A Mathematical Programming Model to Global Supply Chain Management: Conceptual Approach and Managerial Insights

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Abstract

In this paper, we study the design of global facility networks. We present a mixed integer programming model that captures essential design tradeoffs of such networks and explicitly incorporates government subsidies trade tariffs and taxation issues. The resulting formulation can be solved for reasonable size problems with commercially available mathematical programming software. Focusing on special cases of the problem enables us to provide useful insights on preferable international facility networks for various environments. We demonstrate the pervasive, and often dominating, effects of subsidized financing, tariffs, regional trade rules, and taxation in shaping the manufacturing and distribution network of global firms.

1. Introduction

1.1 Different Approaches in Structuring Global Networks

Structuring global manufacturing and distribution networks is a complicated decision making process. The typical input to such a process is a set of markets to serve, a set of products that the company will produce and sell, demand projections for the different markets, and information about future macroeconomic conditions, transportation and production costs. Given the above information, companies have to decide, among other things, where to locate factories, how to allocate production activities to the various facilities of the network, and how to manage the distribution of products (e.g., where to locate distribution facilities). There are three main approaches in structuring global facility networks: (1) Product Family-Focused: where plants may be located in different parts of the world and each specializes in a specific product family (a set of products with similar process and market characteristics). Each product family plant is essentially an independent small company that supplies its product group to all markets in which the product is sold. (2) Process Focused: where individual plants are typically dedicated to performing specific process steps for a variety of different products. Sometimes a product is produced entirely by a single plant, but more often the plant is only one of several in the process chain. (3) Market-Focused: where plants are located at markets that they plan to serve. All products sold in that market are served locally. Each market is essentially insulated from other markets, and plants serve the needs of the local market only.

Most global facility networks firms use are hybrids of the above approaches. For example, ***Product/Process Focused*** networks have plant subnetworks that produce specific product families. The products within a product family can be completed in more than one facility of this subnetwork, and their various subassemblies are allocated to the various plants of the subnetwork. In other words, the plants within the subnetwork are process focused, but the subnetworks are product focused.

1.2 The Importance of Facility Financing and Corporate Taxation

Among the most important factors distinguishing the organization of global production activities from strictly domestic ones are the influences of various governmental policies. Governments often use special financing and taxation incentives to stimulate production investments in their country. The most important of such subsidies are:

- **Cash grants**: usually given as an incentive for investment either in a particular development region or for development of a particular product or industry. Northern Ireland offers tax free grants of up to 50 percent of the cost of new factory buildings, machinery and equipment. Of a similar nature is Israel's Capital Investment Encouragement Law where firms can receive cash subsidies up to 38 percent of the project's cost. Israel has recently provided Intel with a 600 million dollar cash grant for a 1.6 billion dollar new facility.
- **Loans at reduced interest rates**: the size of these loans can be related to the total investment capital and may vary both in size and interest rate according to the importance of the region or the project. For example, in Austria the European Recovery Programme provides loans at interest rates significantly below market levels for several types of investments, and loans for large projects could amount to up to 50% of the total investments.
- **Taxation Related Incentives**: for locating in high priority regions or manufacturing products that the government is trying to foster, firms might be exempt from paying income tax or pay lower rates for a number of years. For example, in Brazil reduced income tax rates are available in the Monaus region - Amazon forest, while in Northern Ireland the corporate income tax rate is among the lowest in the world.

In this paper we present a mathematical modeling framework that explicitly considers financing and corporate taxation issues in the design of ***Hybrid Product/Process Focused*** facility networks. The multiperiod model maximizes the discounted after tax cash flows of the firm. The paper maintains a modeling rather than an algorithmic focus.

1.3 Literature Review

One of the early papers in this area, which presents a single period model for determining simultaneously international plant location and financing decisions under uncertainty, is by Hodder and Dincer [1986]. The model uses a mean-variance approach in the objective function to incorporate price/exchange rate uncertainty and risk aversion in the location problem, an approach that builds on earlier work of Jucker and Carlson [1976] and Hodder and Jucker [1985a, b]. Aspects of subsidized government financing, tariffs and taxation are not modeled.

A succession of papers by Cohen and Lee address a variety of issues of facility network design in a global context. Cohen and Lee [1988] deal with intra-firm international trade issues. In their model, plants are specialized units which produce the sub-assemblies of the final product and the Distribution Centers (DCs) perform the final assembly. Plants are charged with fixed and variable costs, while DCs are charged only with variable costs. Cohen and Lee [1989] developed a normative integer programming model for resource deployment decisions in a global manufacturing and distribution network for a U.S. based manufacturer of personal computers. Their model enables estimation of before and after tax profitability, including exchange rate effects to a numeraire currency. Their implementation is in GAMS/MINOS (Brooke, Kendrick and Meeraus [1988]), which has no integer programming capability. Consequently, they only solve the continuous versions of their models, pre-specifying "alternate sets of integer decisions variables." Cohen, Fisher and Jaikumar [1989] presented a multiperiod extension of the above model, which explores tradeoffs between centralization and localization of supply chain decision making. A hierarchical procedure is proposed as a heuristic solution approach to the problem. Huchzermeier and Cohen [1996] present a modeling framework that integrates the network flow and option valuation approaches to global supply chain modeling. The model maximizes discounted, expected, global after-tax profit for a multinational firm in terms of numeraire currency. The results in the paper provide a methodology for quantifying the risks and returns of flexible global manufacturing strategies. Their work clearly demonstrates how flexible facility networks with excess capacity can provide real options to hedge exchange rate fluctuations in the long term. This work does not emphasize explicit modeling of facility financing and tax incentives and the resulting implications for the global network structure. Finally, various company specific facility network design issues and decision support systems have been discussed in the applications oriented literature, see Breitman and Lucas [1987] work on General Motors, Arntzen et al. [1995]work on Digital Equipment Corporation and Davis [1993] work on Hewlett-Packard.

Our work in this paper is along the research directions pointed out in the recent paper of Revelle and Laporte [1996]. As they point out, even though plant location and configuration of production/distribution networks have been studied for many years, a number of important real world issues have not received adequate attention. Even though there is ample anecdotal evidence on the strong effects of financing and taxation factors on the structure of global manufacturing and distribution networks (see Bartmess and Cerny [1993] and MacCormack et al. [1994]), there is a lack of reasonably simple, yet comprehensive, models which illustrate the effects of such factors on global location/network configuration decisions. Our research in this paper attempts to fill this gap.

The main contributions of this paper are:

a) the incorporation of such issues as government subsidies in facility financing, trade tariffs and taxation in a manageable size linear integer program that captures the multiperiod nature of international plant location and distribution network configuration decisions;

b) a model which explicitly captures intra-firm material flows (from plants to DCs) and provides insights on preferable international facility network structure for various environments;

c) the illustration of the dominating effects of subsidized financing, tariff and local content rules, and taxation in shaping the optimal structure of global facility networks.

The structure of the remaining paper is as follows: In Section 2 we present a mixed integer programming formulation of the global facility network design problem explicitly accounting for government financing and taxation issues, and report on the computational experience with the model via standard mathematical programming software. Section 3 uses a special case of the model ("identical countries") to provide insights on the effects of financing, taxation, regional trading zones and local content rules on the structure of global facility networks. Use of the mixed integer programming model in an illustrative international location decision in Section 4 further demonstrates the pervasive effects of the above factors in global facility network design. Many of the managerial insights obtained in the "identical countries" special case reappear in the realistic environment of our illustrative decision instance.

2. Problem Statement and Formulation

2.1 Problem Statement

A firm uses a Hybrid Product/Process Focus approach in designing its global network of plants and distribution centers. The firm plans to produce a new product with sales expectations in many countries. The product is composed of many different subassemblies, but requires only one unit per subassembly (i.e., a two level product tree, with level 0 the final product and level 1 all its subassemblies). A network of facilities will be developed dedicated to the production of this product, and each one of the plants within the network will be dedicated to the production of a specific subassembly. In order to assemble the final product, distribution centers (DCs) will be located in various countries. To influence the firm's location decision, various governments are willing to grant to it loans with subsidized interest rates and tax incentives that reduce the facility costs. The firm wants to develop a network of plants and DCs that maximizes its discounted after-tax profit over the planning horizon for this product.

2.2 Model Assumptions

- There are two facility levels: plants (producing subassemblies) and distribution centers (assembling the final product).
- Plant and DC locations are selected among an identified set of candidate locations.
- The plants and DCs remain open throughout the finite planning horizon.
- The firm is a price taker in each market. All prices are quoted in the currency of the market the product is sold and then translated into a common currency (say $) by using the real exchange rate.
- The market demand and the selling price are independent of the structure of the facility network.
- At most one Distribution Center (DC) is allowed in each country. The main rationale behind this assumption is that since shipment cost of a subassembly or a final product within a country is assumed constant in our model, the opening of a second DC will result in additional fixed costs with no transportation cost savings.
- Demand and supply clear in each time period and hence there are no inventory costs.
- Corporate income tax is paid on profit in each country of operation.

2.3 Notation

Indices

i: subassembly index, $i = 1,..., I$;

n: country of operation index, $n = 1,..., N$;

k: distribution center (DC) (as well as country that DC is located) index, $k = 1,..., N$;

m: country (potential plant location) index, $m = 1,..., N$;

j: country (market) index, $j = 1,..., J$;

t: time period, $t = 1,..., T$;

Parameters

f_{imt}: fixed cost of plant that produces subassembly i in country m in period t;

v_{imt}: unit variable production cost of subassembly i produced in country m in period t;

F_{kt}: fixed cost of a DC in country k in period t;

V_{kt}: unit variable assembly cost of a DC in country k in period t;

S_{kjt}: cost to ship one unit of the final product from a DC in country k to market j in period t (shipment cost calculations include any assessed trade tariffs and other duties);

$\vartheta_i S_{mkt}$: cost to ship one unit of subassembly i from country m to country k in period t (i.e., subassembly transportation cost is expressed as a fraction of the transportation cost of the

final product, with ϑ_i the fraction for subassembly i);

D_{jt}: demand of the final product in country j in period t;

r_n: per-period interest rate on the loan in country n;

$R_t(r,T)$: capital recovery factor for period t given interest rate r and planning horizon T;

$\rho_t(r,T)$: interest calculation factor for period t given interest rate r and planning horizon T;

A_{im}: required investment to build a plant for subassembly i in country m;

W_k: required investment to build a DC in country k;

t_{nt}: marginal corporate income tax rate in country n in period t;

P_{jt}: sales price of the final product (translated into $ with a real exchange rate) in country j in

period t;

p_{imkt}: transfer price of subassembly i made in country m shipped to DC in k in period t;

d_{nt}: applicable depreciation rate in country n in period t (% per period);

K_{im}: capacity of a plant producing subassembly i in country m;

C_k: capacity of a DC in country k;

β_{nt}: discount rate of after tax cash flows in country n in period t;

B_n maximum loan that country n can give to the firm;

<u>Decision Variables</u>

X_{imkt}: units of subassembly i produced in country m and assembled in country k in period t;

Y_{njt}: units assembled in country n and used to satisfy demand in market j in period t;

w_k: the loan that country k government will grant to the company to build a DC;

ψ_m: the loan that country m government will grant to the company to build subassembly plants;

y_{im}: = 1 if a plant to produce subassembly i is located in country m, and 0 otherwise;

z_k: = 1 if a DC is operated in country k, and 0 otherwise.

2.4 Basic Components of the Model

2.4.1 The Objective Function

Revenue of units assembled (α_{nt}) and subassemblies produced (μ_{nt}) in country *n* in period *t*, where: $\alpha_{nt} = \sum_{j=1}^{J} P_{jt} Y_{njt}$ and $\mu_{nt} = \sum_{i=1}^{I} \sum_{k=1}^{N} p_{inkt} X_{inkt}$.

Transportation costs from a DC (a_{nt}) and subassembly plants (b_{nt}) located in country *n* in period *t*, where $a_{nt} = \sum_{j=1}^{J} S_{njt} Y_{njt}$ and $b_{nt} = \sum_{i=1}^{I} \sum_{k=1}^{N} \vartheta_i S_{nkt} X_{inkt}$.

Annual fixed costs of a DC (δ_{nt}) and subassembly plants (γ_{nt}) in country *n* in period *t*, where: $\delta_{nt} = z_n F_{nt}$ and $\gamma_{nt} = \sum_{i=1}^{I} y_{in} f_{\text{int}}$.

Cost of goods sold for the final product assembled at the DC (c_{nt}) and assembly related costs of a DC (φ_{nt}) in country *n* in period *t*, where: $c_{nt} = \sum_{i=1}^{I} \sum_{m=1}^{N} p_{imnt} X_{imnt}$ and $\varphi_{nt} = V_{nt} \sum_{j=1}^{J} Y_{njt}$.

Variable production costs of subassembly plants in country *n* in period *t*, $e_{nt} = \sum_{i=1}^{I} v_{\text{int}} \left(\sum_{k=1}^{N} X_{inkt} \right)$.

Loan payment in period *t* (g_{nt}) and interest payment (g'_{nt}) for loan given by country *n* for the construction of subassembly plants in its territory, where: $g_{nt} = \psi_n R_t(r_n, T)$ and $g'_{nt} = \psi_n \rho_t(r_n, T)$

Loan payment in period *t* (h_{nt}) and interest payment (h'_{nt}) for loan given by country *n* for the construction of a DC in its territory, where: $h_{nt} = w_n R_t(r_n, T)$ and $h'_{nt} = w_n \rho_t(r_n, T)$.

Depreciation expense in country *n* in period *t*, $\tau_{nt} = \left(\sum_{i=1}^{I} A_{in} y_{in} + W_n z_n \right) d_{nt}$.

Before-tax income in country *n* in period *t*,

$$\pi_{nt} = \left[\alpha_{nt} + \mu_{nt} - \left(a_{nt} + b_{nt} + \gamma_{nt} + \delta_{nt} + c_{nt} + e_{nt} + \varphi_{nt} + g'_{nt} + h'_{nt} + \tau_{nt} \right) \right].$$

Corporate income tax paid in country n in period t, $CT_{nt} = \pi_{nt} t_{nt}$.

Cash expenditures in fixed assets in year 0 that are not financed by external sources.

$$IN = \sum_{m=1}^{N} \left[\left(\sum_{i=1}^{I} A_{im} y_{im} \right) - \psi_m \right] + \sum_{k=1}^{N} \left(W_k z_k - w_k \right).$$

So the objective function which maximizes the net present value is:

$$OBF = \max \left[\sum_{n=1}^{N} \sum_{t=1}^{T} \left(\pi_{nt} + g'_{nt} + h'_{nt} + \tau_{nt} - g_{nt} - h_{nt} - CT_{nt} \right) \Big/ \left(1 + \beta_{nt} \right)^t - IN \right].$$

2.4.2 The Set of Constraints

The Constraints are:

1) Demand Constraints $\sum_{n=1}^{N} Y_{njt} \le D_{jt} \qquad \forall j, t$

2) Plant Capacity Constraints $\sum_{k=1}^{N} X_{imkt} \le K_{im} \qquad \forall i, m, t$

3) DC Capacity Constraints $\sum_{j=1}^{J} Y_{kjt} \le C_k \qquad \forall k, t$

4) Conservation of Subassembly Flows $\sum_{m=1}^{N} X_{imkt} = \sum_{j=1}^{J} Y_{kjt} \qquad \forall i, k, t$

5) Country Budget Constraints $\psi_n + w_n \le B_n \qquad \forall n$

6) Compatibility of Decision Variable Values constraints

   $\sum_{k=1}^{N} \sum_{t=1}^{T} X_{imkt} \le y_{im} \cdot M \qquad \forall i, m$ and $\sum_{j=1}^{J} \sum_{t=1}^{T} Y_{kjt} \le z_k \cdot M \qquad \forall k$

   where M is a large number such that $M \ge \sum_{j=1}^{J} \sum_{t=1}^{T} D_{jt}$.

7) Nonnegative Profit in Each Country in Each Period (assumption of convenience to avoid unnecessarily complicated tax calculations) $\pi_{nt} \ge 0 \qquad \forall n, t$.

8) Loan Ceilings $\psi_m \leq \sum_{i=1}^{I} A_{im} y_{im} \qquad \forall m$ and $w_k \leq W_k z_k \qquad \forall k$.

2.5 Computational Experience with Proposed Model

We report in in the following table computational results for solving various size problems.

Table 1: Computation Time for Various Size Problems

Number of Subassemblies (*I*)	Number of Candidate Location Countries (*N*)	Number of Markets (*J*)	Number of Time Periods (*T*)	Solution Times (seconds)
3	6	50	5	14
5	6	100	5	41
20	6	100	5	106
5	20	100	5	140
5	25	50	5	108
3	35	35	5	121
5	10	250	5	187
5	6	100	15	257
5	10	50	15	273
10	15	50	5	87
10	10	100	5	104

sizes of our model with the use of standard mathematical programming software (specifically GAMS/OSL2) on a Cyrex 686-P90 processor.

We would not, however, want to give the false impression that substantially larger size problems can be solved on standard PCs. Larger size formulations (in our experience up to I=10, N=10, J=100, T=10) can be solved on minicomputers, (i.e. VAX 6400) with the use of standard mathematical programming software in less than an hour of CPU time.

3. Special Case: Identical Countries

3.1 Base Case: Tariff and Transportation Cost Considerations

In this section we analyze a special case of our model to obtain useful insights into the nature of location decisions in a global environment. We have relaxed the capacity constraints on plants and DCs (i.e. uncapacitated situation) and assume straight-line depreciation. Initially, we assume no financing and equal tax rates across countries (we refer to this as the "base case").

We consider "identical countries" and "identical periods" (i.e., $D_{jt} = D$, $P_{jt} = P$, $t_{jt} = t$, and $\beta_{jt} = \beta$ for all j) with a trade tariff assessed on flows crossing their borders. The product consists of I "identical subassemblies" in terms of revenue and cost parameters in our model. For example, $\vartheta_i = \vartheta$ for all i. The assumption is not intended to imply physical similarity but only similarity of cost parameters. We assume that only one plant of each subassembly type will be built (due to, for example, economies of scale). Also, there is no differentiation among subassembly plants or DCs (we use the term "identical plants or DCs" with an analogous meaning) and specifically

$$A_{im} = A,\ v_{im} = v, f_{im} = f \qquad \text{for } i = 1,\ 2,\ldots, I \ \text{ and } m = 1,\ 2,\ldots, N; \ \text{ and}$$

$$W_k = W,\ V_k = V,\ F_k = F \qquad \text{for } k = 1,\ 2,\ldots N.$$

Without loss of generality, we also assume that a DC can be constructed in every market (i.e. $N = J$). The transportation costs within the countries are C per unit of final product (i.e., $S_{kk} = C$); however, they increase by the assessed trade tariff whenever borders are crossed. Specifically, transportation costs per unit of final product across borders equal $S_{kj} = C(1+\Delta)$, $\Delta > 0$, for all (k,j), $k \neq j$. We assume that the transfer prices p are the same for all subassemblies and based on a worldwide market standard that is closely monitored by governments (i.e. the firm cannot change transfer prices to take advantage of tax conditions). Finally, we assume that prices and costs are structured such that the firm will always show nonnegative profit in every country as long as a DC in any country serves at least the total demand for the country of its location.

Proposition 1 shows that we can ignore all cases where subassembly plants are located in different countries.

PROPOSITION 1: Given I identical plants which can be constructed in any of N identical countries, it is preferable, or at least as profitable as any other configuration, to build all I plants in one country.

Thus, it makes sense for all subassembly plants to be located in one country, but we still must determine how many DCs to build. We examine two cases where the number of DCs equal to 1 or q (where $1 < q \leq N$). The Net Present Values (NPVs) of these configurations are given below, and the DC locations that maximize the NPV are assumed (i.e., markets that do not contain a DC are all served from the same DC located in the country containing the subassemblies):

$$\text{NPV}(1\ \text{DC}) = -IA - W + \sum_{\omega=1}^{T} \left\{ (1-t)\left[NPD - (N + N\Delta - \Delta)CD - NI\vartheta CD - If - F - NIvD - NDV\right] + \frac{t(IA+W)}{T} \right\} \Big/ (1+\beta)^{\omega},$$

After rearranging terms, the NPV (q DCs) is equal to:

$$\text{NPV}(q\ \text{DCs}) = -IA - qW + \sum_{\omega=1}^{T} \left\{ (1-t)\left[NPD + CD\left(I\vartheta\Delta(1-q) + \Delta(q-N) - N(I\vartheta+1)\right) - If - qF - NIvD - NDV\right] + \frac{t(IA+qW)}{T} \right\} \Big/ (1+\beta)^{\omega}.$$

The following proposition provides insights on the nature of the DC configuration for this special case.

PROPOSITION 2: For the case of identical plants and identical countries,

(a) It is preferable to either build a single DC in the country where all plants are located or to construct DCs in all countries;

(b) For the infinite time horizon case ($T \to \infty$), a single DC is optimal if either (1) $I\vartheta \geq 1$, or (2)

$I\vartheta < 1$ and $D \leq D^*$, where $D^* = \left[\beta W / (1-t) + F\right] / \left[\Delta C(1 - I\vartheta)\right]$; otherwise a configuration with DCs in all countries is optimal.

According to the above proposition, if it is more expensive to transport the subassemblies individually than to transport the final product ($I\vartheta > 1$), then it is preferable to use a centralized distribution structure with the product transported from the country where it is manufactured and assembled to all of its final markets. If the condition is reversed, i.e., transportation of the final product is more expensive, then given a substantial demand in foreign markets, it is preferable to open a DC in each one of the markets (i.e., a decentralized distribution structure) and transport subassemblies from the subassembly manufacturing plants.

The analysis of this special case provides the following insights for environments where the transportation cost elements (in our case transportation cost differences were generated through the Δ factor, i.e., trade tariffs and other restrictive cross-border flow regulations) tend to dominate:

(a) when transportation of subassemblies is expensive, firms prefer a centralized manufacturing and distribution structure;

(b) as the transportation cost element between countries and/or cross-border flow government imposed penalties increase firms tend to open DCs in markets away from the manufacturing facilities; and

(c) governments can attract DC investments in such environments by offering financing help through loans.

3.2 Government Incentives: Financing and Taxation

Governments can attract facility investments in their country via subsidized financing of facility (plant and/or DC) construction, as the following proposition illustrates:

PROPOSITION 3: For the case of identical plants and identical countries, if only one country offers attractive financing for facility construction with interest rate $r < \beta/(1-t)$, then all I plants and a distribution center will be built in that country.

As we demonstrate in Section 4, in many cases even relatively small subsidization of loan interest rates by the government is adequate to attract facility investments in the country. However, the level of facility investment in the country by a firm is non-decreasing with the level of subsidized financing provided by the government.

Next we explore the situation where one country charges a lower tax rate than the rate of other countries.

LEMMA 1: If there is only one DC, the plants and the DC are located in the country with the lower tax rate.

LEMMA 2: If more than 1 DC is open, the plants and the DC serving any markets without a DC will be located in the country with the lower tax rate.

Proposition 4 follows from the two lemmas.

PROPOSITION 4: For the case of identical plants and identical countries, if one country offers a lower tax rate (t') than the rest (t), then all I plants will be built in that country. In addition, it is preferable to either build a single DC in the lower tax rate country or to construct DCs in all countries.

Let us observe the relevant expressions for NPV(1 DC) - NPV (q DCs) in the base case (see proof of Proposition 2) and lower tax rate country case (see proof of Proposition 4). The difference in these two expressions is the term $(t-t')D[P - Ip - V - C(1+\Delta) + \Delta CI\vartheta]$, which is positive due to the assumption of the price structure ensuring nonnegative profits in each country of operation. This implies that it is easier to satisfy the inequality NPV(1 DC) - NPV (q DCs)>0 in the lower tax rate country case than under the base case. Therefore, the firm is more likely to desire complete centralization of its distribution network when one country offers a lower tax rate than for the case where all countries offer the same tax rate.

According to Proposition 4 and the above observations, by lowering its tax rate, not only may a country entice firms to open plants and/or distribution centers, but also the amount of demand flowing through existing distribution centers in that country may increase. Country environments with differential tax rates tend to favor more centralized manufacturing and distribution network structures. Even rather small tax rate differences can induce firms to move their facility investments to countries with lower tax rates, as will become more apparent through our discussion in the next section.

3.3 Tariff Structure: Regional Trading Zones and Local Content Rules

Governments sometimes enter into multilateral trade agreements which allow for tariff-free trade among nations that belong to the pact. In this section we introduce trading pacts into the special case and describe the changes that the agreements may cause for a firm's global distribution network configuration. We begin by stating two lemmas.

LEMMA 3: For the case of identical plants and identical countries, if the N countries are divided into Z tariff-free trade zones, then no more than one DC should be located in each trading zone.

LEMMA 4: For the case of identical plants and identical countries, if the N countries are divided into Z tariff-free trade zones, then all I plants should be built in any of the countries that form the trading zone which contains the most countries.

Lemmas 3 and 4 allow us to construct the following proposition, which describes the impact that trading zones have on the degree of centralization of a firm's distribution network.

PROPOSITION 5: Consider the case of identical plants and identical countries, where the N

countries are divided into Z tariff-free trade zones. If $I\vartheta > 1$ $(I\vartheta < 1)$, then a completely centralized distribution network, with only one DC, is more likely (less likely) to be optimal than for the case without tariff-free zones.

Proposition 5 implies that the centralization/decentralization distribution network configuration decision is more sensitive to the relative transportation cost of subassemblies vs. the final product when trading zones are introduced. Specifically, if it is more expensive to transport the subassemblies individually than to transport the final product $(I\vartheta > 1)$, then a centralized distribution is more likely than in the base case, as the penalty for transporting the final product from one location is smaller as the home (tariff-free) market is bigger. On the other hand, if transportation of the final product is more expensive $(I\vartheta < 1)$, then centralized distribution is less likely than in the base case, as the penalty for transporting subassemblies across borders is smaller as fewer are charged the tariff (i.e., more subassemblies are transported tariff free to the DC in the same zone).

The impact of trading zones can be summarized by stating that when trading zones are established and the cost of transporting subassemblies is not high compared to the final product, then the distribution network is likely to become "regionalized" instead of centralized in one country or decentralized among all markets. In other words, the network becomes decentralized over trading zones (instead of countries) but centralized within each zone. On the other hand, if economies of scale exist such that only one plant will be built for each subassembly, and if the total cost of transporting subassemblies is high compared to the final product, then the establishment of trading zones will more likely result in manufacturing and distribution centralization, i.e. all facilities in one location. In that case, the zone offering the best incentives may attract all of the firm's worldwide investment.

Many governments establish "local content rules," which require firms to have a certain portion of their final products originate from that country. The percentage requirement has been known to be as high as 90%, and the specific rules and penalties may vary greatly among countries (Munson and Rosenblatt [1997]). Consider a local content rule which imposes a tariff Δ for domestic shipment from the distribution center unless the value of the subassemblies from domestic plants plus the value added at the distribution center is at least as high as the local content percentage times the final good's value. In other words, the country treats the final product as an imported good unless a certain portion of that good is produced in the country. This type of rule prohibits firms from using cheap foreign labor to produce the bulk of the product while adding little value in the country of sale.

Since the countries are identical under the base case scenario, if one government introduces a local content rule, then a DC and all I plants will be diverted to that country (because there would be no penalty for doing so). Therefore, we will examine the situation from Section 3.2 where one of the countries (A) has a lower tax rate than the other countries, and country B introduces a local content rule in order to attract investments. Now if conditions are such that, prior to the introduction of any local content rules, a completely centralized distribution network is optimal, then from Lemma 1, country A will have all of the facilities (including the only DC). The local content rule introduced by country B will have no effect because the firm currently has no DC in country B. Therefore, we will assume that conditions are such that each country has a DC, and (from Lemma 2), all I plants currently reside in country A. Country B introduces the local content rule to try to "force" some of the plants to move to that country.

Clearly, based on Lemma 2, the firm will want to move as few plants as possible from country A to country B in order to satisfy the local content requirement. The local content rule is defined here as $\Phi pD + VD \geq \Omega(IpD + VD)$, where Φ is the number of subassembly plants located in country B and Ω is the local content percentage $(0 \leq \Omega \leq 1)$. Therefore, the number of subassemblies that the firm has to move in order to satisfy local content is the smallest integer Φ^* such that $\Phi^* \geq [\Omega Ip - (1-\Omega)V]/p$. Proposition 6 describes the conditions under which the firm should satisfy the local content requirement imposed by country B.

PROPOSITION 6: For the case of identical plants and identical countries with country A having a lower tax rate than the other countries, it is worthwhile for the firm to move Φ^* subassembly plants from country A to country B in order to satisfy country B's local content rule if:

$$\Phi^* < \frac{-W + \sum_{\omega=1}^{T}\left[(1-t')\Delta CD + \frac{tW}{T} - (1-t)F - (t-t')D(P - Ip - C - V)\right]\Big/(1+\beta)^{\omega}}{\sum_{\omega=1}^{T}(t-t')\left[NDp - (N-1)(1+\Delta)\vartheta CD - \vartheta CD - f - NDv - \frac{A}{T}\right]\Big/(1+\beta)^{\omega}}. \qquad \text{(P6)}$$

If the right-hand-side of (P6) is greater than *I*, then country B can impose any size Ω (up to 100%) and still induce the firm to transfer its production facilities in order to satisfy the local content rule. However, a country can become too greedy and create a "boomerang" effect, whereby setting too high of a rate not only fails to attract investment but also causes the company to leave the country altogether (close its DC), see Munson and Rosenblatt [1997]. For the special case described here, Corollary 1 gives the local content percentage which "backfires" on country B.

COROLLARY 1: For the case of identical plants and identical countries with country A having a lower tax rate than the other countries, the local content percentage Ω imposed by country B will result in the closing of all plants and DCs in that country if

$$\Omega > \frac{P}{Ip+V}\left\{ V + \frac{-W + \sum_{\omega=1}^{T} \left[(1-t')\Delta CD + \frac{tW}{T} - (1-t)F - (t-t')D(P - Ip - C - V) \right] \Big/ (1+\beta)^{\omega}}{\sum_{\omega=1}^{T} (t-t') \left[NDp - (N-1)(1+\Delta)\vartheta CD - \vartheta CD - f - NDv - \frac{A}{T} \right] \Big/ (1+\beta)^{\omega}} \right\}.$$

4. Illustrative Use of the Model: Effects of Financing, Tariffs, Local Content, Regional Trading Zones and Taxation

We explore the potential effects on a firm's location decisions from 1) financing incentives, 2) tax incentives, 3) regional trading blocks, and 4) local content requirements with the use of our model. For the base case problem we consider a company making a product which sells for $2,000 in all markets, irrespective of tariffs. The product has four major subassemblies with significant fixed and variable costs for the subassembly plants. Distribution centers, on the other hand, have lower fixed and variable costs. The firm sells to 40 countries in Europe, Asia, and North America. (The U.S. market is split into two "countries," East and West U.S., in order to account for large geographical distances. Of course, no trade tariffs are charged on flows between these two markets.) Exhibit 1 shows the demand of each country.

The firm has identified 12 of the countries as potential locations for subassembly plants and distribution centers. Exhibit 2 shows the relevant cost information. No financing is offered for the base case. Each country has a 40% effective income tax rate, and cash flows are discounted at 20% in each country. The time horizon is five years, and cost and demand factors do not change over time. All investments have an annual 20% depreciation rate. The subassembly transportation cost factor ϑ_i equals 20% for each subassembly *i*. The transportation costs for the final product are 2 cents per mile per unit. In addition, every final product that crosses a national border is charged a $200 per unit tariff ($40 per unit for each subassembly).

The transfer price p_{imkt} was set equal to a 20% markup over costs calculated as the sum of depreciation and fixed costs for plant *i* in country *m* divided by the total worldwide demand, the transportation cost of subassembly *i* from country *m* to the distribution center in country *k* and the unit variable production cost of *i* in *m*.

Base Case

The base case solution has a net present value of $38,940,519. India has plants for all four subassemblies. In addition, Mexico has a plant for subassembly 4. There are nine active distribution centers. They are located in all potential locations except for Ireland, Romania, and Taiwan. Each distribution center serves its local demand. The distribution center in India also serves the customers of all countries that do not have their own distribution center. The three potential DC locations that did not open were the ones with the smallest demands. As the reader can easily verify, the resulting facility configuration in this more complicated decision environment is along the same lines and fits nicely the insights obtained from the special case discussion in Section 3.1.

Scenario 1 – Government Financing

In this scenario we examine whether government loans can induce investment in that country. In the base case, despite the very low variable cost, the high investment cost for subassembly 1 plant (mostly due to a lack of transportation, telecommunications and technology infrastructure) prevented its location in Romania. However, government financing can make production in Romania attractive. For this example, if Romania offers to finance all possible investments at an interest rate less than or equal to 33.2%, the plants for subassemblies 1 and 3 move from India to Romania (at higher interest rates the base case solution is still optimal).

The shift in locations to Romania has global distribution impacts. With the production network more spread out , it is optimal to now open distribution centers in all 12 potential locations. Also, the DC in India now only serves the markets in Asia which do not have their own DCs. The Romanian DC serves all other markets in Europe and North America without their own DCs.

Reducing the interest rate from 33.2% does not change the new allocation of demand, even when the rate is 0%. The NPV does increase, of course, as the interest rate decreases. Exhibit 3 shows the percent increase in NPV as a function of the interest rate offered by the Romanian government. At 0% the NPV is $44,349,287. The rate of 33.2% necessary to induce the configuration change is the one prescribed in Proposition 3 (i.e., $(\beta/1-t)$).

Scenario 2 – Tax Incentives

Ireland has traditionally offered low tax rates to try to increase foreign investment. Since Ireland has no locations in the base case, in Scenario 2 we lower the tax rate in Ireland while keeping the rate in all other countries at 40%. It only takes a 4% reduction in tax rate to 36% to entice the firm to open a distribution center in Ireland to serve its own customers. All other demand allocations from the base case remain the same.

At 25%, the plant configuration as well as the DC configuration change. The plant for subassembly 1 moves from India to Romania, and the plant for subassembly 3 moves from India to Ireland. In addition, all 12 countries on the candidate location list open distribution centers. India continues to serve the customers in Asian markets without DCs, but all other markets without DCs are now served by Ireland. Another configuration change occurs at a 5% tax rate. The plant for subassembly 2 moves from India to Ireland. In addition, all DCs in Europe except for Ireland's close, and the Ireland DC now serves all markets which do not have their own DCs.

Exhibit 4 shows the percent increase in NPV as a function of Ireland's tax rate. The curve is piecewise-linear, with the kinks occurring at tax rates that cause a change in network configuration and/or demand distribution among DCs. At 0% the NPV is $45,073,946.

The results of our example for Scenario 2 clearly indicate that lower tax rates can encourage companies to change their location decisions, and the larger the difference between the rates of low-tax and high-tax countries, the more centralized the manufacturing/distribution network structure tends to become (i.e. similar insights to Proposition 4). In addition, firms can take advantage of tax rate differences by changing their intra-company transfer prices. (Overindulgence in such activity requires caution, however, because governments often monitor transfer prices.) We ran the model to take additional advantage of Ireland's lower tax rates by setting the transfer prices to cover the subassembly plants' fixed and variable costs only (assuming full satisfaction of worldwide demand). The DC and plant configurations were not always the same for the new transfer prices. For example, if Ireland's tax rate is set to 0%, Romania has the plant for subassembly 1, India has the plants for subassemblies 2 and 4, and Ireland has the plant for subassembly 3; and there are only two DCs – one in India which serves the Indian market only and one in Ireland which serves the rest of the world. The NPV increases substantially with the new transfer prices for lower tax rates and achieves its maximum difference (Exhibit 5) at the 0% tax rate, where the NPV is $50,306,318, a $5,232,372 increase compared to the old transfer price case.

Scenario 3 – Regional Trading Agreements

Regional trading agreements such as NAFTA encourage trade among countries within the region. For this example, we ran the model eliminating the $200 tariff between countries who were members of the same regional trading blocks. We defined three trading blocks as 1) NAFTA: The U.S., Mexico, and Canada; 2) European Union: The U.K., Ireland, Germany, France, Portugal, Spain, The Netherlands, Belgium, Luxembourg, Denmark, Italy, and Greece; and 3) Asian Union: Taiwan, Thailand, Malaysia, Singapore, The Philippines, South Korea, and Japan.

Under the trading blocks scenario, the plants for subassemblies 1 and 3 move from India to Romania. Also, demand gets substantially reallocated among DCs to take advantage of the tariff-free trade zones. Exhibit 6 shows the new demand allocation to DCs, which demonstrates the "regionalization" effect on the distribution network structure. One DC in each of the trading zones is supplying the demand for all countries within the free trading region (except for the DC in the West U.S. which was also open along with the East U.S. DC in the base case due to the significant, albeit tariff-free, distances). This result is along the same lines as the insights of Lemma 3 and Proposition 5. The NPV of Scenario 3 is $42,624,747, a $3,684,228 increase from the base case.

Scenario 4 – Local Content Requirements

We examine the effects of a local content rule which imposes the $200 tariff for domestic shipment from a DC unless the value of the subassemblies from domestic plants plus the value added at the DC is at least as high as the local content percentage times the final good's value.

Symbolically, we altered the program in the following way. If a country has a local content rule, then two new decision variables are added: 1) a binary variable Γ_{kt}, which is activated if country *k* has a DC in period *t* but the local content constraint is not satisfied; and 2) a nonnegative linear variable Λ_{kt} which represents the additional tariff cost for domestic shipment of goods that do not satisfy the local content requirement. Two new constraints per period are needed:

$$(1-\Omega)V_{kt}\sum_{j}Y_{kjt} \geq -M\Gamma_{kt} + \Omega\left(\sum_{i}\sum_{m\in L}p_{imkt}X_{imkt}\right) \qquad \forall k,t\,;$$

and $$\Lambda_{kt} \geq \Delta\left[\sum_{j\in L}Y_{kjt} - M(1-\Gamma_{kt})\right] \qquad \forall k,t \qquad (\Lambda_{kt}\geq 0)$$

where L is a set that contains all of the markets in the tariff-free zone, Ω is the local content percentage, M is a very large number, and Δ represents the additional tariff penalty per unit. The tariff penalty Λ_{kt} is then added to the DC transportation cost term a_{kt} in the objective function.

Trading blocks may impose local content requirements as well. For example, NAFTA uses a 62.5% rule in some cases. In the example problem, we examine the effect of a local content requirement in the Asian Union, where no subassembly plants exist in the optimal solution of Scenario 3. We obtained solutions for local content percentages ranging from 10% to 100%, incrementing by 10%.

At 10%, a plant for subassembly 4 is opened in Taiwan, and the distribution of demand among the DCs remains the same as in Scenario 3. At 30%, however, a major worldwide shift occurs. First, a plant for subassembly 3 is opened in Taiwan in addition to the subassembly 4 plant. Furthermore, the two plants in Romania are closed, and a plant for subassembly 1 is opened in both Mexico and India. This also causes a distribution center to be opened in Mexico to serve the domestic market there. Finally, the DC in Romania closes, and India now serves all of Romania's former markets.

Another change occurs at 50%. The plant configuration in Taiwan is the same, but the plants for subassembly 1 close in both India and Mexico (as does the DC in Mexico), and the subassembly 1 plant is reopened in Romania. This is the high investment, low variable cost plant in Romania. The transfer price per unit of subassembly 1 charged by Romania to Taiwan is \$319.98 vs. a price of \$404.57 charged when Taiwan "received" subassembly 1 from India. (Although the distance from Romania is further and the depreciation expense is larger than from a subassembly 1 plant in India, these effects on the transfer price are more than offset by the substantially lower variable production cost in Romania). So while in a physical sense the same subassemblies (3 and 4) are made in Taiwan under a 50% local content rule vs. a 30% rule, the total value of the product in Taiwan decreases since the transfer price of subassembly 1 decreases by $84.59 compared to the price charged previously by the plant in India. In other words, Taiwan satisfies the local content rule not by increasing the numerator (value of local content), but by decreasing the denominator (value of the total product). This allows the DC in Taiwan to continue to satisfy local content with just two plants. Finally, the opening of the plant in Romania causes its DC to reopen, although India now continues to serve the markets of Norway, Finland, and Russia.

A third plant (for subassembly 1) opens in Taiwan under the 60% rule. Following the insights of Proposition 6, reasonable size increases in the local content rule of a trading region induce further manufacturing investment in the region. This move causes the subassembly 1 plant and the DC to close again in Romania. In addition, the subassembly 1 plants reopen in India and Mexico. The DC configuration returns to the 30% rule case.

Countries or trading blocks can become too greedy, however. An 80% rule in the Asian Union becomes too costly to try to accommodate. At that point all plants in Taiwan are closed. Now India has plants for all four subassemblies, and Mexico has plants for subassemblies 1 and 4. (The DC in Mexico remains open to serve the domestic market there.) Even the DC in Taiwan closes, so now India serves all of the Asian Union.

A similar "boomerang" effect occurred when we tried a local content rule for Germany and China only. The demand was insufficient in those countries to induce any plants to open. Instead, the DCs were forced to close in each case, "robbing" the local governments of any employment or income tax revenue. The insights of the "boomerang" effect of local content rule changes, as well as relevant conditions for it to occur, are also described in Corollary 1 of the previous section. Munson and Rosenblatt [1997] observe a similar effect for a different type of local content requirement.

Clearly local content rules can greatly affect the size and type of investment in a country or trading block, and the implications may affect the entire worldwide configuration. Companies should monitor such rules closely and take them into account early in the network design stages.

5. Conclusion

Government subsidies in facility financing, tariffs and regional trading rules, and favorable corporate taxation laws are main factors in explaining the structure of global manufacturing and distribution networks. We have provided a modeling framework that provides for decision support purposes the effects of such factors on the structure of global facility networks. From our analysis of special cases of the model, we obtained useful insights on the structure of such networks, which we present in a summary form below:

(i) when transportation of subassemblies is expensive, firms prefer centralized manufacturing and distribution structures;

(ii) increased trade tariffs favor gradual decentralization of the distribution networks;

(iii) differential tax rates tend to favor more centralized manufacturing and distribution network structures, with the low tax countries attracting not only plants and DC investments but also serving a larger portion of the worldwide demand via their DCs;

(iv) formation of trading zones in certain environments (e.g., when the transportation cost of subassemblies is relatively insignificant compared to the final product) tends to have a "regionalization" effect on the facility network (i.e., the facility network becomes decentralized over trading zones but centralized within each zone);

(v) reasonable increases in local content requirements within a country or a trading zone entice firms to transfer facilities to that country or zone; however, inappropriate setting of local content requirements may result in exactly the opposite effect (i.e., withdrawal of all facilities from the country or zone);

(vi) even small subsidy of facility financing by a country's government is in most cases adequate to attract facility investments in the country.

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Appendix

Proof of Proposition 1: The only component of the objective function affected by this decision is b_{nt}, i.e., the transportation cost of subassemblies to DCs. For each subassembly *i*, transportation costs are minimized by locating in the country containing the DC serving the largest demand. This way we minimize the additional trade tariffs (i.e., Δ component of the transportation cost). For the case where all countries have DCs in them, the subassembly plant location has no effect on the objective function, and thus the proposed solution of this proposition is among the optimal ones. ■

Proof of Proposition 2: $\text{NPV}(1 \ \text{DC}) - \text{NPV}(q \ \text{DCs}) =$

$$(q-1)\left(W + \sum_{\omega=1}^{T} \left\{ (1-t)[\Delta CD(I\vartheta - 1) + F] - \frac{tW}{T} \right\} \Big/ (1+\beta)^{\omega} \right).$$

The term inside the large parenthesis may be positive or negative. If it is positive, then only one DC should be used. If it is negative, then *N* DCs should be used because the difference $\text{NPV}(1 \ \text{DC}) - \text{NPV}(q \ \text{DCs})$ is maximized when $q = N$. As $T \to \infty$, the term inside the large parenthesis equals $W + (1-t)[\Delta CD(I\vartheta - 1) + F] / \beta$, which is positive if $I\vartheta \geq 1$. If $I\vartheta < 1$, the expression is decreasing in *D* and equals zero when $D = [\beta W/(1-t) + F] / [\Delta C(1 - I\vartheta)]$. ■

Proof of Proposition 3: Due to the deductibility of interest, the cost of debt is $(1-t)r$. Since the firm's cost of capital is β, the company should accept a loan as long as the cost to service the debt is less than what it can earn on the principal, i.e. $(1-t)r < \beta$, or $r < \beta/(1-t)$. This is true for any size investment as long as the firm's debt ratio does not change significantly. Propositions 1 and 2 imply that, for the base case, all *I* plants will be located in a country with a DC. Since the countries are identical, the firm will increase NPV by placing all *I* plants and a

DC in the country offering the financing, assuming that the interest rate satisfies the stated condition. ■

Proof of Lemma 1: Let country A be the one with the lower tax rate (t'). Country B will represent any of the other arbitrary countries with tax rate of $t(t' < t)$. We need to consider four cases:

Case C1 – all markets are served from A and all plants are located in A;

Case C2 – all markets are served from B and all plants are located in B.

Case C3 – all markets are served from A and all plants are located in B;

Case C4 – all markets are served from B and all plants are located in A;

The cases only differ with respect to their annual cash flows (ACF). We use the notation ACF(C1), ACF(C2), etc., to denote annual cash flows for cases C1 and C2, respectively. These expressions are:

$$\text{ACF}(\text{C1}) = (1-t')\left[NPD - (N + N\Delta - \Delta)CD - NI\vartheta CD - If - F - NIvD - NDV\right] + \frac{t'(IA+W)}{T};$$

$$\text{ACF}(\text{C2}) = (1-t)\left[NPD - (N + N\Delta - \Delta)CD - NI\vartheta CD - If - F - NIvD - NDV\right] + \frac{t(IA+W)}{T};$$

$$\text{ACF}(\text{C3}) = (1-t')\left[ND(P - Ip) - (N + N\Delta - \Delta)CD - F - NDV\right] + \frac{t'W}{T}$$

$$+(1-t)\left[NDIp - (1+\Delta)NI\vartheta CD - If - NIvD\right] + \frac{tIA}{T};$$

$$\text{ACF}(\text{C4}) = (1-t)\left[ND(P - Ip) - (N + N\Delta - \Delta)CD - F - NDV\right] + \frac{tW}{T}$$

$$+(1-t')\left[NDIp - (1+\Delta)NI\vartheta CD - If - NIvD\right] + \frac{t'IA}{T}.$$

After subtracting the annual cash flows and rearranging terms:

$$\mathrm{ACF}(\mathrm{C1}) - \mathrm{ACF}(\mathrm{C2}) = (t - t')\left[NPD - (N + N\Delta - \Delta)CD - NI\vartheta CD - If - F - NIvD - NDV - \frac{IA + W}{T}\right];$$

$$\mathrm{ACF}(\mathrm{C1}) - \mathrm{ACF}(\mathrm{C3}) = (t - t')\left[NDIp - NI\vartheta CD - If - NIvD - \frac{IA}{T}\right] + (1 - t)\Delta NI\vartheta CD;$$

$$\mathrm{ACF}(\mathrm{C1}) - \mathrm{ACF}(\mathrm{C4}) = (t - t')\left[ND(P - Ip) - (N - N\Delta - \Delta)CD - F - NDV - \frac{W}{T}\right] + (1 - t')\Delta NI\vartheta CD.$$

All three differences are positive due to the assumption of the price structure ensuring nonnegative profits in each country of operation. Thus, Case 1 has the largest NPV, which proves the lemma. ■

Proof of Lemma 2: We need to consider five cases:

Case C5 – all markets without a DC are served from A and all plants are located in A;

Case C6 – all markets without a DC are served from B, A has a DC, and all plants in B;

Case C7 – all markets without a DC are served from A and all plants are located in B;

Case C8 – all markets without a DC are served from B, A has a DC, and all plants in A;

Case C9 – country A has no facilities.

The cases only differ with respect to their annual cash flows. These expressions for C5-C8 are:

$$\mathrm{ACF}(\mathrm{C5}) = (1 - t')\Big\{[N - (q - 1)]D(P - Ip) - CD - (N - q)(1 + \Delta)CD + NDIp - I\vartheta CD$$

$$-(q - 1)I\vartheta CD(1 + \Delta) - (N - q)I\vartheta CD - If - F - NIvD - [N - (q - 1)]DV\Big\} + \frac{t'(IA + W)}{T}$$

$$+(q - 1)\left\{(1 - t)[D(P - Ip) - CD - F - DV] + \frac{TW}{T}\right\};$$

$$\mathrm{ACF}(\mathrm{C6}) = (1 - t)\Big\{(N - 1)D(P - Ip) - (q - 1)CD - [N - (q - 1)](1 + \Delta)CD + NDIp - I\vartheta CD$$

$$-(q - 1)I\vartheta CD(1 + \Delta) - (N - q)I\vartheta CD - If - (q - 1)F - NIvD - (N - 1)DV\Big\}$$

$$+\frac{t(IA + (q - 1)W)}{T} + (1 - t')[D(P - Ip) - CD - F - DV] + \frac{t'W}{T};$$

$$\mathrm{ACF}(\mathrm{C7}) = (1-t')\{[N-(q-1)]D(P-Ip) - CD - (N-q)(1+\Delta)CD - F - [N-(q-1)]DV\} + \frac{t'W}{T}$$

$$+(1-t)\{NDIp - I\vartheta CD - (N-1)I\vartheta CD(1+\Delta) - If - NIvD\} + \frac{tIA}{T}$$

$$+(q-1)\left\{(1-t)[D(P-Ip) - CD - F - DV] + \frac{tW}{T}\right\};$$

$$\mathrm{ACF}(\mathrm{C8}) = (1-t)\{(N-1)D(P-Ip) - (q-1)CD - [N-(q-1)](1+\Delta)CD - (q-1)F - (N-1)DV\}$$

$$+\frac{t(q-1)W}{T} + (1-t')\{NDIp - I\vartheta CD - (N-1)I\vartheta CD(1+\Delta) - If - NIvD\} + \frac{t'IA}{T}$$

$$(1-t')[D(P-Ip) - CD - F - DV] + \frac{t'W}{T}.$$

After subtracting the annual cash flows and rearranging terms:

$$\mathrm{ACF}(\mathrm{C5}) - \mathrm{ACF}(\mathrm{C6}) = (t-t')\left\{NDIp - I\vartheta CD - (q-1)I\vartheta CD(1+\Delta) - (N-q)I\vartheta CD - If - NIvD - \frac{IA}{T}\right.$$

$$\left. + (N-q)D[(P-Ip) - V - (1+\Delta)C]\right\} + (1-t)(1+\Delta)CD;$$

$$\mathrm{ACF}(\mathrm{C5}) - \mathrm{ACF}(\mathrm{C7}) = (t-t')\left\{NDIp - NI\vartheta CD - If - NIvD - \frac{IA}{T}\right\}$$

$$+I\vartheta CD\Delta[(1-t)(N-1) - (1-t')(q-1)];$$

$$\mathrm{ACF}(\mathrm{C5}) - \mathrm{ACF}(\mathrm{C8}) = (t-t')\{(N-q)D[(P-Ip) - V - (1+\Delta)C]\} + (1-t')(N-q)I\vartheta CD\Delta$$

$$+(1-t)(1+\Delta)CD$$

All three differences are positive due to the assumption of the price structure ensuring nonnegative profits in each country. Finally, Case C5 dominates Case C9 using the following argument. Suppose that (q-1) DCs have already been located in the higher tax rate countries and they serve their home market only. The final DC which serves the rest of the markets must be located in either country A or country B. This is a one-DC location problem described by

Lemma 1, which implies that the DC should be located in country A. ■

Proof of Proposition 4: The first statement is a direct result of Lemmas 1 and 2. The two net present values, then, that need to be considered are:

$$\text{NPV}(1\text{ DC}) = -IA - W + \sum_{\omega=1}^{T} \left\{ (1-t')\left[NPD - (N + N\Delta - \Delta)CD - NI\vartheta CD - If - F - NIvD - NDV\right] + \frac{t'(IA+W)}{T} \right\} \Big/ (1+\beta)^{\omega} ;$$

$$\text{NPV}(q\text{ DCs}) = -IA - qW + \sum_{\omega=1}^{T} \Big((1-t')\Big\{ \left[N-(q-1)\right]D(P-Ip) - CD - (N-q)(1+\Delta)CD + NDIp$$

$$-I\vartheta CD - (q-1)I\vartheta CD(1+\Delta) - (N-q)I\vartheta CD - If - F - NIvD - \left[N-(q-1)\right]DV \Big\} + \frac{t'(IA+W)}{T} \Big\}$$

$$+(q-1)\left\{ (1-t)\left[D(P-Ip) - CD - F - DV\right] + \frac{tW}{T} \right\} \Big) \Big/ (1+\beta)^{\omega} .$$

Subtracting the two: NPV(1 DC) - NPV(q DCs) =

$$(q-1)\left(W + \sum_{\omega=1}^{T} \left\{ (1-t')\Delta CD(I\vartheta - 1) + (1-t)F - \frac{tW}{T} + (t-t')D\left[(P-Ip) - C - V\right] \right\} \Big/ (1+\beta)^{\omega} \right).$$

As with the base case, if the term inside the large parenthesis is positive, then only one DC should be used (in country A). If it is negative, then N DCs should be used because the difference is maximized when $q = N$. ■

Proof of Lemma 3: Each DC which is built requires an investment plus an annual fixed cost. The only benefit of building more than one DC is to avoid the trade tariff Δ. The proof follows since transportation within a tariff-free zone has no Δ component. ■

Proof of Lemma 4: Along the lines of Proposition 2, it can be shown that either one DC should be built for the whole company or one DC should be built in each zone. If Z DCs are built, then subassembly transportation costs are minimized by building all I plants somewhere in zone $Z1$. If one DC is built, then it should be built in $Z1$ to minimize the transportation costs of the final product. In that case as well, subassembly transportation costs are minimized by building those plants in $Z1$. ■

Proof of Proposition 5: Let z' countries be located in the zone $Z1$ that contains the most countries. Then by Lemmas 3 and 4, the NPVs of the two possible configurations are:

$$\text{NPV}(1\text{ DC}) = -IA - W + \sum_{\omega=1}^{T} \Big\{ (1-t)\big[NPD - z'CD - (N-z')(1+\Delta)CD - NI\vartheta CD - If - F$$

$$-NIvD - NDV\big] + \frac{t(IA+W)}{T} \Big\} \Big/ (1+\beta)^{\omega};$$

$$\text{NPV}(Z\text{ DCs}) = -IA - ZW + \sum_{\omega=1}^{T} \Big\{ (1-t)\big[NPD - NCD - z'I\vartheta CD - (N-z')I\vartheta CD(1+\Delta)$$

$$-If - ZF - NIvD - NDV\big] + \frac{t(IA+ZW)}{T} \Big\} \Big/ (1+\beta)^{\omega}.$$

$$\text{NPV}(1\text{ DC}) - \text{NPV}(Z\text{ DCs}) = (Z-1)\left(W + \sum_{\omega=1}^{T} \left\{ (1-t)\left[\frac{N-z'}{Z-1} \Delta CD(I\vartheta - 1) + F \right] - \frac{tW}{T} \right\} \Big/ (1+\beta)^{\omega} \right)$$

.

As with the base case, a centralized distribution network is optimal if and only if the term inside the large parenthesis is positive (it is one of alternate optima if the term equals zero). That term only differs from the corresponding base case by the factor $(N-z')/(Z-1)$, which is greater than 1 assuming that at least one zone other than $Z1$ contains more than one country. Thus, the term $\Delta CD(I\vartheta - 1)$ is weighted more heavily than under the base case. So when that term is positive $(I\vartheta > 1)$, the entire term inside the large parenthesis is more likely to be positive than under the base case, but when that term is negative $(I\vartheta < 1)$, the entire term inside the large parenthesis is more likely to be negative than under the base case. ■

Proof of Proposition 6: The denominator represents the NPV of the cost of moving one subassembly plant from country A to country B. The numerator is the NPV of the cost of not satisfying the local content rule. If the local content rule is not satisfied, then with a tariff of Δ charged to domestic shipments of the final product, the firm would desire to close the DC in country B and serve that market from the DC in country A (due to the lower tax rate and elimination of the tariff-free domestic shipment). If this occurs, then the firm will have one less distribution center but will incur a tariff on final products shipped to country B. The numerator must be positive or it would not have been optimal to have a DC in country B in the first place.

■

Proof of Corollary 1: Let Φ' be the largest Φ which satisfies (P6). Then the local content percentage is too high if $\Phi^* > \Phi'$, which occurs if $[\Omega I p - (1-\Omega)V]/p$ is greater than the right-hand-side of (P6). ■

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