MULTI-PLANT COORDINATION IN A GLOBAL MANUFACTURING AND DISTRIBUTION NETWORK

Nasr-Eddine Dahel, Fisher Graduate School of International Business, Monterey Institute of International Studies, 460 Pierce Street, Monterey, CA 93940, 831-647-4602, edahel@miis.edu

ABSTRACT

This paper addresses the horizontal coordination of production and distribution activities between plants located in different countries. Horizontal coordination gives the multinational firm the flexibility to shift production between plants within its global manufacturing network to take advantage of future changes in production, transportation costs, trade regulations, exchange rates, competitive moves, and government policies. In reaction to and in anticipation of such changes, the question is to determine how to adjust the production and distribution activities of the different plants in the network to maximize the global after-tax profit for the multinational firm. This paper proposes a mixed integer programming model for this problem.

INTRODUCTION

Coordination of production planning among multiple plants is not a new topic. Much research has been carried out on vertical coordination where a large vertically integrated firm may have a hierarchy of production plants making parts, components, and semi-finished products for assembly into final products. Production decisions at these plants must be coordinated in such a way to meet the material requirements of the final assembly schedule at downstream plants. By contrast, there is smaller amount of work devoted to horizontal coordination between plants located in different countries to take advantage of the diversity in international markets. In their review of the models for management of global supply chains, Cohen and Mallik [4] point out to significant gaps in the literature in understanding how firms should achieve the required coordination to respond to changes in market conditions and competitive environments.

Global supply chain coordination decisions are complex. They are influenced by strategic, technological, macroeconomic, political, infrastructure, competitive, and operational factors. An important question that arises in formulating global profit-maximizing production and distribution strategies is how decision-making at the different plants should be coordinated so that the operating policies are optimal for the multinational firm as a whole. This is important because without coordination value-adding decisions at one plant may not produce the expected results at the multinational firm level due to inefficiencies at another plant in the global production network. With over 50 manufacturing plants in 26 countries Toyota has, for example, the capability to serve many markets in the world. But with this capability comes the challenge of how to operate these plants in the face of changing market conditions, and cost structures. The global supply chain must not only routinely produce and deliver products on time to markets worldwide, but it must do so in a way that maximizes the profitability of the multinational firm.

The objective of the paper is to formulate a comprehensive global after-tax profit maximizing multi-plant coordination model that provides unambiguous answers to such important and complex questions as: (1) is it profitable to serve customers in this country with this product? (2) In which plant, in which country, and in what quantity should a product be manufactured? (3) Which plants should be open for production and which plants should be closed in every time period of the planning horizon? (4) Which plants should service which country's product demand, and in what quantity? (5) How much inventory of which products should be stored

at which plant? And finally, (6) what is the most economical way to comply with governmental regulations on taxes, export quotas, import duties, and local content requirements?

MODEL DEVELOPMENT

Consider a global supply chain network in which multiple products are produced at several plants located in different countries. Each plant has a specific cost structure, and can serve customers within the host country as well as other countries. The demand for each product at each country in every time period in the planning horizon is known. Given plant capacities, selling prices of products in the various countries, transportation costs from the various production facilities to the various market countries, production and inventory costs of the various plants, and export incentives import duties and quotas of the various countries, the question is to decide the set of plants to operate, the product mix at each plant, and the quantities that plants ship to each country in each time period; in such a way to maximize the global multi-period after-tax profit for the firm.

Notation

Primary Sets and indices

$P =$ Set of products, $p \in P$;

$C =$ Set of countries, $c, r \in C$;

$F =$ Set of production facilities, $f \in F$;

$T =$ Set of time periods in the planning horizon, $t \in T$.

Induced Sets

$P_c =$ Set of products marketed in country *c*, $P_c \subseteq P$;

$P_f =$ Set of products that can be produced at facility *f*, $P_f \subseteq P$;

$C_p =$ Set of countries where product *p* is marketed, $C_p \subseteq C$;

$F_p =$ Set of facilities capable of producing product *p*, $F_p \subseteq F$;

$F_c =$ Set of production facilities located in country *c*, $F_c \subseteq F$;

$F_r =$ Set of production facilities located in country *r*, $F_r \subseteq F$.

Cost Data

$C_{pft} =$ Fixed cost of producing product *p* at facility *f* in period *t*,

$F_{ft} =$ Fixed cost of operating facility *f* during period *t*,

$L_{ft} =$ Fixed cost of keeping facility *f* closed throughout period *t*,

$T_{pfct} =$ Transportation cost of one unit of product *p* from facility *f* to country *c* in period *t*,

$V_{pft} =$ Variable production cost of one unit of product *p* at facility *f* in period *t*,

$H_{pft} =$ Cost of holding one unit of product *p* in inventory at facility *f* throughout period *t*,

$R_{pct} =$ Sale price of one unit of product *p* in country *c* during period *t*,

$M_{pcrt} =$ Import duty fee of one unit of product *p* into country *c* from country *r* during period *t*,

$E_{pft} =$ Monetary incentive given by the host country of facility *f* for exporting one unit of product *p* to other countries in period *t*,

TX_{ct} = Corporate tax rate (as a coefficient between 0 and 1) in country *c* at period *t*,

A_{ct} = After tax profit retention rate in country *c* at period *t*,

$= 1 - TX_{ct}$.

Supply/Demand Data

D_{pct} = Demand for product *p* (in units) in country *c* at period *t*,

S_{pft} = Production capacity of product *p* (in units) at facility *f* in period *t*,

N_{pcrt} = Quota on the number of units of product *p* that can be exported from country *c* to country *r* in period *t*.

Decision Variables

X_{pfct} = Units of product *p* produced at facility *f* and sold in country *c* in period *t*,

Y_{pft} = Units of product *p* produced at facility *f* in period *t*,

I_{pft} = Units of product *p* held in inventory at facility *f* at the end of period *t*,

$$Z_{pft} = \begin{cases} 1, \text{ if product } p \text{ is produced in facility } f \text{ during period } t; \\ 0, \text{ otherwise.} \end{cases}$$

$$Q_{ft} = \begin{cases} 1, \text{ if facility } f \text{ is open for production in period } t; \\ 0, \text{ otherwise.} \end{cases}$$

Model Formulation

$$\text{Max} \sum_{t\in T}[\sum_{c\in C} A_{ct}[\sum_{p\in P}[\sum_{f\in F_c}[R_{pct}X_{pfct} - C_{pft}Z_{pft} - V_{pft}Y_{pft} - H_{pft}I_{pft} - F_{ft}Q_{ft} - L_{ft}(1-Q_{ft}) + \sum_{(r\neq c)\in C_p}(R_{prt} + E_{pft})X_{pfrt}] + \sum_{f\notin F_c}(R_{pct} - T_{pfct})X_{pfct} - \sum_{(r\neq c)\in C}\sum_{f\in F_r} M_{pcrt}X_{pfct}]]] \quad (1)$$

Subject to:

$$\sum_{f\in F_p} X_{pfct} \le D_{pct}, \qquad p\in P, c\in C_p, t\in T; \quad (2)$$

$$Y_{pft} + I_{pf,t-1} = \sum_{c\in C_p} X_{pfct} + I_{pft}, \qquad p\in P,\ f\in F_p, t\in T; \quad (3)$$

$$\sum_{f\in F_c} X_{pfrt} \le N_{pcrt}, \qquad p\in P, c\in C, (r\neq c)\in C, t\in T; \quad (4)$$

$$Y_{pft} \le S_{pft}Z_{pft}, \qquad p\in P,\ f\in F_p, t\in T; \quad (5)$$

$$Z_{pft} \le Q_{ft}, \qquad p\in P,\ f\in F_p, t\in T; \quad (6)$$

$$Z_{pft}, Q_{ft}, U_{ft} = \{0,1\}, \qquad p\in P,\ f\in F, t\in T; \quad (7)$$

$$X_{pfct}, Y_{pft} \ge 0, \qquad p\in P,\ f\in F_p, c\in C_p, t\in T. \quad (8)$$

Constraint set (2) imposes bounds on the maximum quantity of product *p* that can be sold in country *c* at time period *t*. Observe that in order to allow for the possibility of not serving unprofitable markets this constraint does not require fulfilling an entire market's demand. Constraint (3) imposes product flow conservation among production, inventory, and sale variables at each production facility in every time period. Inventory may be carried to provide better customer service or to satisfy forecasted demand that exceed production capacities in

future time periods. Constraint (4) imposes quotas on the quantity of product *p* that can be exported from country *c* to any other country *r* at time period *t*. In order to provide protection for local production, some countries may apply quotas on selected imports. Constraint set (5) imposes the production capacity of product *p* at facility *f* in period *t*. Constraint set (6) states the condition that product *p* may be produced at facility *f* in period *t* only if that facility is open for production during that time period. Constraints (7) and (8) respectively ensure integrality and nonnegativity on the decision variables.

The objective function (1) maximizes the multi-period global after-tax profit of the multinational firm. For a given period *t* the global after-tax profit is the result of adding all countries' pretax profits multiplied by their respective after-tax profit retention rates.

The pretax profit derived from country *c* at time period *t* may be expressed as follows:
Revenue from products produced and sold locally: $\sum_{p\in P}\sum_{f\in F_c} R_{pct}X_{pfct}$, plus revenue from imported products sold locally: $\sum_{p\in P}\sum_{f\notin F_c} R_{pct}X_{pfct}$, plus revenue from locally made products exported to other countries: $\sum_{p\in P}\sum_{(r\neq c)\in C_p}\sum_{f\in F_c} R_{prt}X_{pfrt}$, plus revenue from product export incentives: $\sum_{p\in P}\sum_{(r\neq c)\in C_p}\sum_{f\in F_c} E_{prt}X_{pfrt}$, minus fixed production cost of products manufactured locally: $\sum_{p\in P}\sum_{f\in F_c} C_{pft}Z_{pft}$, minus variable production cost of products manufactured locally: $\sum_{p\in P}\sum_{f\in F_c} V_{pct}Y_{pft}$, minus inventory holding cost at the local facilities: $\sum_{p\in P}\sum_{f\in F_c} H_{pct}I_{pft}$, minus fixed operating cost of local facilities: $\sum_{f\in F_c} F_{ft}Q_{ft}$, minus fixed closing cost of local facilities: $\sum_{f\in F_c} L_{ft}(1-Q_{ft})$, minus transportation cost of imported products: $\sum_{p\in P}\sum_{f\notin F_c} T_{pct}X_{pfct}$, minus duty fee of imported products: $\sum_{p\in P}\sum_{(r\neq c)\in C}\sum_{f\in F_r} M_{pcrt}X_{pfct}$.
Rearranging the above terms yields the following pretax profit function for country *c* at time period *t*:

$$\sum_{p\in P}[\sum_{f\in F_c}[R_{pct}X_{pfct}-C_{pft}Z_{pft}-V_{pft}Y_{pft}-H_{pft}I_{pft}-F_{ft}Q_{ft}-L_{ft}(1-Q_{ft})+ \sum_{(r\neq c)\in C_p}(R_{prt}+E_{pft})X_{pfrt}]+\sum_{f\notin F_c}(R_{pct}-T_{pfct})X_{pfct}-\sum_{(r\neq c)\in C}\sum_{f\in F_r} M_{pcrt}X_{pfct}]$$

Next, we multiply the above expression by the after-tax profit retention rate, A_{ct}, and sum it over all periods in set *T*, and countries in set *C* yielding the multi-period after-tax global profit maximization objective function of the mixed integer-programming model:

$$\text{Max}\sum_{t\in T}[\sum_{c\in C}A_{ct}[\sum_{p\in P}[\sum_{f\in F_c}[R_{pct}X_{pfct}-C_{pft}Z_{pft}-V_{pft}Y_{pft}-H_{pft}I_{pft}-F_{ft}Q_{ft}-L_{ft}(1-Q_{ft})+ \sum_{(r\neq c)\in C_p}(R_{prt}+E_{pft})X_{pfrt}]+\sum_{f\notin F_c}(R_{pct}-T_{pfct})X_{pfct}-\sum_{(r\neq c)\in C}\sum_{f\in F_r} M_{pcrt}X_{pfct}]]]$$

Other constraints capturing such issues as *Value-Based Offset Trade Restrictions*, *Shipping Capacity*, *Inventory Policy*, *Aggregate Plant Capacity*, and *Number of Open Facilities* may be added to this model (see full version of the paper for further details). These optional constraints, which may be applied uniformly across all production facilities and time periods or selectively to specific ones, give this model the capability of determining comprehensive and optimal global supply chain coordination decisions.