FOUNDATIONS OF COMPUTING AND DECISION SCIENCES
Vol. 47 (2022) No. 4
ISSN 0867-6356
DOI: 10.2478/fcds-2022-0023 e-ISSN 2300-3405

Introduce a New Mathematical Approach to Inventory Management in Production Processes Under Constrained Conditions

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Abstract. Nowadays, some manufacturing organizations may well face production restrictions. For example, in case the number of products goes up, the company might not be capable of producing all products. As a consequence, the company may face backlogging. In the meanwhile, in case the demand for products rises, the given company may experience a restricted capacity to react to that kind of demand properly; thus, it will suffer backlogging. Over the course of this study, that kind of company facing the mentioned circumstances is considered. To meet those exceeded demands, companies would be forced to purchase some products from outside. Thus, the study's primary aim is to define and calculate the optimum make and buy a number of products so that overall inventory cost is reduced and optimized. To do so, a model is proposed referred to as the make-with-buy model. This model is designed and solved by exact solution software in the based branch and bound method. The results of the study confirm the feasibility and efficiency of this method and demonstrate that this model can be applied to lessen the overall inventory costs, including maintenance, order, setup, and purchasing costs, and also the total costs of products.

Keywords: production capacity, make-with-buy, Inventory cost, production restrictions.

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1. Introduction

The main goal of keeping inventory in a manufacturing system is to reduce costs such as order or production establishment, maintenance, and shortage costs [1-3]. Therefore, inventory control is one of the most important issues among academic and industrial researchers. Economic order quantity (EOQ) and economic production quantity (EPQ) are two classic models in the inventory control literature [4,5]. EOQ is derived from a method that comprises annual demand, holding cost, and order cost. This phenomenon aims to strike a balance between the amount you sell and the amount you spend to handle your inventory [6]. Among the main gains of the EOQ model are customized recommendations for any particular company. When a manufacturing company buys an item from a foreign supplier, the EOQ model is employed to define the economic order size [7,8].

On the other hand, when a product is manufactured inside the company, the manufacturer uses the EPQ model to determine the optimal production batch size [9-11]. Over the past few years, researchers have added considerations to EPQ and EOQ models to raise their utility. Most of these considerations are related to the duplication of manufacturing of some defective products [12-14], limited space [15,16], returned orders and maintenance operations. This study focuses on a specific multi-product EPQ model with production capacity constraints. Some researchers have proposed a production policy that states that a shortage occurs when there is insufficient production capacity to meet annual demand [17-19]. Goyal and Gopalakrishnan [11] evaluated the EPQ model with limited production capacity. Also, they assumed that excess annual demand was lost.

Furthermore, given that the production rate is lower than the demand rate, it seems logical to assume that the consumption period can only begin after a batch is fully produced. Based on this sales hypothesis, they developed a computational model that maximizes profit and minimizes costs. Cárdenas-Barrón [3] developed an EPQ model for a single product created in a single-stage production process, which generates defective products, all of which must be reconstructed in the same cycle. This model assumes that the production rate is higher than the demand rate. Pentico and Drake [15] used EPQ for integrated programming of a product and its components, where the final product is at risk of delayed order for unmet demands.

Taleizadeh et al. [21] investigated a multi-product manufacturing model with random defective items and constraints at repair and service levels. The assumption of having only one device in their research led to limited production capacity and shortages. These studies mostly focused on determining the optimal cycle length, optimal production amount and optimal delayed orders of each product, such that the overall expected cost (maintenance, shortage, manufacturing, installation, defective items and repair costs) is minimized. A study by Hariga [10] is one of the studies that is closely related to this research. He proposed a production order policy for displacing limited production capacity status. The model was limited to one product, and the inventory control policy was related to receiving an external order at the time of discontinuation of the production line.

Chiu and Chiu [5] considered decision-making for single-product procurement based on EPQ and EOQ models with backlogging permitted. They also evaluated the effect of different parameters, such as setup and delayed order costs, on purchasing (ordering) or production (manufacturing) decisions. A dual procurement policy is used, which includes an optional purchase or construction option to meet demand. Pahlevan et al. [14] proposed a mathematical model for supplying inventory in the supply chain. Specifically performed in the field of aluminum, the mentioned research identified the highest level of inventory, and minimization occurred with the help of several metaheuristics. In another study, Soleymanfar et al. [19] introduced EOQ and EPQ sustainable models in a multi-layer supply chain. They developed a mathematical model that was able to optimize the inventory policy of different members of the supply chain. To this end, a decrease in environmental pollution and an increase in created jobs were optimized in addition to reducing costs. In the present research, the EPQ model is developed for several products with limited production capacity. In the proposed model, demands for each product may be met simultaneously through in-company production and external orders. Foreign orders can be received at any time during the inventory cycle.

The current study focuses on a multi-product production order model in definite environments. This model can be applied when the production rate is lower than the demand rate or when we are faced with limited production capacity in multi-product conditions. Assume that a single machine manufactures a particular number of products, and the machine produces all products with backlogging. Nevertheless, the machine may fail to make all products when there is a rise in the demand rate or the number of products. Thus, we will face backlogging and huge costs. In such situations, we must purchase some of the products and store them, which frees time for the machine to produce all of the products [4,20-22]. When faced with this situation, the inefficiency of previous researchers can be seen due to the fact that they have mainly utilized the assumption of permitted shortage and delayed orders. At the same time, it may not be the case in reality. To tackle this issue and prevent inventory storage by the manufacturer, we permit meeting a part of the demands from the outside. In the current research, the problem is formulated so that the objective function is to decrease the overall inventory costs, including maintenance, order, setup, and purchasing costs, as well as the full costs of products. After solving the model, the optimal order and production amounts are defined for each product in each cycle.

2. Materials and Methods

2.1. Problem assumptions and symbols

The parameters used in the present study are shown as follows:

Q_1: Order quantity for purchase
Q_2: Production amount
R: Net inventory at the beginning of the production period
P: Production rate
D: Demand rate
h: Inventory cost rate
TMC: Total manufacturing cost
THC: Total handling cost
TOC: Total ordering costs
TIC: Total inventory cost
NS(t): Net inventory at t moment
A_1: Ordering cost

A_2: Procurement cost for production
C_1: Purchasing cost of each product unit
C_2: cost of each product unit manufacturing
T: Period of the production round
t_p: The length of the production period in each round of production
TIC: Total inventory cost

2.2. Research assumptions

There are some assumptions considered in the current study as follows:

1. The production rate and demand rate are determined and definite.
2. A shortage is not allowed.
3. All products are manufactured by one machine.
4. The machine can produce only one product in a time unit.
5. All items in the inventory system are consumed continuously.

2.3. Problem and modeling

As mentioned in Section 2, the make-with-buy model can be used in two modes:

First mode: The production rate is higher than the demand rate, but there is a production limit.

Second mode: The production rate is lower than the demand rate.

To describe the modeling method, the make-with-buy model is evaluated for a product, and the model is subsequently expanded to several products.

2.4. Make-with-buy Model: Single Product (Production Rate Higher than Demand Rate)

In this model, a machine that produces one product is considered, and the rate of production is considered to be higher than the demand rate. Moreover, production limitation leads to purchasing a certain amount of demand. The objective is to determine the optimal order and purchase amount such that the total inventory costs, including maintenance, order, purchasing and production costs, are minimized. Figure 1 shows the net changes in inventory over some time. The purchased amount (Q_1) is received at the beginning of the period. This batch of products is consumed for a period of t_1 with a demand rate of (D) until the inventory level decreases to R_1. Afterward, the machine starts the production process for a period of t_p, during which production and consumption occur simultaneously. The net inventory increases in t_p time with a rate of (P-D) since the production rate is higher than the demand rate. The production process stops at the end of t_p, and inventory is consumed with a demand rate of (D) until the inventory amount decreases to zero. Other periods continue similarly. The problem model is presented in Figure 1.

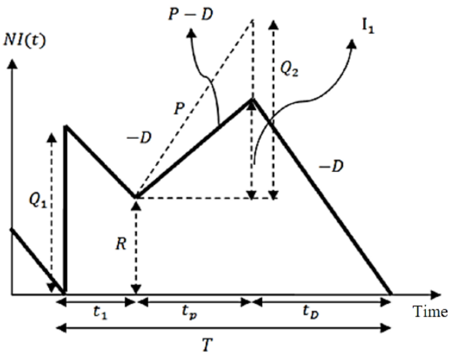

Figure 1. Net inventory level when P>D for a product

$$D=\frac{Q_1-R_1}{t_1}\Rightarrow t_1=\frac{Q_1-R_1}{D} \qquad , \qquad \frac{I_1+R_1}{t_D}=D\rightarrow\ {}^{t}D=\frac{I_1+R_1}{D} \tag{1}$$

$$\begin{cases}\frac{Q_2}{t_p}=P\rightarrow t_p=\frac{Q_2}{P}\\ \frac{I_1}{t_p}=P-D\rightarrow I_1=t_p(P-D)\end{cases}\Rightarrow I_1=Q_2(1-\frac{D}{P}) \tag{2}$$

$$t_1+t_p+t_D=T\rightarrow T=\frac{Q_1+Q_2}{D} \tag{3}$$

$$TMC=(C_1Q_1+C_2Q_2)\times\frac{1}{T}=(C_1Q_1+C_2Q_2)\times\frac{D}{Q_1+Q_2} \tag{4}$$

$$TOC=(A_1+A_2)\times\frac{1}{T}=(A_1+A_2)\times\frac{D}{Q_1+Q_2} \tag{5}$$

$$THC=h\times\frac{1}{T}\left[\frac{(Q_1+R_1)(t_1)}{2}+\frac{(2R_1+I_1)(t_p)}{2}+\frac{(I_1+R_1)(t_D)}{2}\right]=$$
$$h\times\frac{D}{Q_1+Q_2}\left[\frac{(Q_1+R_1)(Q_1-R_1)}{2D}+\frac{\left[2R_1+Q_2\left(1-\frac{D}{P}\right)\right]\times(Q_2)}{2P}+\frac{\left[Q_2\left(1-\frac{D}{P}\right)+R_1\right]^2}{2D}\right] \tag{6}$$

We can formulate the total inventory costs as follows:

$$TIC=TMC+TOC+THE \tag{7}$$

$$TIC=(C_1Q_1+C_2Q_2)\frac{D}{Q_1+Q_2}+(A_1+A_2)\frac{D}{Q_1+Q_2}+$$
$$\frac{hD}{Q_1+Q_2}\left[\frac{(Q_1+R_1)(Q_1-R_1)}{2D}+\frac{\left[2R_1+Q_2\left(1-\frac{D}{P}\right)\right]\times(Q_2)}{2P}+\frac{\left[Q_2\left(1-\frac{D}{P}\right)+R_1\right]}{2D}\right] \tag{8}$$

$$TIC = \frac{D(C_1Q_1+C_2Q_2)+D(A_1+A_2)+\frac{h}{2}\left(Q_1^2+Q_2^2\left(1-\frac{D}{P}\right)+2R_1Q_2\right)}{Q_1+Q_2} \tag{9}$$

$s.t$:

$R_1 \leq Q_1$

$Q_1, Q_2, R_1 \geq 0$

Decision variables: R_1 and Q_2 and Q_1

2.5. Make-with-buy Model: Single Product (Production Rate Lower than Demand Rate)

Figure 2 demonstrates the net inventory changes over a period for a product. The purchased amount of (Q_1) is received at the beginning of the period. This batch of products is consumed for a period of t_1 with a demand rate of D until the net inventory decreases to R_2. At this time, the machine starts the production process for a period of t_2 till the inventory amount reduces to zero. During this period, production and consumption co-occur. The net inventory decreases during t_2 with a rate of (D-P) since the production rate is lower than the demand rate. The production process ceases to operate at the end of the period and other production rounds occur similarly. Modeling of this mode is presented in Figure 2.

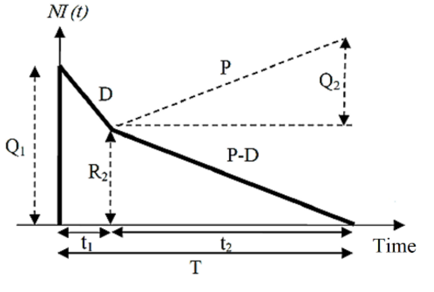

Figure 2. Net inventory level when P<D for a product

$$\frac{Q_1-R_2}{t_1} = D \rightarrow t_1 = \frac{Q_1-R_2}{D} \quad , \quad \frac{R_2}{t_2} = D-P \quad \rightarrow t_2 = \frac{R_2}{D-P} \quad , \quad \frac{Q_2}{t_2} = P \quad \rightarrow t_2 = \frac{Q_2}{P} \tag{10}$$

$$\Rightarrow \frac{Q_2}{P} = \frac{R_2}{D-P} \rightarrow Q_2 = \frac{P}{D-P} \times R_2 \tag{11}$$

$$T = t_1 + t_2 = \frac{Q_1-R_2}{D} + \frac{Q_2}{P} = \frac{(Q_1-R_2)P+Q_2D}{PD} \tag{12}$$

$$\frac{(Q_1-R_2)\times P+\frac{P}{D-P}\times R_2\times D}{PD} = \frac{Q_1-R_2+\frac{D}{D-P}\times R_2}{D} = \frac{Q_1\times(D-P)-R_2D+R_2P+R_2D}{D(D-P)} \tag{13}$$

$$\frac{Q_1+R_2\times\frac{P}{D-P}}{D} = \frac{Q_1+Q_2}{D} \Rightarrow \frac{1}{T} = \frac{D}{Q_1+Q_2} \tag{14}$$

$$TMC = (C_1Q_1 + C_2Q_2) \times \frac{1}{T} \quad , \quad TOC = (A_1 + A_2) \times \frac{1}{T} \quad , \quad THC = h \times \frac{1}{T}\left[\frac{(Q_1+R_2)t_1+R_2t_2}{2}\right] \tag{15}$$

In this mode, the total cost of inventory is also equal to:

$$TIC = TMC + TOC + THC \tag{16}$$

$$TIC = \frac{1}{T}\left[(C_1Q_1 + C_2Q_2) + (A_1 + A_2) + \frac{h}{2}\left(\frac{(Q_1+R_2)\times\frac{(Q_1-R_2)}{D}+R_2\times\frac{R_2}{D-P}}{2}\right)\right] \tag{17}$$

$$TIC = \frac{D}{Q_1+Q_2}\left[(C_1Q_1 + C_2Q_2) + (A_1 + A_2) + \frac{h}{2}\left(\frac{Q_1^2(D-P)+R_2^2P}{D(D-P)}\right)\right] \tag{18}$$

$$s.t:$$

$$Q_2 = \frac{P}{D-P} \times R_2$$

$$R_2 \leq Q_1 \tag{19}$$

$$Q_1, Q_2, R_2 \geq 0$$

Decision variables: R_2 and Q_2 and Q_1

2.6. Make-with-buy Model: Multiproduct

In this section, we extend the models of section 4.1. and 4.2. to multiple products. Each product is denoted by i index and the cost of each product is denoted by c_i. Therefore, we will have:

$$STIC = \sum_{\forall i} \frac{D_i(C_{1i}Q_{1i}+C_{2i}Q_{2i})+D_i(A_{1i}+A_{2i})+\frac{h_i}{2}\left(Q_{1i}^2+Q_{2i}^2\left(1-\frac{D_i}{P_i}\right)+2R_{1i}Q_{2i}\right)}{Q_{1i}+Q_{2i}} \tag{20}$$

$$+\sum_{\forall j} \frac{D_j}{Q_{1j}+Q_{2j}}\left[(C_{1i}Q_{1i} + C_{2i}Q_{2i}) + D_i(A_{1i} + A_{2i}) + \frac{h_i}{2}\left(\frac{Q_{1i}^2(D_j-P_j)+R_{2j}^2P_j}{D_j(D_j-P_j)}\right)\right] \tag{21}$$

The duration is assumed to be the same for all items- i.e., $T_1=T_2=\ldots=T_n=T$. Therefore, the machine can produce all products with only the following two constraints:

$$\sum_{k=1}^{n} t_{pk} + \sum_{k=1}^{n} S_k \leq T \tag{22-a}$$

$$\frac{Q_{1i}+Q_{2i}}{D_i} = T \tag{22-b}$$

Where S_k is the machine procurement period for producing k-type products, and t_{pk} is the production period for a k-type product, which is equal to Q_{2k}/P_k. In the end, the model of the problem will be, as follows:

$$\min STIC = \sum_{\forall i} \frac{D_i(C_{1i}Q_{1i} + C_{2i}Q_{2i}) + D_i(A_{1i} + A_{2i}) + \frac{h_i}{2}\left(Q_{1i}^2 + Q_{2i}^2\left(1 - \frac{D_i}{p_i}\right) + 2R_{1i}Q_{2i}\right)}{Q_{1i} + Q_{2i}}$$

$$+ \sum_{\forall j} \frac{D_j}{Q_{1j}+Q_{2j}}\left[(C_{1i}Q_{1i} + C_{2i}Q_{2i}) + D_i(A_{1i} + A_{2i}) + \frac{h_i}{2}\left(\frac{Q_{1i}^2(D_j-P_j)+R_{2j}^2P_j}{D_j(D_j-P_j)}\right)\right] \quad (23)$$

$$\sum_{k=1}^{n} \frac{Q_{2k}}{P_k} + \sum_{k=1}^{n} S_k \leq T \quad (24)$$

$$T_k = T; k = 1, \dots, n$$

$$R_{1i} \leq Q_{1i} \quad ; \quad \forall i \quad (25)$$

$$\mathrm{Q_{2j}} = \frac{\mathrm{P_j}}{\mathrm{D_j - P_j}} \times \mathrm{R_{2i}} \quad ; \quad \forall \mathrm{i} \quad (26)$$

$$\mathrm{R_{2i}} \leq \mathrm{Q_{1j}} \quad ; \quad \forall \mathrm{j} \quad (27)$$

$$\mathrm{Q_{1k}, Q_{2k}, R_{1k}, R_{2k}} \geq 0; \mathrm{k} = 1, \dots, \mathrm{n} \quad (28)$$

$$T \geq 0$$

3. Results and Discussion

Consider a company with four products and data that are randomly generated from a uniform distribution at certain intervals [5,13] based on Table 1. It is aimed to determine the optimal purchasing and production amounts for each product by using the model proposed in the present study. According to Table 1, it is observed that: $P_3 > D_3$, $P_2 < D_2$, $P_4 < D_4$ $P_1 > D_1$.

Table 1. Data related to products and inventory system

Product	D	P	C_{1i}	C_{2i}	A_{1i}	A_{2i}	h_i	S_i
1	2972	3915	23	12	100833	76846	110	0.01
2	3682	4469	22	15	102937	61519	163	0.003
3	2004	3890	28	11	129790	80730	193	0.005
4	3615	3820	20	14	131873	81437	105	0.003

Since $\sum_{k=1}^{4} \frac{D_k}{P_k} = \frac{400}{800} + \frac{200}{140} + \frac{700}{850} + \frac{1000}{800}$, a single machine cannot produce all four products. Therefore, a make-with-buy model is used. BARON, which is a branch and bound algorithm, is utilized to solve the formulated model. In that problem, BARON 7.5.3. and AIMMS version 3.12 are utilized by limiting the continuity of the objective function in the appropriate region, where the overall optimality is guaranteed. The results are presented below:

Q_{11} = 1024 Units $\quad$ Q_{21} = 1016 Units $\quad$ R_{11} = 146 Units
Q_{12} = 864 Units $\quad$ Q_{22} = 156 Units $\quad$ R_{22} = 67 Units

Q_{13} = 2328 Units	Q_{23} = 1241 Units	R_{13} = 284 Units
Q_{22} = 4188 Units	Q_{24} = 912 Units	R_{24} = 228 Units
T = 5.1 days	STIC = 3149829 $/day	

According to the results, the duration of the production and consumption period of each product is 5.1 days. In total, 1024 units are bought from the outside in each round to meet product 1 demands. Order is received at the beginning of the round, and the machine starts manufacturing 1016 product units when the inventory value reaches 146. The results related to other products can be interpreted similarly. Notably, this system's total inventory cost is $3149829 per day.

4. Conclusion

Customer demand or the number of products increases with the development of a company. However, the company fails to meet customers' demands due to a fixed number of machines. This leads to excess inventory and enormous costs for the company. To deal with the issue, the company purchases part of the products. The present study focused on formulating the problem and determining the optimal manufacturing and purchasing values using BARON to minimize the total inventory costs. One of the most critical applications of the proposed model concerning outsourcing strategy is supply chain management, in which the manager makes decisions about the amount of purchasing or outsourcing products and the type of products in this regard. Hence, the results of the study can contribute to reducing the overall inventory costs, including maintenance, order, setup, and purchasing costs, and total costs of products as well.

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Received 10.08.2022, Accepted 21.11.2022