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An extension of the GOMA model for determining the optimal number of depots

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To solve distribution problems, one can use either complex mathematical modeling or simple rules of thumb. The latter give approximate answers, but have the advantage of requiring only little data. In this paper we focus on one of these simple rules. We discuss a number of refinements of the *General Optimal Market Area* (GOMA)-model to determine the optimal number of depots serving a set of uniformly distributed customers in a particular area. The refinements concern a more precise modeling of fixed costs, of inventory costs and of transport costs. Numerical examples show that the refinements lead to different results for the optimal number of depots, notably in the case of substantial inventory and/or handling costs.

1. Introduction

To solve distribution problems, there are two possible approaches:

- Complex mathematical modeling, that yields the optimal answer but requires lots of data and familiarity with advanced mathematical programming techniques.
- Simple rules of thumb, that may give approximate answers or even wrong ones, but require little data and little insight into complex mathematics.

The importance of such rules and, at the same time, the limited extent to which they are available, is noted by various authors, see for example Geoffrion (1976, 1979), Graves (1981), Hax and Candea (1984) and Rogers *et al.* (1991). Interestingly, the two approaches are sometimes connected in that an approximate answer to a distribution problem may sometimes be used as a starting point for a heuristic procedure to solve a complex mathematical model for such a problem. An example of such an approach can be found in Erlebacher and Meller (2000).

For a specific distribution problem, i.e., determining the optimal number of distribution centers, there are several simple rules of thumb available. In this paper we first review these rules and then show how some assumptions underlying these rules, specifically regarding

fixed costs, inventory levels and transportation, can be refined so that the rules more accurately reflect the real-world situation. It should be stressed, however, that even these refined rules are still, in a sense, ‘quick and dirty’ and only meant to give a reasonable estimate of the required number of distribution centers in cases where a quick answer is required and little data is available. More detailed modeling is required in case a precise answer is required, for example for investment decisions.

In this paper, we wish to find the optimal number of depots, N_d^* , for a given area of size A , in which N_c customers are uniformly located. Each customer is served N_s times per year and the total demand over all customers equals V_{tot} items per year. Here, optimal means that total costs (consisting of such components as fixed costs, transport costs, inventory costs etc.) are minimal as a function of the number of depots.

In the next section, we will present the general optimal market area model that is used as a basic model. Section 3 will give a refinement of the model on each of its three cost components. In Section 4 the differences between the models will be discussed and finally in Section 5 some conclusions are given.

2. The general optimal market area model

Erlenkotter (1989) describes the General Optimal Market Area (GOMA) model. The purpose of this model is to determine the optimal area served from a single production

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point (or depot). Thus, when the total size of the area is known, the optimal number of depots can be easily determined by dividing the total area by the optimal area per depot. The general optimal market area model is based on the following assumptions (a list of symbols is presented in Appendix A):

1. Demand is distributed uniformly over an infinite plane, with demand density $\rho > 0$ per unit area.
2. The cost for a facility producing the amount x is $c_f x^\alpha + c_p x$, where $c_f > 0$ is the fixed cost for the facility, $0 \leq \alpha \leq 1$ (economies-of-scale factor), and $c_p \geq 0$ is the variable facility and production cost per unit.
3. Unit transport costs are related to the distance traveled, y , by the expression $c_t y^\beta$, where $c_t > 0$ (per item per unit distance) and $\beta > 0$ (economies-of-distance).
4. Various regular two-dimensional market shapes may be specified, with the following letters codes: C = circle, H = regular hexagon, S = square, D = diamond (a square rotated 45°).
5. Distances are measured according to the Euclidean norm (E) or the Manhattan metric (M).
6. Subject to assumptions (1)–(5), the average cost per unit of demand (or per unit area) is to be minimized.

To specify an instance of the General Optimal Market Area model, Erlenkotter uses the form $GOMA(\alpha, \beta, s, d)$, where α and β are the values of the exponents in assumptions 2 and 3 respectively, s denotes the market shape in assumption 4 and d denotes the distance norm in assumption 5.

The total cost function for the GOMA model now is

$$C(x) = c_f x^\alpha + c_p x + \sigma(\beta, s, d) c_t x \left(\frac{x}{\rho} \right)^{\beta/2}, \quad (1)$$

where $\sigma(\beta, s, d)$ is a ‘configuration factor’ reflecting the market shape s , the distance metric d and the transport cost exponent β . Equation (1) expresses the total costs for any $GOMA(\alpha, \beta, s, d)$ model with a regular two-dimensional market shape, provided that $\sigma(\beta, s, d)$ can be evaluated.

We will only give the equations for $GOMA(0, 1, S, E)$ because our refinements of the GOMA model are restricted to the formulas for a square area. Extending the model to other shapes is possible, although Eilon *et al.* (1971) and Geoffrion (1979) note that the influence of the shape of the area on the total cost function is negligible. Eilon *et al.* (1971) present a table of values for the configuration factor; the value for $\sigma(1, S, E)$ equals 0.3826.

In order to extend the model to determine the optimal number of depots, we need to carry out some transformations. The density of demand in the GOMA model, ρ , equals the total demand divided by the total area: V_{tot}/A . We assume that the total size of the country is A and not infinite. This arises from the fact that Erlenkotter (1989)

focuses on the optimal market area size for each depot (with an infinite plane) while we focus on the optimal number of depots, from which we can derive the optimal market area given our assumption of a country of area A . It should be noted that the ‘boundary effect’ may be important if the number of depots is relatively small.

The amount produced per facility, x , can be replaced by the total demand divided by the number of depots: V_{tot}/N_d . Including these transformations and the value of $\sigma(1, S, E)$ in Equation (1), gives the following cost function for $GOMA(0, 1, S, E)$:

$$C = c_f + c_p \frac{V_{\text{tot}}}{N_d} + 0.3826 c_t \frac{V_{\text{tot}}}{N_d} \sqrt{\frac{A}{N_d}}. \quad (2)$$

Equation (2) gives the total cost per facility. The total cost for the whole market area, A , can be determined by multiplying by N_d , the number of depots:

$$C(N_d) = c_f N_d + c_p V_{\text{tot}} + 0.3826 c_t V_{\text{tot}} \sqrt{\frac{A}{N_d}}. \quad (3)$$

The optimal number of depots, N_d^* , then is:

$$N_d^* = \left(\frac{0.3826 c_t V_{\text{tot}} \sqrt{A}}{2 c_f} \right)^{2/3}. \quad (4)$$

3. Model refinements

3.1. First refinement: fixed costs

In his model, Erlenkotter (1989) includes the possibility to refine the fixed costs via an economies-of-scale factor α . This is a rather basic refinement, which, nevertheless, gives complex formulas for $0 < \alpha < 1$. Moreover, it seems that a realistic value of α is hard to determine. Therefore, as an alternative, we propose to base the fixed costs of a depot on three factors:

- First, there will always be some truly fixed costs which are independent of the size of the depot (usually some basic labor costs). We will denote these costs by c_{fix} .
- Second, the rent costs of a depot will change when the volume changes. The rent costs can be assumed to depend on the annual throughput of a depot divided by the turnover rate, and multiplied by the rent costs per unit. The annual throughput per depot equals V_{tot}/N_d . Thus the rent costs equal $c_r V_{\text{tot}}/(N_d R)$, where R denotes the turnover rate and c_r the rent costs per unit. Note that the size of a depot should account for the *maximum* inventory level rather than the *average* inventory level; therefore the turnover rate R is defined as the annual throughput divided by the maximum inventory level.
- Third, the handling costs in a depot will change when the volume changes. We assume that the handling

costs depend on the mean distance walked in the depot for picking orders multiplied by the throughput of the depot. If we assume that the distance traveled within the (square) depot depends on the area of a depot, and that the metric within the depot is rectangular (Manhattan), then the mean distance walked can be taken to be proportional to the square root of the volume (i.e., throughput divided by turnover rate). Note that we are implying diseconomies of scale in modeling the handling costs. This is primarily done to allow for a fair comparison between the models. The handling costs per depot then are $c_h V_{\text{tot}}/N_d f \sqrt{V_{\text{tot}}/(N_d R)}$, where c_h denotes the handling costs per unit per meter.

Thus, the fixed costs of a depot can be split up as follows: $c_f = c_{\text{fix}} + c_{\text{rent}} + c_{\text{handling}}$. If the volume and thus the size of the depot increase, then the rent and handling costs increase. The total cost function (over all depots), given in Equation (3), now becomes:

$$C(N_d) = c_{\text{fix}} N_d + c_r V_{\text{tot}}/R + c_h V_{\text{tot}} f \sqrt{\frac{V_{\text{tot}}}{N_d R}} + c_p V_{\text{tot}} + 0.3826 c_t V_{\text{tot}} \sqrt{\frac{A}{N_d}}. \quad (5)$$

3.2. Second refinement: inventory

The GOMA model includes fixed costs per depot, production costs and transport costs. Since a distribution center doesn't actually produce items, the production costs can be viewed as costs related to holding inventory. In the GOMA model, these costs ($c_p V_{\text{tot}}$) do not depend on the number of depots. However, when the number of depots increases, the total amount of inventory will increase, since more safety stock is needed. We assume that the level of cycle stock is held constant independent of the number of depots. Geoffrion (1979) mentions that the amount of safety stock increases approximately in proportion to the number of locations raised to an exponential power between one-half and one; additional support is given by Schwarz (1981). We will refine the GOMA model by including the amount of safety stock, as follows:

- The total amount of safety stock, expressed as a fraction of yearly demand ($m V_{\text{tot}}$), depends on the number of depots. If more depots are used, then it can be assumed that safety stock increases by the square root of the number of depots. In other words, total amount of safety stock is proportional to $m V_{\text{tot}} \sqrt{N_d}$. Note that m is the safety stock as a fraction of yearly demand for $N_d = 1$.
- The associated costs are:
 - * Interest on invested capital: $c_i m V_{\text{tot}} \sqrt{N_d}$.

- * Remaining variable costs (such as interest on cycle stock), denoted by: $c'_p V_{\text{tot}}$.

Replacing the production costs in Equation (5) leads to the following total costs per year:

$$C(N_d) = c_{\text{fix}} N_d + (c_r/R + c'_p) V_{\text{tot}} + c_h f V_{\text{tot}} \sqrt{\frac{V_{\text{tot}}}{N_d R}} + c_i m V_{\text{tot}} \sqrt{N_d} + 0.3826 c_t V_{\text{tot}} \sqrt{\frac{A}{N_d}}. \quad (6)$$

3.3. Third refinement: transport

In the previous equations for total costs we use the mean radial distance ($0.3826 \sqrt{A/N_d}$) and the amount delivered (V_{tot}) to determine the transport costs. However, if several customers are delivered to in one tour, we can calculate the length of the tour related to the number of customers visited and estimate transport costs more precisely. Eilon *et al.* (1971) present the following equation for determining the length of a tour.

$$D_0 = C_1 \frac{D_r}{\varepsilon} + C_2 \sqrt{a} \sqrt{D_r}, \quad (7)$$

with

- D_0 = tour length;
- D_r = sum of radial distances;
- C_1 = constant;
- C_2 = constant;
- ε = number of stops per tour;
- a = length of the side of the area ($= \sqrt{A/N_d}$).

The first part of Equation (7) can be interpreted as the 'line-haul' portion of each tour/vehicle, which is shared by ε customers. The second term can be interpreted as the amount of 'detour' distance needed to actually deliver to each customer, since the term is proportional to the distance between nearest neighbors. This equation applies to a square area. If the depot is located in the center of the area, C_1 equals 1.8 and C_2 equals 1.1. The expected value of D_r is given by Christofides and Eilon (1969); under their assumptions $E\{D_r\} = 0.3826 n_s a$ (with n_s the number of stops per year in the area of one depot). Hence Equation (7) can be adjusted to obtain the following estimate for the total annual distance traveled in the area of one depot:

$$D_0 = 1.8 \frac{0.3826 n_s a}{\varepsilon} + 1.1 \sqrt{a} \sqrt{0.3826 n_s a}. \quad (8)$$

The resulting transport costs over all depots is therefore given by:

$$C_{\text{transport}}(N_d) = D_0 c'_t N_d = \left(\frac{1.8 \times 0.3826 n_s a}{\varepsilon} + 1.1 a \sqrt{0.3826 n_s} \right) c'_t N_d. \quad (9)$$

Note that the cost factor is now denoted by c'_t (cost per kilometer per truck).

The amount transported can be limited either by volume or by time. If limited by volume, ε will denote the number of stops at which the volume equals the vehicle capacity. If limited by time, ε will denote the number of stops at which the travel time equals the maximum allowed travel time per tour. It can be argued that usually ε will be limited by volume, because if ε is limited by time, then the load factor of the vehicles will be less than one and hence most probably smaller vehicles would have been used. We will therefore assume that vehicles with an appropriate size are used and that ε is thus limited by volume.

When the vehicle capacity is denoted by $v_{\max}$ and the average drop size $\bar{d}$ is known, then $\varepsilon = v_{\max}/\bar{d}$. Given the number of customers (N_c) and the number of stops per customer per year (N_s), the mean drop size and the number of stops per depot can be determined, which results in the following transport costs

$$\bar{d} = \frac{V_{\text{tot}}}{N_c N_s}, \text{ and } n_s = \frac{N_c N_s}{N_d},$$

$$C_{\text{transport}}(N_d) = \left(\frac{1.8 \times 0.3826a V_{\text{tot}}}{v_{\max}} + 1.1a \sqrt{0.3826 N_c N_s N_d} \right) c'_t. \quad (10)$$

In order to compare the differences between the models we will have to determine c'_t . The original transport cost factor, c_t is given per unit per kilometer. The new factor, c'_t , is given per truck per kilometer. If we assume that the vehicle is always loaded to its capacity (as described above), then the mean volume available in the vehicle during a tour will be $v_{\max}/2$. Hence we can assume that $c'_t \approx (v_{\max} c_t)/2$. Equation (10) now becomes:

$$C_{\text{transport}}(N_d) = (0.9 \times 0.3826a V_{\text{tot}} + 0.55a v_{\max} \sqrt{0.3826 N_c N_s N_d}) c_t. \quad (11)$$

Replacing the transport costs in Equation (6) by (11) leads to the following total costs per year:

$$C(N_d) = c_{\text{fix}} N_d + (c_r/R + c'_p) V_{\text{tot}} + c_h f V_{\text{tot}} \sqrt{\frac{V_{\text{tot}}}{N_d R}} + c_i m V_{\text{tot}} \sqrt{N_d} + 0.9 \times 0.3826 c_t V_{\text{tot}} \sqrt{\frac{A}{N_d}} + 0.55 c_t v_{\max} \sqrt{0.3826 A N_c N_s}. \quad (12)$$

When comparing Equation (12) to Equation (6), we see that the transport costs in Equation (6) now are multiplied by 0.9. Also an additional cost factor is included that depends on the number of customers and the number of stops per customer, but not on the number of depots.

Equation (12) leads to the following equation for the optimal number of depots:

$$N_d^* = \left(\frac{z^{2/3} + x^2 - xz^{1/3}}{6c_{\text{fix}} z^{1/3}} \right)^2, \quad (13)$$

with

$$x = c_i m V_{\text{tot}},$$

$$y = c_h f V_{\text{tot}} \sqrt{V_{\text{tot}}/R} + 0.9 \times 0.3826 c_t V_{\text{tot}} \sqrt{A},$$

$$z = 54 c_{\text{fix}}^2 y - x^3 + 6 c_{\text{fix}} \sqrt{3} \sqrt{y(27 c_{\text{fix}}^2 y - x^3)}.$$

4. Comparing the models

4.1. Parameter comparison

Before we can compare the models, we have to discuss the differences between the parameters of both models. In both models, the only parameter that depend on the number of depots is a set-up cost (c_f in the GOMA model and c_{fix} in our model). For comparison sake, the value of these parameters should therefore be identical in the two models.

In the GOMA model, total demand (V_{tot}) is multiplied by the production costs (c_p), whereas in our model the total demand is multiplied by the rent costs (c_r/R) and the remaining variable costs (c'_p). The inventory costs are explicitly modeled in our model and depend on the total demand and the number of depots, whereas in the GOMA model the inventory costs are implicitly included in the production costs and only depend on the total demand. Nevertheless, for a fair comparison we put $c_p \equiv c_r/R + c'_p + c_i$.

Finally, the transport part in both models only differs in a multiplier (0.9). The handling costs only appear in our model.

4.2. Analysis

If the 'new' costs are set to zero, i.e., $c_i = c_h = 0$, then Equation (13) reduces to

$$N_d^* = \left(\frac{0.9 \times 0.3826 c_t V_{\text{tot}} \sqrt{A}}{2 c_{\text{fix}}} \right)^{2/3},$$

which is identical to Equation (4) except for the multiplier in the transport costs. Table 1 shows the basic values of the parameters as used for the case study. As an example, we will show what happens if the value of one of the parameters changes. For the case of increasing inventory costs (through either increasing interest rates or increasing product value), our model finds an optimal number of depots which is substantially **lower** than the optimal number determined by the GOMA model. For the pa-

Table 1. Basic parameter values as used for the case study

Name	Units	Variable	Value
Fixed costs	Dfl/year	$c_f = c_{fix}$	100 000
Handling costs	Dfl/unit meter	c_h	0
Rent costs	Dfl/unit year	c_r	250
Transport costs	Dfl/unit km	c_t	0.0375
Inventory costs	Dfl/unit year	c_i	0
Production costs	Dfl/unit	c_p	20.83
Rest variable costs	Dfl/unit	c'_p	0
Product value	Dfl/unit	w	50
Country surface	km ²	A	2500 000
Total demand	units (m ³)	V_{tot}	1000 000
Safety stock factor	–	m	1/24
Turnover rate	–	R	12

parameter set of Table 1, for example, changing the interest rate to 12% leads to an optimal number of depots equal to 18 in our model, whereas the GOMA model finds $N_d^* = 23$, as is shown in Fig. 1.

For the case of handling costs, our model finds an optimal number of depots which is, for most values, substantially *higher* than the optimal number determined by the GOMA model. For the parameter set of Table 1, for example, changing handling costs to Dfl 0.04 per unit leads to an optimal number of depots equal to 29 in our model, whereas the GOMA model again finds $N_d^* = 23$, as is shown in Fig. 2. Only for small values of the handling costs, is the optimal number of depots in our model smaller, but this could be caused by the multiplier (0.9) in our transport cost.

In other cases, for example the case where there are different transport costs, different country surfaces or different turnover rates, the differences between the two models are relatively small.

Fig. 1. The optimal number of depots for the case with increasing inventory costs. **Fig. 2.** The optimal number of depots for the case with increasing handling costs.

5. Summary and conclusions

In this paper we have discussed a number of refinements of the GOMA model to determine the optimal number of depots serving a set of uniformly distributed customers in a particular area. The refinements concern a more precise modeling of the fixed costs, of inventory costs and of transport costs, and lead to different results for the optimal number of depots, notably in the case where there are substantial inventory and/or handling costs.

Although we claim that our model reflects distribution costs in a more accurate way than the original GOMA model, and should therefore give a better answer to the question of what the optimal number of depots is, we would like to stress once more that we are discussing diagnostic tools that give rough, but reasonably accurate estimates to the required number of depots. More detailed modeling, that takes practical issues and circumstances into account, is required before any final decisions regarding the number and exact location of the depots can be made.

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Appendix A

List of symbols

- A = Total size of the country (kilometer²).
- a = Length of the side of the area of one depot ($a = \sqrt{A/N_d}$).
- c_f = Fixed cost of operating a distribution center in the GOMA model (Dfl per year).
- c_{fix} = Fixed cost of operating a distribution center in the current model (Dfl per year).
- c_h = Handling cost.
- c_i = Inventory cost (= w_i).
- c_p = Production cost (Dfl per m³).
- c'_p = Production cost minus safety stock costs.
- c_r = Rent cost (Dfl per m³ per year).
- c_t = Transport cost (Dfl per kilometer per m³).
- c'_t = Transport cost (Dfl per kilometer per truck) (= $(v_{max}c_t)/2$).
- $\bar{d}$ = Average drop size (= V_{tot}/N_cN_s).
- f = Scale factor to convert square root of volume to distance walked.
- i = Interest percentage.
- m = Safety stock per distribution center (fraction of yearly demand).
- N_c = Number of customers in the total area.
- N_d = Number of depots.
- N_d^* = Optimal number of depots.

- N_s = Number of stops per customer per year.
- n_s = Number of stops per year in the area of one depot (= N_cN_s/N_d).
- R = Turnover rate.
- v_{max} = Vehicle capacity.
- V_{tot} = Total demand per year (m³).
- w = Value of the product (Dfl per m³).
- α = Economies of scale factor for production.
- β = Economies of scale factor for transport.
- ε = Number of stops per tour.
- ρ = Demand density (V_{tot}/A).

Biographies

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