CAPACITY MANAGEMENT IN THE CHEMICAL SUPPLY CHAIN

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Abstract: Long term capacity planning involves locating and allocating the production capacities and inventory capacities, and short term capacity planning involves the production allocation and distribution of materials. Most existing literature deals with them individually and also consider only investments in capacities and do not consider disinvestment. Combining the above problems into one would give a holistic picture of the entire supply chain and allows in better planning, leading to greater efficiency in terms of reduced costs or increased profit. In this work, we present a new deterministic capacity management model, which considers facility location, (dis)investment in capacity, production allocation, distribution of materials and regulatory factors among others. Also, we have improved the formulation of existing literature by using fewer binary variables.

Keywords: capacity, planning, distribution, discrete time, linear programming, optimization

1. INTRODUCTION

Capacity planning involves locating and allocating capacities, process planning, and allocating production. Long term capacity planning deals with (dis)investment in facilities (also called the location allocation problem) and short term capacity planning deals with production allocation and distribution (also called production distribution problem). Capacity management involves both long term and short term capacity planning.

Organizations strive towards meeting the customer demand, both in order to maintain good customer satisfaction and make profit. In an ever changing world, the demand for products changes with time. New products are introduced, old products are improved technologically, and some are no longer manufactured as customer demand drops. Hence, it is important for an organization to expand existing capacity or invest in new capacity in order to meet increased demand for existing products or to explore new markets, invest in new capacity for new products, disinvest old plants that no longer meet the latest technological specifications or if there is no demand. In order to remain profitable while meeting customer satisfaction, these decisions are to be made appropriately.

Previous work in the area of production allocation and distribution problem includes those of Arntzen, et al. (1995), Bradley and Arntzen (1999), Cohen and Lee (1989), Gjerdrum et al. (2001), Goetschalckx, et al. (2002), Pyke and Cohen (1994), Ryu and Pistikopoulos (2005), Tsiakis et al. (2001). These do not consider the location of new facilities and expansion of the existing facilities. Levis and Papageorgiou, (2004), Oh and Karimi (2004), Papageorgiou et al. (2001), have considered the issue of new facility location; however, there is only partial or no representation of the production allocation and distribution issue. In all of the above, disinvestment was not considered.

In this work we consider only the location and allocation of capacities and allocation of production, while not explicitly considering process planning (for further information on process planning, the readers are referred to Ahmed and Sahinidis, 2000). A multi echelon supply chain network is considered and a new deterministic model, which combines both of the location allocation problem and production distribution problem into an integrated location allocation production distribution problem (LAPD problem), is presented. The problem is formulated as a novel mixed integer linear programming (MILP) model with the ability to incorporate production changeover costs, depreciation, tax and regulatory factors among others, and is solved as maximizing the net present value of the profit. To the best of our knowledge, this is the first study that includes disinvestment, and we use fewer binary variables as compared to Oh and Karimi (2004).

2. PROBLEM STATEMENT

The supply chain of a multinational corporation (MNC) is considered in this work (Fig. 1). Let P be the set of all existing and future production facilities (p), I be the set of input inventories at production facilities (i), O be the set of output inventories (o), S be the set of existing and future suppliers of raw materials (s), D be the set of existing and future inventories at distribution centres (d) and C be the set of existing and future inventories at customer

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locations (c). Given the demand profiles for all products from all customers, raw material availability profiles from all suppliers, price forecasts for raw materials and products, and other supply chain information and costs, the desired capacity management model should determine the location, timing and amount of change in capacity, purchase-distribution-sales of material such that the profit (net present value-NPV) is maximized.

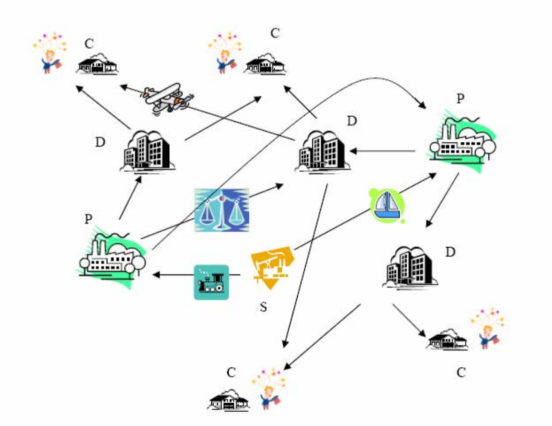

Fig. 1. Schematic representation of a chemical supply chain of an MNC.

To address this problem we make the following assumptions: 1.) Each production facility represents a specific process of producing products from the raw materials. Several such processes may exist at a single location and each is considered a distinct facility. 2.) Each production facility processes several materials and all materials are taken into consideration in mass balance. The utilization of capacity is the total weight of all the material in the facility at that time. 3.) The limits on transportation, production, and expansion polices are all known (ex: a facility may not expand more than thrice in the planning horizon). 4.) The time in between the starting of construction and starting of operation of a plant (cl_p) /inventory is fixed and is known. It may be different for different plants and inventories. Expansion does not affect the production and an expansion/construction cannot be started while a previous expansion/construction is in process. 5.) An existing capacity may expand by small amounts, but the first addition for a possible new facility have to be above a certain minimum, once this exists, it can expand in small increments. 6.) A facility is disinvested completely and this cannot be done partially. 7.) A facility once disinvested cannot be purchased again 8.) Interval is a few periods. A production facility can operate for only a fixed number of periods (op) in any given interval (ex: 11 periods in any given 12 periods) to allow time for maintenance. 9.) Costs of transportation from the point of purchase of raw materials from suppliers to the point of customer location are born by the MNC. 10.) Inventory (+ve) is carried forward from one period to another and there is no allowance for negative inventory or back orders i.e., material can be sold only when it is available. 11.) All costs and income are considered to be linear functions. 12.) The amount of investment that can be made in a given interval (in, di) is limited and is known, similarly constraints apply on disinvestment (IB, DR) (ex: the amount of investment that can be made in a year is one billion). 13.) Throughput is the product of throughput factor and capacity.

3. PROBLEM FORMULATION

A chemical supply chain, which consists of raw material suppliers, production facilities, input and output inventories at the production facilities, inventories at the distribution centres and customer locations is considered. The strategic plan should decide the timing, amount and location attributes of each of the variables under consideration such as the capacity change and utilization of a facility, and purchase/sales of raw materials/products and distribution of the same. Additional features like depreciation, interest rate and after tax profit are taken into account and tax at customer location for sales is born by the customer. To address this problem, the following formulation is presented as a.) Capacity Change Constraints, b.) Capacity Constraints, c.) Inventory Balance Constraints, d.) Costs and Income constraints.

1.1 *Constraints on Capacity Change*

The number of times that a plant may expand in the horizon is limited (np).

$$\sum_t PY_{pt} \le np \qquad \text{1a}$$

where, PY is the plant expansion variable.

An expansion cannot start while a previous expansion is in process.

$$\sum_{t-cl_p+1}^{t} PY_{pt} \le 1 \qquad (t \ge cl_p) \qquad \text{1b}$$

The following constraints relate plant expansion variable PY, plant disinvestment variable PX, plant existence variable PEY and plant sold off variable PSY (PY, PX are binary variables and PEY, PSY are 0-1 continuous variables).

$$PEY_{pt} \ge PY_{pt} \qquad \text{1c}$$

$$PEY_{p(t-1)} \le PEY_{pt} + PSY_{pt} \qquad \text{1d}$$

$$PEY_{pt} \le PEY_{p(t-1)} + PY_{pt} \qquad \text{1e}$$

Once, the plant is sold off, it does not exist any more and this is indicated by the variable PSY, also, it is not possible for the plant to simultaneously exist and be sold off.

$$PSY_{pt} \ge PSY_{p(t-1)} \qquad \text{1f}$$

$$PEY_{pt} + PSY_{pt} \le 1 \qquad \text{1g}$$

A plant once disinvested cannot be purchased.

$$PY_{pt} \le 1 - PSY_{pt} \qquad \text{1h}$$

A plant may be sold off only once in the given horizon. This is taken care of by the variable PX as this can be ‘1’, only if the plant existed in the previous period.

$$PSY_{pt} \geq PX_{pt} \quad \text{1i}$$

$$PEY_{p(t-1)} \geq PX_{pt} \quad \text{1j}$$

$$PSY_{pt} \leq PSY_{p(t-1)} + PX_{pt} \quad \text{1k}$$

A plant may add capacity at an existing location or a new location and there are different minimum limits on expansion at existing location and construction of new facility. No additions are possible at plant (p) at time (t) if it is slated for disinvestment at that time. PA, a positive variable, is the amount of capacity added in any period. $Pcap_{pt}$ is the capacity of a plant (p) at time (t), PA_p^{LN} is the lower limit of capacity addition for a new plant and PA_p^{LO} is the lower limit of capacity addition for an old plant.

$$Pcap_{pt} - Pcap_{p(t-1)} \leq PA_{pt} \leq Pcap_{pt} - Pcap_{p(t-1)} + Pcap_p^U PSY_{pt} \quad (t \geq 2)$$

$$PA_{pt} \leq Pcap_p^U PY_{pt} \quad \text{2a,b}$$

$$Pcap_{pt} \leq Pcap_p^U (1 - PSY_{pt}) \quad \text{2c}$$

$$PA_{pt} \geq PA_p^{LN} (PY_{pt} - PEY_{p(t-1)}) + PA_p^{LO} (PEY_{p(t-1)} + PY_{pt} - 1) \quad \text{2d}$$

Similarly, $Icap_{it}$, $Ocap_{ot}$ and $Dcap_{dt}$ are written and similar constraints are written for inventories.

1.2 *Capacity Constraints*

There are limits on transportation and the transportation time is negligible compared to a period. The total amount of raw material (m) purchased at supplier (s) and sent to all inventories (i) at time (t) does not exceed the amount of the raw material available for purchase. SI_{msit} is the amount of material (m) purchased at supplier (s) and sent to inventory (i) at time (t). Similarly, OI, OD and DC are written. SM_{mst} is the amount of material (m) available for purchase from supplier (s) at time (t).

$$\sum_i SI_{msit} \leq SM_{mst} \quad \text{3}$$

The total amount of materials that an inventory (i) can receive in a time (t) is less than or equal to its throughput.

$$\sum_{m \in mi_i, s} SI_{msit} + \sum_{m \in mi_i, o} OI_{moit} + \sum_{m \in mi_i, p \in ipi_i} PI_{mpit} \leq tfI_{it} Icap_{it} \quad \text{4a}$$

where, tfI_{it} is the throughput factor of inventory (i) at time (t), mi_i is the set of all materials that an inventory (i) may hold and ipi_i is the set of plants (p) that an inventory (i) supplies material to. The subscript and the first letter of the set indicate the particular facility, second and third letters indicate ‘from’ and ‘to’ facility. Similarly, tfO_{ot}, mp_p, mo_o, md_d, mc_c, ioi_i, pip_p, ppo_p, ppi_p, opo_o and ooi_o are written.

Similar equations for throughput are written for the throughput of (o), (d) and (c). However, the corresponding terms for SI, OI, PI in equation 4a are modified to reflect the incoming materials appropriately ((o) receives material only from plants (p), (c) receives material only from distribution centres (d)).

$$\sum_{m \in md_d, o} OD_{modt} \leq tfD_{dt} Dcap_{dt} \quad \text{4b}$$

The amount of the materials in an inventory (i) at time (t) does not exceed the holding capacity in that period.

$$\sum_{m \in mi_i} IM_{mit} \leq Icap_{it} \quad \text{4c}$$

IM_{it} is the total amount of all the materials present in inventory (i) at time (t). Similar equations are written for the material in (o), (d) and (c).

The amount of material that a plant can accept and process in any time period is within the utilization limits. PZ is the binary variable for plant operation.

$$\sum_{m \in mp_p, i \in pip_p} IP_{mipt} \leq Pcap_{pt} \quad \text{5a}$$

$$\sum_{m \in mp_p, i \in pip_p} IP_{mipt} \geq ut_{pt} Pcap_{pt} - Pcap_p^U (1 - PZ_{pt}) \quad \text{5b}$$

$$\sum_{m \in mp_p, i \in pip_p} IP_{mipt} \leq Pcap_p^U PZ_{pt} \quad \text{5c}$$

where, mp_p is the set of materials that a plant (p) can process. pip_p is the set of inventory (i) that supplies material to plants (p), ut_{pt} is the utilization of plant (p) at time (t)

A plant may operate only if it exists.

$$PEY_{pt} \geq PZ_{pt} \quad \text{6a}$$

The number of periods that a plant may operate in any given interval is known.

$$\sum_{t-op_p^p+1}^{t} PZ_{pt} \leq op_p \qquad (t \geq op_p^p) \quad \text{6b}$$

1.3 *Inventory Balance Constraints*

Inventory balance equations are written for each of the inventories and stoichiometry is written for the plants. The amount of material (m) in an inventory ((i), (o), (d) or (c)) at time (t) is equal to the amount of the material at time (t-1) plus the amount of material that came in at time (t) minus the amount of material that went out at time (t). Initialization is done appropriately.

$$IM_{mit} = IM_{mi(t-1)} - \sum_{p \in ipi_i} IP_{mipt} + \sum_{p \in ipi_i} PI_{mpit} + \sum_s SI_{msit} + \sum_{o \in ioi_i} OI_{moit} \quad \text{7a}$$

$$\frac{\sum_i IP_{mipt}}{st_{mp}^{ip}} = \frac{\sum_i IP_{m'ipt}}{st_{mp}^{ip}} = \frac{\sum_o PO_{m''pot}}{st_{mp}^{po}} = \frac{\sum_i PI_{m'''pit}}{st_{mp}^{pi}} \quad \text{7b}$$

$$(m \neq m' \neq m'' \neq m''')$$

$$OM_{mot} = OM_{mo(t-1)} - \sum_d OD_{modt} + \sum_{p \in opo_o} PO_{mpot} - \sum_{i \in ooi_o} OI_{moit} \quad \text{7c}$$

$$DM_{mdt} = DM_{md(t-1)} - \sum_c DC_{mdct} + \sum_o OD_{modt} \quad \text{7d}$$

$$CM_{mct} = CM_{mc(t-1)} - Sa_{mct} + \sum_d DC_{mdct} \quad \text{7e}$$

$$Sa_{mct} \leq DE_{mct} \quad \text{7f}$$

where, IP_{mipt} is the amount of material (m) transferred from inventory (i) to plant (p) in time (t), st_{mp} is the stoichiometry coefficient of material (m) in plant (p), DE_{mct} is demand and Sa_{mct} is sales of material (m) at customer location (c) at time (t). Similarly, PO is written.

1.4 *Constraints on Costs and Income*

The cost incurred in the purchase of raw materials is proportional to the amount of raw material purchased.

$$RC_{mst} = \sum_{i,r \in rsi_{si}} SI_{msirt} msC_{mst} \quad \text{8}$$

Where, RC_{mst} is the raw material purchase cost and, msC is the unit cost of raw material.

The costs due to transportation are born by the inventory at the arrival location. Storage costs and production costs include fixed operational costs irrespective of the amount of material and costs related to the amount of material handled. Similarly, they are written for distribution centres and customer locations while production costs are only written for the production facilities.

$$TCI_{i,t} = \sum_{m \in mi_i, s} TCmsi_{msit} SI_{msit} + \sum_{m \in mo_o, o} TCmoi_{moit} OI_{moit} \quad \text{9}$$

$$SCI_{i,t} = fiC_{it} IEY_{it} + \sum_{m \in mi_i} Cmi_{mit} IM_{mit} \quad \text{10}$$

$$PC_{p,t} = fpC_{pt} PEY_{pt} + Cmp_{pt} \sum_{m \in mp_p, i \in pip_p} IP_{mipt} \quad \text{11}$$

where TCI is the transportation cost paid by inventory, TCmsi and TCmoi are unit transportation costs for (s) to (i) and (o) to (i), SCI is storage cost at inventory, fiC is fixed inventory operation cost, miC is unit material handling cost at inventory, fpC is fixed plant operation costs, mpC is unit material processing costs and PC is production costs.

Plants incur a change-over cost due to stopping or starting production. s1, s2 are starting and stopping (changeover) costs.

$$Csw1_{pt} \geq s1_{pt}(POpe_{pt} - POpe_{p(t-1)}) \quad (t \geq 2)$$

$$Csw2_{pt} \geq s2_{pt}(POpe_{p(t-1)} - POpe_{pt}) \quad (t \geq 2)$$

$$Csw_{p,t} = Csw1_{pt} + Csw2_{pt} \quad (t \geq 2)$$

12a,b,c

The revenue (R) from sales is directly proportional to the amount of sales. mr is unit price of the product.

$$R_{c,t} = \sum_{m \in mc_c} Sa_{mct} mr_{mct} \quad \text{13}$$

The depreciation cost due to an existing capacity and a new addition are calculated based on different rates of depreciation and it is calculated only for a plant that exists. Similarly depreciation is calculated for all inventories.

$$PDC_{p,t} \leq Pcap_{p1} DP_{pt} rdpo_{pt} + (Pcap_{pt} - Pcap_{p1}) DP_{pt} rdpn_{pt} \quad (t \geq 2) + Pcap_p^U DP_{pt}(1 - PEY_{pt})$$

14a

$$PDC_{p,t} \geq Pcap_{p1} DP_{pt} rdpo_{pt} + (Pcap_{pt} - Pcap_{p1}) DP_{pt} rdpn_{pt} \quad (t \geq 2) \quad \text{14b} - Pcap_p^U DP_{pt}(1 - PEY_{pt})$$

$$PDC_{p,t} \leq Pcap_p^U DP_{pt} PEY_{pt} \quad (t \geq 2) \quad \text{14c}$$

$$IDC_{i,t} = Icap_{i1} DI_{it} rdio_{it} + (Icap_{it} - Icap_{i1}) DI_{it} rdin_{it} \quad (t \geq 2) \quad \text{14d}$$

where, PDC is the plant depreciation costs, DP is the value of plant considered in depreciation (depreciated plant value), rdpo is rate of depreciation of plant for old section, rdpn is for new section of the plant.

There are fixed and variable costs due to an investment. The total investment in any interval (in) cannot exceed IB. Similarly, disinvestment in any interval (di) cannot exceed DR.

$$CI_t = \sum_p fcip_{pt} PY_{pt} + \sum_p vcip_{pt} PA_{pt}$$
$$+\sum_i fcii_{it} IY_{it} + \sum_i vcii_{it} IA_{it} +$$
$$\sum_o fcio_{ot} OY_{ot} + \sum_o vcio_{ot} OA_{ot} \qquad (t \geq 2)$$
$$+\sum_d fcid_{dt} DY_{dt} + \sum_d vcid_{dt} DA_{dt}$$
$$+\sum_c fcic_{ct} CY_{ct} + \sum_c vcic_{ct} CA_{ct}$$

15a

$$\sum_{t-in+1}^{t} \begin{pmatrix} \sum_p fcip_{pt} PY_{pt} + \sum_p vcip_{pt} PA_{pt} \\ +\sum_i fcii_{it} IY_{it} + \sum_i vcii_{it} IA_{it} + \\ \sum_o fcio_{ot} OY_{ot} + \sum_o vcio_{ot} OA_{ot} \\ +\sum_d fcid_{dt} DY_{dt} + \sum_d vcid_{dt} DA_{dt} \\ +\sum_c fcic_{ct} CY_{ct} + \sum_c vcic_{ct} CA_{ct} \end{pmatrix} \leq IB \qquad (t \geq in)$$

15b

where, fcip is fixed capital investment at plant and vcip is variable capital investment at plant. Similarly, fcii, fcio, fcid and fcic, vcii, vcio, vcid, and vcic are written.

cip is the fixed capital investment for the addition of a capacity, which is divided into fixed cost for the addition at a new location and fixed cost for the addition at an existing location as follows. *cip* is a positive variable and it is always kept to a minimum as this is a maximizing NPV problem.

$$cip_{pt} \geq fcip^n_{pt}(PY_{pt} - PEY_{p(t-1)}) + fcip^o_{pt}(PEY_{p(t-1)} + PY_{pt} - 1)$$

15c

where, n (o) represents new (old) plant.

There is an income from the sales of an asset/capacity

$$RDP_{pt} \leq Pcap_{pt} ap_{pt} \qquad 16a$$

$$RDP_{pt} \geq Pcap_{pt} ap_{pt} - Pcap^U_p ap_{pt}(1 - PX_{p(t-1)}) \qquad 16b$$

$$RDP_{pt} \leq Pcap^U_p ap_{pt} PX_{p(t-1)} \qquad 16c$$

$$RD_t = \sum_p RDP_{pt} \qquad 16d$$

$$\sum_{t-di+1}^{t} RDP_t \leq DR \qquad (t \geq di) \qquad 16e$$

where, RDP is the revenue from disinvestment of a plant, ap is the unit asset price of the plant that is realized on disinvestment and RD is total revenue from disinvestment at time (t).

The taxable income is calculated based on the nation (n) in which the facilities fall.

$$CT_{n,t} \geq \sum_{(s \in sn_n, i \in in_n, p \in pn_n, o \in on_n, d \in dn_n, c \in cn_n)} CTx\, TR_{n,t}$$

17a

where,

$$CTx = R_{c,t} - RC_{s,t} - PC_{pt} - Csw_{pt}$$
$$-TCI_{it} - TCD_{dt} - TCC_{ct}$$
$$-SCI_{it} - SCO_{ot} - SCD_{dt} - SCC_{ct}$$
$$-PDC_{pt} - IDC_{it} - ODC_{it} - DDC_{dt} - CDC_{ct}$$

17b

$$NPV = \sum_t \frac{NPVt}{(1 + ir(t))^{(yr(t)-1)}} \qquad 18a,b$$

where,

$$NPVt = \sum_c R_{c,t} - \sum_s RC_{s,t} - \sum_p PC_{pt} - \sum_p Csw_{pt}$$
$$-\sum_i TCI_{it} - \sum_d TCD_{dt} - \sum_c TCC_{ct}$$
$$-\sum_i SCI_{it} - \sum_o SCO_{ot} - \sum_d SCD_{dt} - \sum_c SCC_{ct}$$
$$-CI_t + \sum_p RDP_{pt} - \sum_n CT_{nt}$$

4. ILLUSTRATION

LAPD is a challenging problem and preliminary analysis on the above formulation is a first step to address the problem and a further improvement of the formulation is required in order to improve the efficiency.

To analyze the performance of the formulation, we considered an example with five raw materials, six intermediates, and seven products. Two suppliers supply all the raw materials and the intermediates, however, the plants can also manufacture the intermediates. Eight existing production plants and six potential locations for new plants, five existing input and output inventories at plants are considered. For case 1, three existing distributions centres, three customer locations, and two new possible inventories at each of these locations are considered. For case 2, five existing distribution centres, fifteen customer locations, five possible new distribution centres, and fifteen possible new customer locations are considered. We consider the disinvestment of plants only in this example for simplicity. However, both plants and inventories are considered for investment. A horizon of sixty one-month periods is considered. It takes two years and one year respectively for the plants and inventories to begin operation; hence, no new expansion can start operation at 6th, 12th, and 18th month for plants and 6th month for inventories. A plant can expand at 24th, 30th, 36th, 42nd, 48th, and 54th months only. Furthermore, a plant can be sold between 18th and 48th months only. Also, there is no incentive in beginning any operation at the end of the horizon (i.e., 60th month). The model was solved using CPLEX 9.0 solver within GAMS 21.7 on

Windows XP workstation with an Intel Xeon dual (3.6GHz) processor. The model statistics are given in the Table 1 and preliminary results related to (dis)investment for Case 1 are presented in Table 2. It shows that some plants are disinvested at time forty eight, while there is no investment in plants. However, there is investment in the inventories at various locations.

Table 1 Computational statistics for the capacity management model

	Case 1	Case 2
Variables	732933	1169733
Constraints	575009	905549
Binary variables	1258	1498
Non-zeros	3191745	5223055
CPU Time (h)	10	6
% Gap	8.6	291.4

Table 2 Expansion and disinvestment variables indicating investment and disinvestment

p,o,d,c \t	Plant disinvest ment	Input invent-tory	Output invent-tory	Customer location invent-tory
1	48	-	-	-
2	48	-	-	-
3	48	-	-	-
4	48	-	-	12
6	-	-	12	-
7	-	12	12	-
8	-	-	12	-
9	-	-	12	-
10	-	-	12	-

From the above preliminary results, it can be seen that the model appropriately considers capacity expansion and contraction. Though the model considers these for all inventories at all time periods, we have limited it to consider disinvestment only for plants, and investment at certain times only in order to reduce solution time and highlight the various features of the formulation. It may be noted that regulatory factors and insurance may be incorporated appropriately in the transportation cost parameters. The results indicate that selling the plants at the 48^{th} period is more profitable than using them to make products. The remaining plants are operated in order to make profit from the sale of products. In the case of the investment in inventory, the investment is made early in order to capture the high demand for the products. Since, the earliest the inventory can start operation is the 12^{th} month; they do so in order to capture the demand at the earliest.

5. CONCLUSION

We have presented a new formulation to address various aspects such as the capacity expansion and contraction, distribution of materials, regulatory factors and depreciation among others in strategic planning for a deterministic case in an end-to-end supply chain for a single MNC. However, the formulation and analysis are only preliminary. Improvements need to be done in order to increase the efficiency of the formulation such that it can handle larger problems in reasonable computational time. A decomposition procedure or a heuristic to solve such large problems may be an appropriate way to apply this model in practice.

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