Modeling Production Economies of Scale in Supply Chain Network Design DSS for a large FMCG Firm

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Abstract: This paper describes an optimization based model and Decision Support System (DSS), developed for strategic and tactical supply chain planning for a large FMCG firm that manufactures and distributes a wide range of bakery products. The DSS uses Mixed Integer Linear Programming (MILP) model labeled as Facilities Installation Planner (FIP). FIP is a facilities location-capacity-technology selection and facilities allocation model. It was extended to incorporate economy of scale in installation of production facilities. The model, while recommending improved network designs, showed 5-6 % reduction in the total cost of the FMCG firm as compared to what it is incurring in its existing supply chain network. Model formulation and results are discussed.

Keywords: Economy of Scale, DSS, Location and/ Allocation Planning, Supply Chain Network Design

I. Introduction

A common problem for large process based manufacturing organizations with geographically wide distribution is the need to rationalize economy of scale in production with a large and complex supply chain network. There is a trade-off between economy of scale achieved through increased production at a more distant site versus additional transportation costs involved [5]. Most FMCG industries face conflicting pressures to take advantage of significant production economy of scale on the one hand and be customer responsive through fast and lean distribution system on the other hand. Therefore explicit modeling of economy of scale is necessary to evaluate supply chain design alternatives.

The DSS can be used to find different strategic decisions like facility locations, line (technology) selection at each facility and tactical decisions like product mix on each line, quantity to be supplied from each plant to depot and depot to market.

For decision making, the DSS requires input data like candidate options of plants, depots, annual demand for different products at different demand centers, fixed and variable costs, transportation costs, taxes etc. The cost associated with each facility exhibits economy of scale. In case of process industries, including FMCG production, this effect could be significant.

The DSS takes input data from user through front end developed in Java. It stores data in the back end developed in Oracle Database. According to the data and options selected in the front end, optimization model file with respective equations and input data is generated. We use GAMS/CPLEX software to write and run the MILP optimization model. The DSS invokes GAMS/CPLEX to solve MILP model and generates reports after successful completion of a scenario run.

Several scenarios representing alternate supply chain network designs for a large Indian FMCG firm were run using the DSS. Results based on real data demonstrate significant potential for reduction in costs.

II. Literature Review

There is a huge literature on supply chain network design. Most of them inadequately cover important issues like economies of scale, facility location decisions on more than one location, and trade-offs between location, capacity and technology [4]. A few papers like [3] [4] [5] [6] consider modeling of economy of scale explicitly. All these papers formulated this problem as non linear integer program and proposed solutions using different methods like Lagrangian relaxation, scenario improvement approach, sub routines etc.

[5] [2, p.282] gives an idea of modeling piece wise linear curve using mixed integer linear programming. The base idea for this work is taken from these papers.

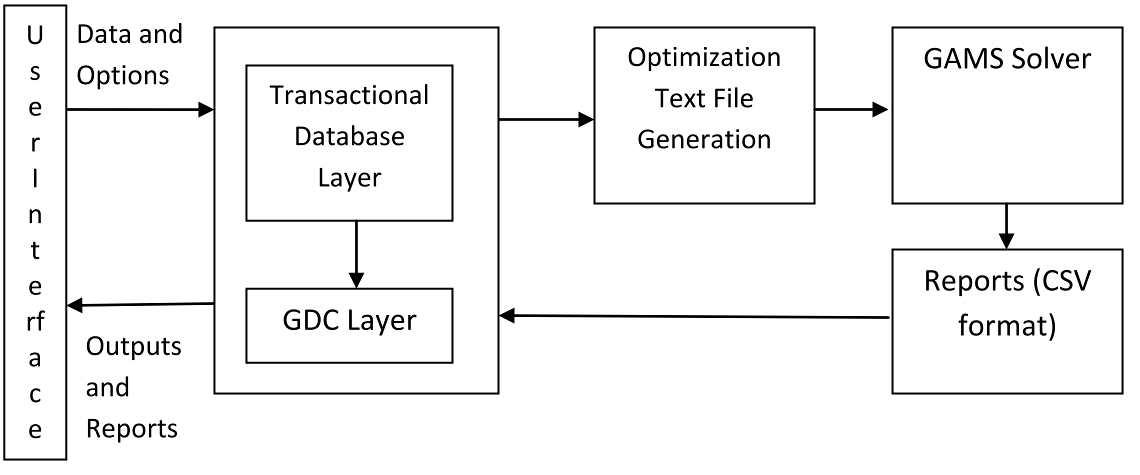
III. Problem Description

The company has about 50 candidate options for plant locations, 20 production line (technologies) options for each location, 100 candidate options for depots, 200 demand centers, and 40 product groups. Each plant needs to have small, medium and large lines with hard dough, soft dough and flexible technology options. Each line option has different capital installation cost, fixed running cost and variable running cost. A line’s capacity is defined the total number of shifts available for production in a year and the set of SKUs that can be produced using its shared equipment. Certain lines have restriction that only one or a fixed number of SKUs can be produced from the given set. Utilization of a line reduces as number of SKUs produced increases, owing to more changeovers.

There are different costs involved at different levels. Location wise fixed installation cost exhibits economy of scale. That is, the rate of increase in plant and machinery cost and fixed over head cost decreases with each additional line installed in the same location (or plant). Then there is line related fixed capital cost which is directly proportional to the number of instances (or integer chunks) of a line installed at a location. In addition, there are labor, power, fuel and raw material costs for each line. Each installed depot has fixed and variable costs. Transportation costs are incurred for transporting SKUs from plant to depot and depot to demand centre. Taxes like VAT, Octroi, Excise, CST and Income tax are applicable.

Here optimal plant locations, line combinations for each plant, capacity of each line, product mix on each line, depot locations, and allocation plan need to be calculated.

Figure 1 Steps in DSS



IV. Methodology

DSS Description

Figure 1 shows the broad steps of data transfer in the DSS. User enters data through the front end developed in Java. Complete data is stored in the database developed in Oracle. GDC (GAMS Data Centre) layer developed in Oracle fetches respective data from data base layer as per the options selected in front end and generates text file with MILP formulation and respective data. Java interface invokes GAMS execution file to run the MILP text file. After successful execution and validation of results, reports from GAMS in CSV format are dumped into the data base. Important aggregate results are displayed on front end and detailed reports in excel format are stored in the path and folder specified by user.

The decision outputs from DSS are:

a) Plant locations and integer chunks of capacity of a line installed at each plant location
b) Depot locations
c) Quantity to be supplied from each plant location to depot and depot to demand centre
d) Set of SKUs to be produced on each line in each plant location

Model formulation

The important variables, data, objective and constraints in the model are briefly mentioned below.

Indices:
p - Products
pl - plant locations
i - lines
j - warehouse
m - transport mode
t - time

Non-Integer Variables:
$Y_{p,pl,i,j,m,t}$ - Flow of a product p from a line i installed at a plant location pl to a depot j though a transport mode m in time period t
$Z_{p,j,k,m,t}$ - Flow of a product p from a depot j to a market k though a transport mode m in time period t
$S_{p,k,t}$ - Shortage incurred for a product-market pair

Integer Variables:
$Line\_Install_{pl,i}$ - Integer chunks of capacity of a line i installed at a plant location pl

Binary 0-1 Variables:
$WH\_Install_j$ - Status of warehouse j (whether warehouse is open or closed)
$Product\_Status_{p.pl.i}$- Status of a product p being produced on a line i in a plant location pl
$Line\_Index_{pl,n}$- 1 if n number of lines installed in plant location pl.

Parameters:
CTP_m - Cost of primary transport
CTS_m - Cost of secondary transport
$CAPITAL\_COST_{pl,n}$ - Fixed capital costs with economy of scale
$LINE\_COSTS_i$ - Linearly increasing capital costs for each line
WH_COST_j - Fixed installation cost for depot
$CP_{pl,i,p}$ - Cost of labor, fuel, power, raw material
M - Very big number
NO_SHIFTS_i - Number of shifts in each line
$DEMAND_{p,k,t}$ - Demand at demand centers
$MAX\_PROD\_LINE_{pl,i}$ - Upper limit on products
VAT, Octroi, Excise, CST and Income tax

Objective Function:
Minimize the sum of costs of primary transport, secondary transport, fixed & capital cost depending on number of lines installed at each location, capital installation cost of new lines, capital installation cost of new depots, production costs, and cost of shortage

$$\sum_{p,pl,i,j,m,t\in V(pl,j,m)}(CTP_m * Y_{p,pl,i,j,m,t}) + \sum_{p,j,k,m,t\in V(j,k,m)}(CTS_m * Z_{p,j,k,m,t}) + \sum_{pl,n}(Line\_Index_{pl,n} * CAPITAL\_COST_{pl,n}) + \sum_i(LINE\_COSTS_i * \sum_{pl} Line\_Install_{pl,i}) + \sum_j(WH\_COST_j * WH\_Install_j) + \sum_{p,pl,i,t}(CP_{pl,i,p} * \sum_{j,m\in V(pl,j,m)} Y_{p,pl,i,j,m,t}) + \sum_{p,k,t}(M * S_{p,k,t}) \quad (1)$$

Constraints:
Economies of scale:
Figure 2 shows one example for Economies of scale. To model this step function, a binary variable $Line\_Index_n = (0,1)$ is assumed to represent each step [5]. Where n represents number of lines installed. $N(n) = n$.

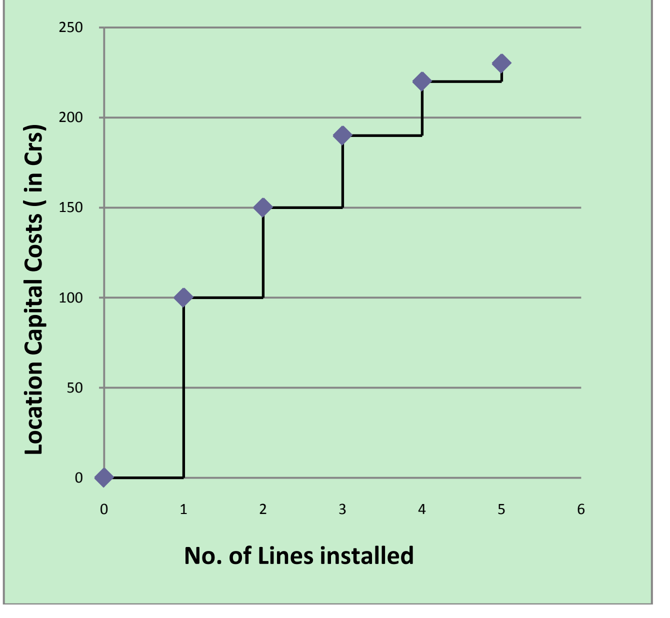
Equation 3 forces only one step segment to be active at a time for each location. Equation (2) relates $Line\_Index_{pl,n}$ and $Line\_Install_{pl,i}$ so that both take values appropriately. The binary variable $Line\_Index_{pl,n}$ is used in the objective function to apply costs appropriately.

$$\sum_i Line\_Install_{pl,i} = \sum_n(Line\_Index_{pl,n} * N(n)) \quad \forall pl \quad (2)$$
$$\sum_n Line\_Index_{pl,n} \le 1 \quad \forall pl \quad (3)$$

Supply Constraint:
Equation (4) represents shared production capacity constraint for a line in a plant location (measured as number of shifts)

$$\sum_{p\in PS(i,p)} \frac{1}{PC_{i,p}} * \sum_{i,m\in V(pl,j,m)} Y_{p,pl,i,j,m,t} \le NO\_SHIFTS_i * Line\_Install_{pl,i} \quad \forall pl, i \in V(pl,i) \quad (4)$$

Figure 2 Economies of Scale in Location Capital Costs



Demand Constraint:
Equation (5) represents that sum of supply of a product in a market and the shortage must meet its demand

$$\sum_{j,m} Z_{p,j,k,m,t} + S_{p,k,t} = DEMAND_{p,k,t} \quad \forall p,k,t \quad (5)$$

Balance Constraint:
Flow balance of a product at a depot. As there is no inventory storage capacity for depots, whatever comes in, goes out

$$\sum_{pl,i,m\in V(pl,j,m)} Y_{p,pl,i,j,m,t} = \sum_{k,n,t\in V(j,k,m)} Z_{p,j,k,m,t} \quad \forall p,j \quad (6)$$

If a line at a plant location produce a positive quantity, its integer installation variables is positive; if the integer installation variable is zero then it does not produce anything which is taken care with Equation (7)

$$\sum_{p,j,m,t\in V(pl,j,m)} Y_{p,pl,i,j,m,t} \le M * Line\_Install_{pl,i} \ \forall pl.i \quad (7)$$

Equation (8) and Equation (9) makes sure that Depot can get allocation from a plant only if its open and Depot will be open only if total quantity flow though that Depot is greater than a lower bound specified.

$$\sum_{p,pl,i,m,t\in V(pl,j,m)} Y_{p,pl,i,j,m,t} \leq M * wh\_Install_j \quad \forall j \quad (8)$$
$$\sum_{p,pl,i,m,t\in V(pl,j,m)} Y_{p,pl,i,j,m,t} \geq LB_j * wh\_Install_j \quad \forall j \quad (9)$$

Limit on maximum products in a line:
A Binary variable captures status of a product being produced at a line at a plant location. Limit is applied on sum of those binary variables. Equation (10), Equation (11), Equation (12) represents this.

$$Product\_Status_{p.pl.i} \geq \frac{\sum_{j,m,t\in V(pl,j,m)} Y_{p,pl,i,j,m,t}}{M} \quad \forall\, p, pl, i \quad (10)$$
$$Product\_Status_{p.pl.i} \leq \left(\sum_{j,m,t\in V(pl,j,m)} Y_{p,pl,i,j,m,t}\right) * M \quad \forall p, pl, i \quad (11)$$
$$\sum_p Product\_Status_{pl,i,p} \leq MAX\_PROD\_LINE_{pl,i} \forall p, pl \quad (12)$$

In addition, there are several customized constraints for the company like production of a particular SKU should be certain percentage of its brand production, cost of under utilization of a shift, lower and upper bounds on number of lines etc.

Scenarios
The scenarios for which the model was run can be broadly classified into three types:

Allocation Planning Scenarios:
These scenarios are for pure allocation problem which reflect business as usual. In these scenarios we considered present locations as installed. Here the model calculated the optimal quantity to be moved from each plant location to depot and from depot to demand centre.

Greenfield expansion:
These scenarios consider possibility of investing in new plants. That means here only new candidate locations are considered. These scenarios consider economies of scale. Results of these scenarios give optimal locations and capacity chunks of different lines at each location. These scenarios present an ideal case which reflects the starting of the company from scratch.

Brownfield expansion:
These scenarios consider incremental capacity addition over the existing plants as well as new locations. These are practical cases where we freeze existing plants with their actual capacities. These scenarios are considered with demand forecast for future years. These also consider economies of scale.

Allocation planning scenarios give minimum possible cost with existing network and capacities. Green field scenarios are used for filtering some new plant locations out of many options. The outputs of Greenfield scenarios are used as input into Brownfield scenarios. The potential candidate locations combined with existing locations gives practical case. The outputs of these scenarios are used to redesign present supply chain network. The total costs incurred in Brownfield scenarios minus installation costs can be compared with allocation planning scenario to find out running costs savings with new supply chain network.

Solution Methodology
CPLEX solver uses branch and bound search algorithm with algorithmic features such as cuts and heuristics. The problem size was large. There were about 6000 to 8000 binary variables, 1000 integer variables, 3 million non-integer variables and 5000 constraints. Average run time for a Green field scenario on a 64-bit quad-core processor machine was about 10 hrs to reach an optimal solution within 1% accuracy limit. Average run time for Brown field scenario was about 1 hr on the same machine.

For certain large dataset scenarios, in order to achieve good accuracy and reduce run time, the problem was divided into two steps. In the first step, demand was considered at depots and the model selected optimal plant location and line installation plan. In the second step, demand was considered at demand centers and plant locations and lines were fixed as per the first step results, and the model selected optimal locations for depots. Some complex constraints which had certain binary variables were relaxed in certain scenarios to reduce run time.

A suitable decomposition technique can be applied to improve the performance of the model in a robust manner. The present problem has a decomposable structure with complicating constraints. Hence it would require the use of Branch and Price algorithm or its extensions [1]. These are the areas for future work.

V. Results and Discussion

Here we present some results of our analysis. For the purpose of comparison and to show the effect of economy of scale, we considered one scenario each from Greenfield, Brownfield and Allocation planning scenarios. These three scenarios considered have same demand and production capacities but location options are different.

Table 1 Comparison between Different Scenarios

	Greenfield	Brownfield	Allocation Planning
Production Cost	8.72E+08	1.06E+09	9.6E+08
Transportation Cost	1.34E+09	1.47E+09	1.7E+09
Total Cost	2.21E+09	2.54E+09	2.7E+09

Table1 shows that Green field scenario has around 18% less total annual cost and Brownfield scenario has around 6% less total annual cost compared to the existing network. As some of the data are confidential, we have changed the numbers and hidden plant names while retaining the relative differences.

The results of Green field and Brownfield scenarios are given in Table 2 and Table 3 respectively. In Brown field scenario, loc101 to loc110 are existing locations which are bound with their actual capacities. Economies of scale in location costs are better utilized in Greenfield scenario as presented in Table 2 and Table 3. 9 locations are selected in Greenfield scenario and 15 locations are selected in Brownfield scenario. Table 1 shows that Greenfield scenario has 13% less total cost compared to Brown field scenario.

Table 2 Location Wise Lines Installed in Greenfield Scenario

Location	No. of Lines installed
loc10	6
loc12	7
loc14	12
loc17	8
loc20	3
loc23	10
loc4	9
loc7	9
loc8	4
Grand Total	68

Table 3 Location Wise Lines Installed in Brownfield Scenario

Location	No. of Lines installed
loc101	5
loc102	4
loc103	6
loc104	7
loc105	6
loc106	6
loc107	5
loc108	4
loc109	5
loc110	4
loc14	1
loc16	7
loc20	4
loc24	3
loc9	8
Grand Total	75

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