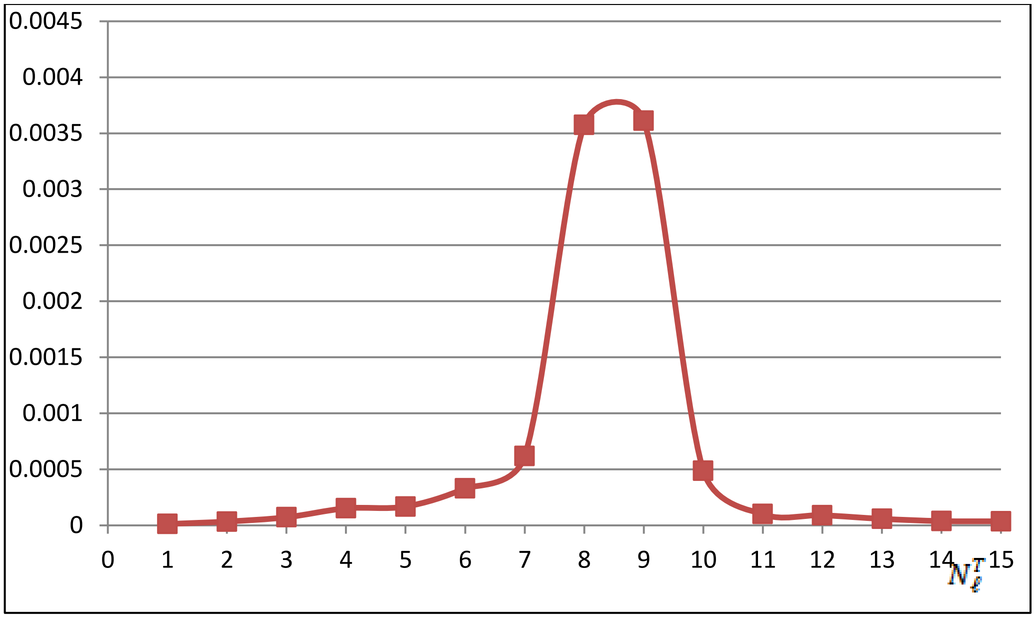


Figure 9. Run time (sec.) vs # of N_ℓ^T (|T|=15, $|K_\ell|$=15, |E|=3)

13.5 Demonstration of model use

We now describe results for one instance with demand scenario 1 and another with demand scenario 2 to promote an intuitive interpretation in using our DSCR models. The instances demonstrate how time varying demand can lead to openings, capacity expansions and contractions, and closings over the planning horizon. Figure 10 depicts two scenarios with different demand trends. Scenario 1 assumes that each product follows the life cycle theory, so that the demand for each product increases in the early periods and decreases as the end of the product life cycle approaches. Scenario 2 represents an economic downturn with recovery, for which the demand for each product decreases and then increases again.

Each instance comprises |E|=2, |EC|=4, |P|=2, |L|=20, and |T|=8 with 5 locations in each echelon, where $L = \{1, \dots, 20\}$, $L_S = \{1, \dots, 5\}$, $L_P = \{6, \dots, 10\}$, $L_{DC} = \{11, \dots, 15\}$ and $L_{CZ} = \{16, \dots, 20\}$. A single opening capacity is considered to facilitate presentation in this demonstration, thus, reducing $O_{k\ell t}$ to $O_{\ell t}$. Costs and other parameters are generated randomly using the uniform distributions defined by Table 17. The demands for each product over 8 time periods for each of the two scenarios are given in Table 26. We report test results that show how our DSCR models prescribe capacity changes over time for each of these scenarios in Figure 10 and Tables 27 and 28. In Figure 10, the solid line represents demand, i.e., the summation of demands of two products, and the dashed line represents the summation of capacities of two locations over the planning horizon of 8 time periods.

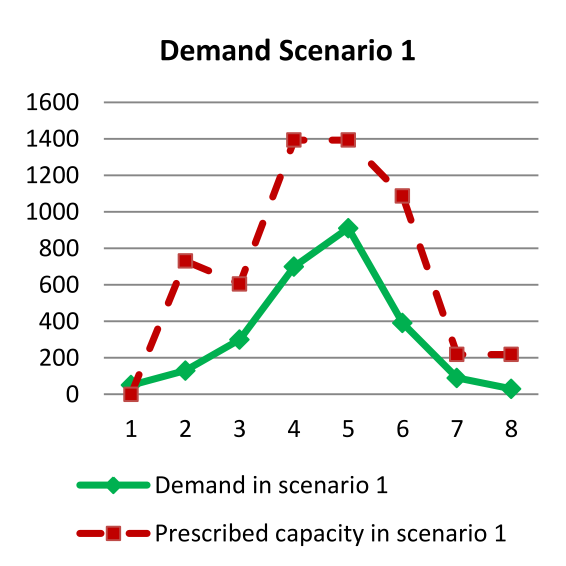
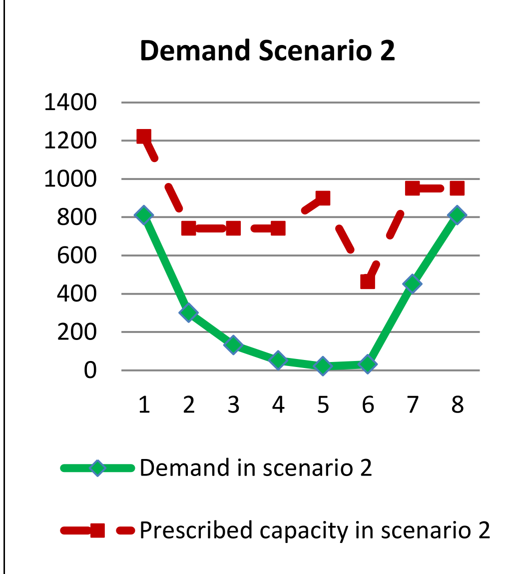
Scenario 1: Product life cycle	Scenario 2: Economic downturn with recovery
	

Figure 10. Prescribed capacity for different demand over time

Table 26. Demand of product 1 and 2 for each scenario

Time Period	Scenario 1		Scenario 2	
	P=1	P=2	P=1	P=2
1	30	20	400	410
2	60	70	150	150
3	150	150	60	70
4	350	350	30	20
5	450	460	10	10
6	200	190	10	20
7	50	40	240	210
8	10	20	400	410
TOTAL	1300	1300	1300	1300

Tables 27 and 28 give test results for locations 8 and 9, which are manufacturing plants in echelon 2. Employing decision variable, $\widetilde{K}_{\ell t}$, we keep track of the accumulated capacity of facility ℓ in each time period t. Test results in Table 27 exemplify how the supply chain configuration varies over a planning horizon of eight time periods. The relationship between three binary variables, $O_{\ell t}$, $M_{\ell t}$, and $C_{\ell t}$ are proven to be correct, i.e., $M_{\ell t}$ is set to one once a facility is opened $(O_{\ell t} = 1)$ and remain operating $(M_{\ell t} = 1)$ until the facility is closed $(C_{\ell t} = 1)$. We observe that the capacity of each facility increases $(E_{j\ell t} = 1)$ to meet the increasing demand and facilities are contracted $(D_{i\ell t} = 1)$and/or closed $(C_{\ell t} = 1)$ as the demands decrease as the end of planning horizon approaches.

The capacity profile for Scenario 1, $\widetilde{K}_{\ell t}$, meets demand at the lowest operating cost; that is, capacity increases in the early periods and decreases in subsequent periods. We also observe that $\overline{\overline{K}}_{\ell t} \leq \widetilde{K}_{\ell t}$. As shown in the $\widetilde{K}_{\ell t}$ column, the accumulated capacity, $\widetilde{K}_{\ell t}$, is retained even after a facility has been closed; however, as observed in the $\overline{\overline{K}}_{\ell t}$ column, once a facility is closed, available capacity and, thus, capacity usage is zero. The related cost $F_{\ell t}$ for each unit of excess capacity, $\widehat{K}_{\ell t}$, is addressed in the objective function for the DSCR formulations.

Table 27. Results of demand scenario 1

$O_{\ell t}$; o_LT [*,*]

t=	1	2	3	4	5	6	7	8
8	0	0	1	0	0	0	0	0
9	0	1	0	0	0	0	0	0

$M_{\ell t}$; m_LT [*,*]

: t=	1	2	3	4	5	6	7	8
8	0	0	1	1	1	1	1	0
9	0	1	1	1	1	1	1	0

$C_{\ell t}$; c_LT [*,*]

: t=	1	2	3	4	5	6	7	8
8	0	0	0	0	0	0	0	1
9	0	0	0	0	0	0	0	1

$E_{j\ell t}$; e_JLT [1,*,*]

: t=	1	2	3	4	5	6	7	8
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0

$E_{j\ell t}$; e_JLT [2,*,*]

: t=	1	2	3	4	5	6	7	8
8	0	0	0	1	0	0	0	0
9	0	0	0	0	0	1	0	0

$D_{i\ell t}$; d_ILT [1,*,*]

: t=	1	2	3	4	5	6	7	8
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0

$D_{i\ell t}$; d_ILT [2,*,*]

: t =	1	2	3	4	5	6	7	8
8	0	0	0	0	0	1	1	0
9	0	0	1	0	0	0	1	0

$\widetilde{K}_{\ell t}$; accumulated capacity available, k_tilde_LT [*,*]

:	1	2	3	4	5	6	7	8
8	0	0	349	1137	1137	658	204	204
9	0	730	256	256	256	428	14	14

$\overline{\overline{K}}_{\ell t}$; Capacity used

:	1	2	3	4	5	6	7	8
8	0	0	300	0	1029	590	100	0
9	0	120	0	0	0	380	0	0

* CPLEX 9.0.0: optimal (non-)integer solution within mipgap or absmipgap; objective 5026474; 126384 MIP simplex iterations; 12973 B&B nodes; 13 integer variables rounded; Currently integrality = 1e-05.

Table 28 for Scenario 2 shows that results for demand scenario 2 satisfy the decreasing, then increasing demand scenario at the lowest possible cost. The capacity profile for Scenario 2, i.e., the cumulative capacity $\widetilde{K}_{\ell t}$ and capacity usage $\overline{\overline{K}}_{\ell t}$, follow the demand pattern over time, that is, the capacity decreases in the early periods and increases in the subsequent periods. As seen in the table, locations 10 and 11 remain operating in period t=|T| to satisfy demand at the end of planning horizon.

Table 28. Results of demand scenario 2

$O_{\ell t}$; o_LT [*,*]

	t=1	2	3	4	5	6	7	8
10	1	0	0	0	0	0	0	0
11	1	0	0	0	0	0	0	0

$M_{\ell t}$; m_LT [*,*]

	t= 1	2	3	4	5	6	7	8
10	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1

$C_{\ell t}$; c_LT [*,*]

	t= 1	2	3	4	5	6	7	8
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0

$E_{j\ell t}$; e_JLT [1,*,*]

	t=1	2	3	4	5	6	7	8
10	0	0	0	0	1	0	0	0
11	0	0	0	0	0	0	0	0

$E_{j\ell t}$; e_JLT [2,*,*]

	t=1	2	3	4	5	6	7	8
10	0	0	0	0	0	0	1	0
11	0	0	0	0	0	0	0	0

$D_{i\ell t}$; d_ILT [1,*,*]

	t= 1	2	3	4	5	6	7	8
10	0	0	0	0	0	1	0	0
11	0	1	0	0	0	0	0	0

$D_{i\ell t}$; d_ILT [2,*,*]

	t = 1	2	3	4	5	6	7	8
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0

$\widetilde{K}_{\ell t}$; accumulated capacity available, k_tilde_LT [*,*]

t=	1	2	3	4	5	6	7	8
10	438	438	438	438	596	159	647	647
11	784	303	303	303	303	303	303	303

$\overline{\overline{K}}_{\ell t}$; Capacity used

t=	1	2	3	4	5	6	7	8
10	438	0	0	20	10	20	210	410
11	410	150	130	0	10	0	240	248

* CPLEX 9.0.0: optimal (non-)integer solution within mipgap or absmipgap; objective 4988035; 261541 MIP simplex iterations; 557113 B&B nodes; 13 integer variables rounded; Currently integrality = 1e-05.

CHAPTER XIV

CONCLUSIONS AND RECOMMENDATIONS FOR THE FUTURE RESEARCH

14.1 Integrating theories of international economics in the strategic planning of global supply chains*

The first part of the dissertation relates three theories of international economics and discusses their interrelationships, describing measures provided by two well-known annual competitiveness reports and illustrating applications of the theories to support its thesis and justify the questions that we pose for future research. The theories of comparative advantage, competitive advantage, and competitiveness have not been embraced by the OR/MS community, even though they provide information that is important to the strategic planning of global supply chains. We argue that it is crucial for an international enterprise to identify the competitiveness indicators that contribute most significantly to its success. Corresponding indicators reported by annual competitiveness reports can be prioritized according to their influence on the success of an industry so that, for example, an enterprise can locate its facilities in the most advantageous countries.

The dissertation formulates the thesis that incorporating these theories of international economics in the form of individual competitiveness indicators in OR/MS

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models offers promise to potentially enhance decision support for the strategic planning of global supply chains in general and for locating facilities in particular. To provide support for our thesis, we discuss phenomena that recently affected the global economy and present examples that illustrate use of competitiveness indicators. First, we analyzed the trade shift that the U.S. made from Mexico to China over the last decade and the corresponding relocation of international enterprises, reflecting the evolving comparative advantages of the two countries. Second, we described examples, showing that competitiveness indicators can explain location selections that have been made in the automotive industry. Third, we discussed studies that show how some competitiveness indicators have been employed to analyze the performance of a logistics system, which may play an important role in location selection. Fourth, we illustrated how clustering can be explained using competitiveness indicators in application to the automobile industry and discussed the benefits than clustering can provide. Each of these examples explains a prior decision by analyzing selected indicators; none demonstrate explicit use of individual competitiveness indicators to prescribe these strategic decisions. In addition, using the model formulated by Wilhelm *et al.* (2005), we proposed specific ways in which competitiveness indicators can be incorporated in OR/MS models to potentially enhance decision-support tools.

We pose research questions that fulfill the purpose of the dissertation, offering fertile avenues for future research: what methodologies can be devised to (1) assess the relevance of international economics theories to strategic planning, (2) select a set of individual indicators that are relevant to a particular industry, (3) forecast indicators with an accuracy sufficient to base decision support models on them, and (4) incorporate useful ones in strategic models. Since strategic models deal with long-term horizons, this approach could result, for example, in a strategic plan that locates and then relocates facilities over time to optimize global competitiveness.

The dissertation provides a vision to foster future research that will enhance the profitability of international enterprises under NAFTA. After reviewing the current state-of-the-art, we propose a vision of research needs relative to four different arenas with the goal of fostering academic research on international trade in general and NAFTA trade in particular. We expect that further research will contribute to the economic development of NAFTA member countries, to the well being of their citizens, and the profitability of their businesses.

14.2 DSCR with capacity expansion and contraction

In achieving objectives of this paper, our research contributes in two ways: providing a comprehensive mathematical modeling framework for the DSCR problem with alternative reformulations and tests to identify the computational characteristics of each model to determine if one offers superior solvability in comparison with the others.

The first model that we propose establishes a framework that has the flexibility to deal with many practical aspects of dynamic supply chain reconfiguration, providing a unique capability to open and close facilities as well as expand and contract the capacity of each operating facility within a multi-period, multi-product, multi-echelon supply chain network to meet a time varying demand and/or cost structure. Thus, the model provides the adaptability and responsiveness needed in the competitive modern business environment. The model incorporates practical features that have not been taken into account in prior models, including budget constraints, single sourcing, inventory, backordering, outsourcing, and limits on the numbers of capacity expansions and contractions.

Second, we propose an alternative, network-based formulation DSCR-N that relates decision variables according to a convenient network structure. Based on the resulting DSCR-N model, we propose two B&P schemes. Our tests showed that the DSCR-N formulation offers superior solvability compared to the DSCR-T formulation.

Our preliminary tests show that SP1 subproblems can be solved quite quickly, enabling the B&P approach. We also present run time sensitivity relative to factor levels. Two instances with different demand scenarios demonstrate how the DSCR model prescribes opening, expanding, contracting, and closing the facilities at a selected sub set of locations.

This research contributes by showing how to apply an effective RCSPP algorithm to solve a SP in a B&P approach. This research also contributes because it is applicable to a number of areas in both of public (e.g., school network planning (Antunes and Peeters, 2001)) and private sectors.

Future research could develop an improved formulation and/or effective solution methods, perhaps including heuristics to solve larger instances in less time. Another direction of the future research could devise an effective solution method to optimize a stochastic version of the DSCR problem that reflects the uncertainty of future demands and costs. The proposed DSCR models deal with domestic financial issues; however, they could easily be extended to address the international business environment by incorporating corresponding financial issues (e.g., transfer prices, tariffs, income tax rates, local contents rules).

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APPENDIX A

NOTATION FOR THE DSCR-T MODEL IN A TABLE FORMAT

Indices

$i \in I_\ell$ capacity contraction alternative

$j \in J_\ell$ capacity expansion alternative

$k \in K_\ell$ opening capacity alternative

$\ell \in L$ location alternative

$t \in T$ time period

$p \in P$ product

Index sets

J_ℓ expansion alternatives at location ℓ

I_ℓ contraction alternatives at location ℓ

K_ℓ opening capacity alternative at location ℓ

L locations at which facilities can be opened to produce or process products

L_S locations at which suppliers can be opened, $L_S \subset L$

L_P locations at which manufacturing plants can be opened, $L_P \subset L$

L_{DC} locations at which DC facilities can be opened, $L_{DC} \subset L$

L_{PDC} union of $L_P \cup L_{DC}$, where $L_P \cap L_{DC} = \emptyset$

L_{CZ} locations of customer zones, $L_{CZ} \subset L$

T time periods $t = 1, \ldots, T$

P products

Parameters (all costs are discounted to present worth values)

$G^O_{k\ell t}$ fixed cost to first open a facility with capacity alternative k at location ℓ in of period t

$G^C_{\ell t}$ fixed cost to close a facility at location ℓ at the start of period t (or at the end of $t-1$)

$G_{\ell t}^{M}$ fixed cost to operate a facility at location ℓ in period t

$G_{j\ell t}^{E}$ fixed cost to incorporate expansion alterative j at location ℓ at the start of period t

$G_{i\ell t}^{D}$ fixed cost to incorporate contraction alterative i at location ℓ at the start of period t

$U_{\ell\ell' t}^{p}$ unit variable cost to ship product p from location ℓ to location ℓ' in period t

$H_{\ell t}^{p}$ unit variable cost to hold product p in inventory at a facility at location ℓ in period t

$Q_{\ell t}^{p}$ unit variable cost for backordering product p at a facility at location ℓ in period t

$R_{\ell t}^{p}$ unit variable cost to purchase one unit of product p from an outside supplier at the facility at location ℓ in period t

$F_{\ell t}$ variable cost to keep a capacity of a facility at location ℓ during period t (cost with this parameter will be proportional to the capacity of the facility)

$K_{k\ell}$ initial capacity with alternative k associated with first opening of a facility at location ℓ

$\overline{K}_{j\ell t}$ capacity associated with expansion alterative j at location ℓ in period t

$\underline{K}_{i\ell t}$ capacity associated with contraction alternative i at location ℓ in period t

$b_{\ell t}^{p}$ demand for end product p at a facility at location ℓ during period t.

δ_{ℓ}^{p} unit capacity consumption factor of product p at a facility at location ℓ

$V_{\ell\ell' t}$ maximum upper bound capacity associated with transportation channel $\ell\ell'$ in period t

B_{ℓ} budget constraint for fixed costs over the entire planning horizon for location ℓ

N_{ℓ}^{E} maximum number of allowed expansions for a facility over the planning horizon

N_{ℓ}^{D} maximum number of allowed contractions for a facility over the planning horizon

N_{ℓ}^{T} maximum number of allowed expansions and contractions for a facility over the planning horizon.

Binary decision variables (each is 0 if the condition to be 1 is not satisfied)

$E_{j\ell t}$ = 1 if a facility at location ℓ incorporates expansion alterative j at the start of period t

$D_{i\ell t}$ = 1 if a facility at location ℓ incorporates contraction alterative i at the start of period t

$O_{k\ell t}$ = 1 if a facility with capacity k at location ℓ is opened at the start of period t (action of opening)

$C_{\ell t}$ = 1 if a facility at location ℓ is closed at the start of period t (action of closing) (i.e., at the end of period $t-1$)

$M_{\ell t}$ = 1 if a facility at location ℓ is operating in period t (i.e., to purchase, process, produce, or distribute products)

$S_{\ell\ell' t}$ = 1 if the transportation channel from location ℓ to location ℓ' is established in period t

Continuous decision variables (possibly integer decision variables)

$x^p_{\ell\ell' t}$ = amount of product p shipped from location ℓ to location ℓ' in period t

$y^p_{\ell t}$ = amount of product p held in inventory at a facility at location ℓ at the end of period t

$v^p_{\ell t}$ = amount of backorder of product p at a facility at location ℓ at in period t

$r^p_{\ell t}$ = amount of product p purchased from an outside supplier (i.e., outsourcing) at the facility at location ℓ in period t

$\widehat{K}_{\ell t}$ = amount of excess capacity of facility ℓ in period t

APPENDIX B

ADDITIONAL NOTATION FOR THE DSCR-N MODEL IN A TABLE FORMAT

Indices

$j, k \in K_\ell$ capacity alternative

Index sets

$\vec{K}_{j\ell t}$ feasible capacity-expansion alternatives that can be used in $t+1$ at location ℓ

$\overleftarrow{K}_{j\ell t}$ feasible capacity-contraction alternatives that can be used in $t+1$ at location ℓ

Parameters (all costs are discounted to present worth values)

$\overline{U}_k$ amount of capacity provided by alternative $k \in K_\ell$

$G^{ME}_{jk\ell t}$ fixed cost to operate and expand from capacity alternative j to k a facility at location ℓ in period $t+1$, where $G^{ME}_{jk\ell t} = G^{E}_{jk\ell t} + G^{M}_{j\ell t}$

$G^{MD}_{jk\ell t}$ fixed cost to operate and contract from capacity alternative j to k a facility at location ℓ In period $t+1$, where $G^{MD}_{jk\ell t} = G^{D}_{jk\ell t} + G^{M}_{j\ell t}$

Binary decision variables (each is 0 if the condition to be 1 is not satisfied)

$z_{jk\ell t} = 1$ if the facility at location $\ell \in L$ utilizes capacity alternative j in period t and expands or contracts to use capacity alternative k in period $t+1$

VITA

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