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Selection of Plant Location to Minimize Total Shipping and Labor Costs

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SELECTION OF PLANT LOCATION TO MINIMIZE TOTAL SHIPPING AND LABOR COSTS

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ABSTRACT

A method is presented for determining the optimal geographical location for a plant engaged in a specified manufacturing activity. The manufacturing activity is defined as the conversion of several raw materials and sub-assemblies into a finished product. The optimal plant location is defined as the one which minimizes costs of shipping raw materials from various optional sources to the plant, the cost of shipping the finished product to specified markets, and the cost of labor involved in the assembly process. The method of solution is described, as is the computer program for implementing the method. Some illustrative examples are also given.

This project was suggested by a problem of the Industrial Research and Information Services of the Nebraska Department of Economic Development.** The computer program described in the paper is a useful tool for investigating the relative merits of locating a manufacturing activity in an area such as Nebraska.

INTRODUCTION

Whenever a company needs more manufacturing capacity the question of the optimal plant location arises. Expansion at the existing facilities may not be the best solution. The factors that influence the selection are many. The proximity to sources of raw materials and to market outlets, the availability and the cost of labor, variances in state and local taxes, and other sociological factors such as congestion and general living conditions might all be important. Three types of costs are considered in this paper; costs of shipping raw materials or sub-assemblies to the plant, costs of shipping finished products from the plant to markets and costs of labor expended at the plant. The plant location which minimizes the sum of these three costs is termed optimal. This optimal solution is meant to apply only to a very specific plant operation because the raw materials and their sources vary for different manufacturing activities, shipping rates vary with the type of material being shipped as well as the amount and the distance. The market outlets vary with the product as do the labor rates and hence the total cost of labor. Because of all the variables mentioned, a great deal of detailed information is needed to evaluate the situation for a particular company or industry. This paper describes a method for evaluating these data and leads to the selection of the plant location which is optimal with regard to these shipping and labor costs. Equally important is the determination of the relative ranking of other potential plant locations in terms of these costs.

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PROBLEM DEFINITION

The object of the plant under consideration is to manufacture a given product. One unit of this product is denoted P and consists of m raw materials, subassemblies or purchased parts in specified amounts. Letting y_i be a unit amount of the i^{th} ingredient or material in the finished product, and letting α_i be the number (or some fractional number) of units of y_i required to make one unit of the finished product, the manufacturing process can be described by

$$P = \sum_{i=1}^{m} \alpha_i y_i \tag{1}$$

Each of the materials y_i can be obtained from anyone of a set of optional supply sources $J_i = [\![S_{1i}, S_{2i}, \cdots S_{max}]\!]$. The number of possible sources may differ for each material.

The amount of labor required to produce a unit product P is assumed known and adequately described by a single number, L, man-hours of an average labor grade per unit P.

After combining labor and materials to form the finished product P, the result is shipped to market outlets. It is assumed that the portion to be shipped to each of R markets M_j, is known. That is, for each unit product, k_j of it is shipped to market M_j, so that

$$P = \sum_{j=1}^{R} k_j P \tag{2}$$

or

$$\sum_{j=1}^{R} k_j = 1 \tag{3}$$

It is assumed that the factors k_j are known from marketing data or sales forecasts.

The costs to be considered in the operation of the proposed plant are costs of shipping materials y_i to the plant from the sources S_{qi}, the cost of shipping the finished product to the markets M_j and the labor cost. All costs are keyed to the production and shipment of β units of the finished product. Thus β could represent the annual plant capacity, quarterly capacity, one thousand units of P, or a single unit of P depending on the circumstances of an individual problem.

The labor cost for β units of P are simply

$$C_L' = \beta LF(\underline{X}) \tag{4}$$

where $\underline{X}$ is the position vector of a possible plant location in some suitable coordinates and $F(\underline{X})$ is the hourly wage rate applicable in that location for the type of labor required.

Shipping costs, both for raw materials and finished product, are functions of distance shipped, amount shipped and the type of commodity being shipped. The kinds of commodities are known for a given plant. It is assumed that inventory and re-ordering policies are such that the most economical lot sizes (car load, truck load, etc) would be shipped at any given time. The shipping distance is a function of the material or market location and the unknown plant location $\underline{X}$. In this study a piecewise linear relationship between distance and shipping cost is assumed per unit of a particular commodity. That is, the cost of shipping one unit of material i from source S_{qi} to a plant located at X is of the form

$$CI_i(\underline{X}) = U_i + v_i \| \underline{X}_{S_{Qi}} - \underline{X} \| \tag{5}$$

where the constant term U_i and the mileage rate term v_i take on different values depending on whether the distance is considered short range, i.e. $0 \leqslant \| \underline{X}_{SQi} - \underline{X} \| \leqslant D_1$ or intermediate range, i.e. $D_1 \leqslant \| \underline{X}_{SQi} - \underline{X} \| \leqslant D_2$ or long range, i.e. $D_2 \leqslant \| X_{SQi} - \underline{X} \|$. The use of straight line Euclidean distances is justified by the fact that constants U_i and v_i will normally be determined as average values over a large number of actual shipments and will be influenced to a certain extent by factors other than those considered here.

Similarly, the cost of shipping one unit of the finished product from the plant at $\underline{X}$ to market M_j located at X_{Mj} will be of the form

$$CO_j(\underline{X}) = U + v \| \underline{X}_{Mj} - \underline{X} \| \tag{6}$$

Again the constant values of U and v will be conditioned by the shipping distance and the type of commodity. Since the same commodity is shipped to each market, these constants are not subscripted with respect to the markets.

The incoming shipping costs CI_i and the outgoing shipping costs CO_j as represented by Equations (5) and (6) are for one unit of the commodity being considered. The costs of interest are for β units of the finished product, so the factor $a_i\beta$ must be applied to each cost represented by Equation (5) and the factor βk_j must be applied to each cost represented by Equation (6). The problem being considered here can be summarized as follows. Find the plant location, $\underline{X}$, which minimizes the total shipping and labor costs for β units of the product P. That is, find $\underline{X}$ to minimize

$$C(\underline{X}) = \beta\{LF(\underline{X}) + \sum_{i=1} \alpha_i \, CI_i(\underline{X}) + \sum_{j=1} k_j \, CO_j(\underline{X}) \} \tag{7}$$

(TOTAL COST) = CAPACITY ⟦LABOR COST PER UNIT CAPACITY + INCOMING SHIPPING COST PER UNIT CAPACITY + OUTGOING SHIPPING COST PER UNIT CAPACITY⟧.

Roughly speaking, the problem is to determine the centroid of the material sources and market outlets, weighted by their respective importance, and weighted by the regional labor costs.

PROBLEM SOLUTION

The solution to be presented utilizes a grid of N discrete points for the potential plant locations. Thus the results obtained may not be mathematically optimum, but several distinct advantage are gained. The discrete approach is the natural one for digital computation. Furthermore, it prevents meaningless answers such as finding the optimum location in the middle of Lake Michigan. The discrete approach gives the user the capability of comparing the relative merits of prespecified locations or regions. Finally, as the number of grid points, N, becomes large, the continuum of possible locations can be approached with acceptable accuracy.

Each of the N potential plant locations is defined by two coordinates, a local wage rate factor, and a four letter name, $(x_i,y_i,F_i,NAME_i, i = 1,2, \ldots, N.)$. In addition there are R discrete market outlet points described by two coordinates and the market share factor, (x_j,y_j,k_y). The sources where each of the M raw materials are available must also be described by two coordinates and the amount of material required, a_i. However, each material may have several optional sources, so the total number of source locations, T, is equal to the number of elements in each of the m sets J_i mentioned earlier. In general the total number of grid points required will be considerably less than N + R + T because some points will simultaneously be sources of several materials, markets and potential plant locations. The approach used here is to select the N potential plant locations so as to include all sources and market locations. Thus, a grid of N points is used, with N being on the order of 100. Each of these points is identified by the 4 items $(x_i,y_i,F_i,NAME_i)$. A subset of R of these points are markets, identified by a grid point number and a market share factor, (M_j,k_j). Each raw material is characterized by a set of grid point numbers $J_i = (S_{1i},S_{21}, \ldots S_{maxi})$ and the relative amount required, a_i. The numbers S_{1i},S_{1i}, etc. are integers identifying all grid points at which material U can be found.

The computational procedure is to first find the minimum cost associated with each of the N grid points, according to included in the cost totals. This information would indicate within which category the relative advantages and disadvantages of the potential sites fall. The computer printout also indicates which of the optional source locations were selected in arriving at the minimum costs. In order to make the computer print-out as self explanatory as possible, four-letter abbreviations, rather than numbers, are used to identify all grid points and materials.

FIRST EXAMPLE

A simple example is presented first to illustrate the main features of the program. A grid consisting of six points, shown in Figure 1, is considered.

Each of these six points is a potential plant location. The plant under consideration is to "manufacture" finished beef by combining four "materials", calves, feed, salt and water. It is assumed that a calf can be obtained only at the point N.E., feed can be obtained only at the point S.E., salt can be obtained only at the point S.W., and water can be obtained either at N.W. or WEST. No materials are available at the center (CNTR), but this point is the market for all finished product. Labor rates at all points were taken as \$3.00 per hour, except at S.E., where it was \$.95 per hour. Shipping costs for one unit of each material and a unit of the finished product were all of the form where d is the distance shipped.

$$\text{Shipping cost per unit} = \begin{array}{lll} 5 + 4d & \text{if} & 0 \leqslant d \leqslant .5 \\ 10 + 2d & \text{if} & .5 \leqslant d \leqslant 1.2 \\ 15 + d & \text{if} & 1.2 \leqslant d \end{array}$$

Considering $\beta = 775$ units of finished product and $L = 6.4$ manhours per unit, the results of Table I are obtained. These results indicate that S.E. is the most favorable plant location, mainly due to the low labor costs at that point. A plant located at that point would achieve the minimum imbound freight costs if the four materials are purchased at N.E., S.E., S.W. and N.W. respectively. The second best plant location is CNTR, because of its minimal outbound shipping costs. There is no cost distinction between fourth and fifth ranked locations, as should be apparent from the symmetry of the problem. The poorest location is the point WEST, primarily because it is furtherest from the market and thus has the highest outbound freight costs.

SECOND EXAMPLE

A somewhat more realistic sounding example is now considered. The data used are entirely fictional however, so no significance can be attached to the results. This example is titled "A Study of the Mobile Home Industry in

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PROGRAM:    PLACC...A PROGRAM FOR PLANT LOCATION AND COST COMPARISONS...
AUTHORS:    W.L. BROGAN AND J.M. INGUANZO
LOCATION:   ELECTRICAL ENGINEERING DEPARTMENT, UNIV. OF NEBR.
DATE:       SPRING OF 1970.
TITLE:      A TRIVIAL TEST CASE.
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RESULTS ARE BASED ON 775. UNITS OF THE FINISHED PRODUCT AND ASSUMES 6.4 MANHOURS LABOR PER UNIT

RANK	MINIMUM INBOUND FREIGHT $-(000)	OUTBOUND FREIGHT $-(000)	TOTAL SHIPPING COST $-(000)	ADD LABOR COST $-(000)	TOTAL COST IN THIS LOCATION $-(000)	POTENTIAL PLANT LOCATION SITES	MINIMUM INBOUND FREIGHT COST ASSUMES MATERIAL PURCHASES FROM THE FOLLOWING SOURCES			
							CALF	FEED	SALT	WATR
1	11011	12721	23732	4712	28444	S.E.	N.E.	S.E.	S.W.	N.W.
2	12721	3875	16596	14880	31476	CNTR	N.E.	S.E.	S.W.	N.W.
3	10897	12721	23618	14880	38498	S.W.	N.E.	S.E.	S.W.	WEST
4	11011	12721	23732	14880	38611	N.E.	N.E.	S.E.	S.W.	N.W.
5	11011	12721	23732	14880	38611	N.W.	N.E.	S.E.	S.W.	N.W.
6	11187	13175	24362	14880	39242	WEST	N.E.	S.E.	S.W.	WEST

the Mid-West." One mobile home is assumed to consist of known amounts of glass, fixtures, aluminum, steel and miscellaneous. It is assumed that 200 manhours of labor are required per mobile home. Twenty potential plant sites are considered and it is assumed that known percentages of the finished product are shipped to eleven specified markets. Each of the five materials is assumed available at three or four optional sources. Ficticious labor rates are assigned to each potential plant location. The annual output of the plant is assumed to be 1000 mobile homes. Using all these data, the results of Table 2 are obtained. These ficticious results indicate that Grand Island, Nebraska (GRIS) is the optimal plant site and that the glass should come from Sioux City (SCTY), the miscellaneous from Denver (DENV), the fixtures from Kansas City (KCTY), the aluminum from Omaha (OMHA) and the steel from Lincoln (LINC). The results further indicate that labor costs are the main reasons why Grand Island is the best choice. Des Moines (DESM) is second best on an overall cost basis because of a combination of near minimal shipping costs and medium labor costs. Actually Des Moines is nearest the centroid of the eleven markets, as indicated by its minimal outbound freight costs. Las Vegas is the poorest location of the twenty considered because of high labor costs and high shipping costs. The high shipping costs indicate that Las Vegas was remotely located from the assumed material sources (inbound freight costs) and from the assumed markets (outbound freight costs). Lincoln and Omaha rank fourth and fifth respectively even though they are most favorably located with respect to material sources, as evidenced by their low inbound freight costs. Table 2 also shows how the best source of each material varies from one potential plant location to another. For example, the "miscellaneous" item should be obtained from Denver (DENV), Saint Louis (STLU), Chicago (CHIC) or Phoenix (PHNX) depending on which location is nearest the plant site being considered.

CONCLUSIONS

A technique for selecting plant locations which are optimal with regard to shipping and labor costs has been presented. The computer program for carrying out the technique has been described and illustrative examples have been presented. Considerable flexibility has been built into the program so that a variety of problems of the type presented can be treated. In addition, other obvious applications are possible. By setting labor costs to zero and by re-interpreting the incoming "material," problems of where to locate regional warehouses can be considered. In fact the weighted centroid of N points can be found and numerous interpretations of this problem could be given. The kind of weights that can be attached are point weights (labor costs) and path weights (shipping costs).

PROGRAM: PLACC...A PROGRAM FOR PLANT LOCATION AND COST COMPARISONS...
AUTHORS: W.L. BROGAN AND J.M. INGUANZO
LOCATION: ELECTRICAL ENGINEERING DEPARTMENT, UNIV. OF NEBR.
DATE: SPRING OF 1970.
TITLE: A STUDY OF THE MOBILE HOME INDUSTRY IN THE MID-WEST.

RESULTS ARE BASED ON 1000. UNITS OF THE FINISHED PRODUCT AND ASSUMES 200.0 MANHOURS LABOR PER UNIT

RANK	MINIMUM INBOUND FREIGHT $-(000)	OUTBOUND FREIGHT $-(000)	TOTAL SHIPPING COST $-(000)	ADD LABOR COST $-(000)	TOTAL COST IN THIS LOCATION $-(000)	POTENTIAL PLANT LOCATION SITES	MINIMUM INBOUND FREIGHT COST ASSUMES MATERIAL PURCHASES FROM THE FOLLOWING SOURCES GLAS	MISC	FIXT	ALUM	STEL
1	185668	263224	448892	350000	798892	GRIS	SCTY	DENV	KCTY	OMHA	LINC
2	140411	221888	362299	600000	962299	DESM	SCTY	STLU	DESM	DESM	LINC
3	303428	316138	619566	350000	969566	VLTN	SCTY	DENV	DESM	DENV	LINC
4	124825	237531	362356	620000	982355	LINC	SCTY	DENV	KCTY	OMHA	LINC
5	125448	227179	352627	640000	992627	OMHA	SCTY	STLU	DESM	OMHA	LINC
6	180713	238200	418913	600000	1018913	SCTY	SCTY	DENV	DESM	OMHA	LINC
7	345075	359548	704623	400000	1104622	CORN	SCTY	DENV	DESM	DENV	LINC
8	171173	245543	416716	700000	1116715	KCTY	KCTY	STLU	KCTY	OMHA	LINC
9	203541	284726	488268	700000	1188267	MINN	SCTY	CHIC	MINN	MINN	CHIC
10	216168	292098	508266	700000	1208266	STLU	KCTY	STLU	STLU	DESM	CHIC
11	164110	304988	469098	750000	1219097	CHIC	CHIC	CHIC	STLU	DESM	CHIC
12	256937	358846	615783	650000	1265783	DENV	SCTY	DENV	KCTY	DENV	LINC
13	219852	328507	548359	750000	1298358	MILW	CHIC	CHIC	MINN	MINN	CHIC
14	250581	350292	600873	760000	1360873	GRBY	CHIC	CHIC	MINN	MINN	CHIC
15	397163	371006	768169	640000	1408168	OKCY	KCTY	DENV	KCTY	DENV	LINC
16	417111	486731	903842	580000	1483842	WYOM	SCTY	DENV	DESM	DENV	SLCY
17	402023	567481	969504	600000	1569504	SLCY	SCTY	DENV	KCTY	DENV	SLCY
18	499459	511917	1011376	760000	1771375	ALBQ	KCTY	PHNX	KCTY	DENV	SLCY
19	615836	675656	1291492	750000	2041492	PHNX	KCTY	PHNX	KCTY	DENV	SLCY
20	621571	713354	1334924	800000	2134924	LASV	SCTY	PHNX	KCTY	DENV	SLCY

For the main problem considered, finding optimal plant locations, three major cost factors have been considered. These results would provide a good starting point in considering the many other factors such as taxes, land cost and general living conditions. It is hoped that these results will be a useful tool in the economic expansion of an area such as Nebraska.