Chapter 2
Production and Inventory Planning Models with Demand Shaping

Abstract This chapter considers the state of prior literature on operations models that account for demand flexibility. In particular, we focus on generalizations of the models discussed in Chap. 1 that treat demands as decision variables. These generalizations typically involve pricing models, and they provide a foundation for the models we will study in subsequent chapters.

2.1 EOQ Models with Pricing

Whitin [37] provided a seminal paper on inventory control and pricing under the EOQ model assumptions (this paper also considers a single-period stochastic problem, which we discuss in the following section). This model generalizes cost equation (1.4) to account for price-dependent demand and subsequently maximizes profit per unit time instead of cost. In order to do this, a linear price–demand function is assumed that takes the form

$$D = \beta - \alpha p, \tag{2.1}$$

where α and β are scalars (which are typically assumed to be positive) and p denotes price. Using this demand function (2.1) along with cost Eq. (1.4), we can write the average profit per unit time as a function of p, denoted as $\Pi(p)$, as

$$\Pi(p) = (p - C)(\beta - \alpha p) - \sqrt{2S(\beta - \alpha p)H}. \tag{2.2}$$

Letting $Q^*(p) = \sqrt{2S(\beta - \alpha p)/H}$, Arcelus and Srinivasan [3] provide the following form of the stationary-point solution for the optimal price[1]:

$$p^* = \frac{1}{2}\left[\frac{\beta}{\alpha} + C + \frac{S}{Q^*(p^*)}\right], \tag{2.3}$$

[1]One can verify that the second derivative of $\Pi(p)$ with respect to p is strictly increasing in p; thus the profit function $\Pi(p)$ is either convex in p for all $p \geq 0$, in which case an optimal extreme point solution exists (i.e., either $p^* = 0$ or $p^* = \beta/\alpha$), or $\Pi(p)$ is concave on some interval [0, $\tilde{p}$] and convex for $p \geq \tilde{p}$. In the latter case, either an extreme solution or the stationary-point solution (2.3) is optimal (assuming such a stationary point exists).

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where

$$Q^*(p^*) = \sqrt{\frac{2S(\beta - \alpha p^*)}{H}}. \tag{2.4}$$

This generalized version of the EOQ model permits selecting the *optimal* demand level when demand is price-dependent (for simplicity, we have considered a linear price–demand function, although more complex functions have been explored). Numerous additional generalizations of this basic model have been addressed in the literature, including problems with more general demand functions ([23, 25, 31]), quantity discounts ([1, 8, 9]), and investment and storage constraints ([7, 24]).

2.2 The Newsvendor Problem with Pricing and Demand Shaping

As noted in the previous section, Whitin [37] first considered a single period inventory problem with pricing under demand uncertainty. This problem used a marginal analysis with a unit profit for items sold and a unit loss associated with excess inventory remaining after demand is realized. Assuming that expected demand is a linear function of the profit margin and that demand is uniformly distributed between zero and twice the expected demand, Whitin [37] derived an expression for the optimal profit margin. The demand model used by Whitin [37] is effectively a *multiplicative* model, as both the expected value and the variance of the demand distribution depend on price. This is in contrast with the *additive* model, where demand is expressed as a deterministic function of price plus a random error term, which is independent of price. That is, letting $D(p,\varepsilon)$ denote the demand function, where ε is a random variable, then in an additive model, $D(p,\varepsilon) = y(p) + \varepsilon$, where $y(p)$ is a deterministic function of price and ε is a random variable with mean μ and variance σ^2. Under a multiplicative model, we have $D(p,\varepsilon) = y(p)\varepsilon$. The form of the demand model assumed fundamentally affects both the quantitative and qualitative results of the model. We will first briefly illustrate the application of a simple additive demand model and then discuss more general work that subsumes both the additive and multiplicative cases.

We initially consider the basic newsvendor problem under normal demand discussed in Chap. 1. Consider a generalized version of the expected profit equation (1.10) in which the expected demand μ_D is price dependent. In particular, assume that $\mu_D = \alpha - \beta p$. In this case, Eq. (1.10) becomes

$$\Pi_n(Q^*, p) = (p - C)(\alpha - \beta p) - K(z^*)\sigma_D. \tag{2.5}$$

This profit equation is concave in p with stationary-point solution (and therefore optimal solution) $p_a^* = (1/2)(C + (\alpha/\beta))$, where the subscript a corresponds to the additive case. Observe that for this additive demand model, the optimal price depends only on the profit margin $(p - C)$ and the expected demand, i.e., the optimal price is the same as that for the zero-variance (risk-free) case. The same is not true in a multiplicative model.

To illustrate this, suppose that, in addition, σ_D is a linear function of price, i.e., $\sigma_D = (\alpha - \beta p)\sigma$. This is equivalent to a multiplicative model in which $y(p) = (\alpha - \beta p)$ and ε is normally distributed with expected value one and variance σ^2. In this special case, the expected profit equation remains concave in p, and the stationary-point optimal solution becomes $p_m^* = (1/2)(C + (\alpha/\beta) + K(z^*)\sigma) = p_a^* + (K(z^*)\sigma/2)$, where the subscript m corresponds to the multiplicative case. Thus, the price in the multiplicative case equals the risk-free (additive) price plus a premium for the way in which price affects uncertainty.

Petruzzi and Dada [29] provide an excellent, general, and detailed analysis of the newsvendor problem with pricing. We next summarize their main results, which unify the treatment of the additive and multiplicative cases. These results build on the foundations provided in [13, 21, 28, 37, 38], and [39]. Petruzzi and Dada [29] consider an expected profit function of the form

$$\begin{aligned}\Pi(Q,p) = (p - C)\mathrm{E}\big[\mathrm{Sales}(\zeta,p)\big] - (C + H)\mathrm{E}\big[\mathrm{Leftovers}(\zeta,p)\big]\\ - B\mathrm{E}\big[\mathrm{Shortages}(\zeta,p)\big],\end{aligned} \tag{2.6}$$

where a one-to-one correspondence exists between the variable ζ and the order quantity Q at any price. The relationship between Q and ζ depends on the form of the demand function. In the additive case, ζ is defined using $\zeta = Q - y(p)$. In the multiplicative case, ζ is defined using $\zeta = Q/y(p)$.

Petruzzi and Dada [29] show that, for both the additive and multiplicative demand cases, ζ can be written as

$$\zeta = \mu + \mathrm{SF}\sigma, \tag{2.7}$$

where SF is defined in [32] as the safety factor, which is the number of standard deviations by which the order quantity differs from the expected value of demand, i.e.,

$$\mathrm{SF} = \frac{Q - \mathrm{E}[D(p,\varepsilon)]}{\mathrm{SD}[D(p,\varepsilon)]}, \tag{2.8}$$

where $\mathrm{SD}[D(p,\varepsilon)]$ is the standard deviation of $D(p,\varepsilon)$. They then define the *base price*, $p_B(\zeta)$ as the price that maximizes the expected contribution to profit from sales, i.e., the price that maximizes $(p - C)\mathrm{E}[\mathrm{Sales}(\zeta,p)]$ (note that $p_B(\zeta)$ maximizes the risk-free profit, i.e., expected profit when variance equals zero). Their first main result shows that for both the additive and multiplicative cases, for a given ζ, $p_B(\zeta)$ is determined by the unique value of p satisfying

$$p = C - \frac{\mathrm{E}[\mathrm{Sales}(\zeta,p)]}{\partial \mathrm{E}[\mathrm{Sales}(\zeta,p)]/\partial p}. \tag{2.9}$$

The second main result states that the optimal price in both the multiplicative and additive cases is bounded from below by $p_B(\zeta)$ for any given ζ. This implies that for both cases we can view the optimal price as the optimal base price plus a premium. In the additive case this premium equals zero because, for any given ζ, the expected leftover and shortage costs are independent of price. In the multiplicative case, the premium depends on the impact the price has on expected holding and shortage costs. Petruzzi and Dada [32] provide functional forms for the optimal price in both the multiplicative and additive cases, as well as methods to determine the optimal corresponding order quantity.

In addition to shaping demand through pricing, a few papers have considered different dimensions of demand flexibility in a stochastic demand setting. Petruzzi and Monahan [30] consider a fashion goods context with a primary and secondary market, where the decision maker must determine the optimal time at which to move a good from the primary to the secondary market. Carr and Duenyas [5] consider a production system with two classes of demand, each of which has a Poisson distributed arrival rate. Type 1 demands are called make-to-stock demands, and Type 2 demands are called make-to-order demands. Type 1 demands result in a shortage cost if a demand occurs and stock is depleted, while Type 2 demands may be accepted or rejected, although those accepted demands are made-to-order. This work provides an optimal production and order acceptance policy for this problem class. Carr and Lovejoy [6] consider a single-period newsvendor-type problem in which a number of prioritized demand portfolios are available, and a single resource with random capacity may be used to satisfy demands. The decision maker must determine the amount of demand to select within each portfolio in order to maximize expected profit.

2.3 Lot Sizing with Pricing

The earliest work on integrating pricing in the ELSP appears to be that of Thomas [33]. His work generalized the ELSP to incorporate the dependence of demand in each period on price. In this model, price may vary from period to period, and demand in period t depends on the price in period t, p_t, according to the function $D_t(p_t)$. This generalization of the ELSP can be formulated as follows:

$$[\text{ELSP}'] \quad \text{Maximize} \quad \sum_{t=1}^{T}\left\{p_t D_t(p_t) - S_t y_t - C_t Q_t - H_t I_t\right\} \tag{2.10}$$

$$\text{Subject to} \quad I_t = Q_t + I_{t-1} - D_t(p_t), \quad t = 1, \ldots, T, \tag{2.11}$$

$$Q_t \leq M_t y_t, \quad t = 1, \ldots, T, \tag{2.12}$$

$$Q_t, I_t, p_t \geq 0, \quad t = 1, \ldots, T, \tag{2.13}$$

$$y_t \in \{0, 1\}, \quad t = 1, \ldots, T. \tag{2.14}$$

The solution approach relies on the fact that for any given price vector, the problem reduces to the ELSP, and the zero-inventory-ordering (ZIO) property continues to hold. This implies that the shortest path solution approach discussed in Chap. 1 may still be applied in principle, although it becomes an acyclic longest path problem in which arcs are assigned profits instead of costs. If, for example, production in period t satisfies demand in periods t through s, then the profit on the arc from node t to node $s+1$ is obtained by solving the following pricing subproblem PSP where, with a slight abuse of notation, $H_{t,\tau} = \sum_{u=t}^{\tau-1} H_u$:

$$\text{[PSP]} \quad \text{Maximize} \quad \sum_{\tau=t}^{s} \big\{ (p_\tau - C_t - H_{t,\tau}) D_\tau(p_\tau) \big\}. \tag{2.15}$$

The PSP above decomposes by period, and its difficulty depends on the specification of the demand functions $D_t(p_t)$. If the optimal solution value to the PSP is less than or equal to the fixed order cost in period t, S_t, then the maximum arc $(t, s+1)$ profit equals zero; otherwise the arc profit equals the optimal objective function value less S_t. Thomas [33] illustrates the case in which $D_t(p_t)$ is linear in p_t for $t = 1, \ldots, T$, which implies that the PSP is easily solved using first order conditions.

Kunreuther and Schrage [22] subsequently considered the problem when price must be time-invariant, which is equivalent to adding the constraints $p_t = p_{t+1}$ for $t = 1, \ldots, T-1$, to the ELSP$'$ formulation. This restriction of the problem leads to a very different algorithm for solving the problem, because the problem can no longer be solved by decomposition into smaller time horizons, and the shortest path solution we described is no longer possible. However, as we know that for any given price $p = p_1 = p_2 = \cdots = p_T$, the problem again reduces to the ELSP. Thus, we know that an optimal solution exists that satisfies the ZIO property and that may be completely characterized by the sequence of order periods. That is, if we know there are ρ order periods $t_1, t_2, \ldots, t_\rho$, then the corresponding ZIO solution produces $\sum_{\tau=t_j}^{t_{j+1}-1} D_\tau(p)$ in period t_j for $j = 1, \ldots, \rho$. We will refer to a specific set of order periods $t_1, t_2, \ldots, t_\rho$ as an *order plan*. Kunreuther and Schrage [22] assume that demand in any period t is a linear function of a *price effect* function $d(p)$, which is time invariant. That is, $D_t(p) = \alpha_t + \beta_t d(p)$ for $t = 1, \ldots, T$, where α_t and β_t are nonnegative constants for each period t. For the special case in which $d(p) = -p$, we have the familiar linear price–demand function $D_t(p) = \alpha_t - \beta_t p$.

Observe that, given any price p, a vector of demands $[D(p)] = [D_1(p), \ldots, D_T(p)]$ results. The revenue associated with this demand vector equals $\sum_{t=1}^{T} p D_t(p)$. The cost associated with this vector of demands depends on the order plan utilized (we confine ourselves to the order plans defined in the previous paragraph, since we know that an optimal solution exists from among these solutions). As shown in [22], the cost of any order plan can be expressed as a linear function of the price effect $d(p)$. Assuming $d(p) = -p$, or a linear price–demand relationship in each period, this implies that the minimum cost as a function of p is a piecewise linear and concave function of p, where each linear segment corresponds to a specific order plan. If we can specify this piecewise linear function, or *envelope*, then it is possible to evaluate the maximum profit associated with every candidate order plan contained in an optimal solution. In this case, for each segment of the piecewise linear function, we can compute the optimal price for the given order plan. Specifying this piecewise linear function is not trivial, however.

Kunreuther and Schrage [22] suggest a heuristic approach that assumes the optimal price must fall on some interval $[p_L, p_U]$. We next briefly sketch the way this heuristic works. First, recall that for any fixed price, the problem reduces to an ELSP. Thus, we can initially solve the problem at the price p_L, which requires solving an instance of the ELSP. This solution provides an optimal order plan at the price p_L. The cost of this order plan is linear in price, and the associated line must form a segment of the piecewise linear concave envelope. Given this order plan, we next determine the price that maximizes profit when restricting ourselves to this particular order plan. If this price differs from p_L, then we can solve the ELSP corresponding to this new price. If the optimal order plan differs from the previous one, then we have identified an additional segment of the piecewise linear concave envelope. We continue this procedure iteratively, until the price and order plan converge. Call the resulting price after convergence p_L^*. We then repeat this process using the starting price p_U, and converging to the price p_U^*. As shown in [22], the optimal price, p^*, satisfies $p_L^* \le p^* \le p_U^*$.

Gilbert [15] considered a special case of this model in which costs are time-invariant and $D_t(p) = \beta_t d(p)$. For this case, he showed that the piecewise linear concave envelope has at most $\mathscr{O}(T)$ segments, and that these segments can be identified in polynomial time. Van den Heuvel and Wagelmans [35] then provided an algorithm that permits identifying the entire piecewise linear concave envelope for the general case defined in [22]. Beginning with the solutions p_L^* and p_U^*, they show how to identify whether an unidentified segment of the piecewise linear concave envelope exists by solving the problem at the intersection of the lines corresponding to the optimal order plans at the prices p_L^* and p_U^*. If a new line segment is identified, and its optimal price is also identified, this permits eliminating part of the interval of uncertainty[2] between p_L^* and p_U^*. This can then be repeated for any remaining intervals of uncertainty. Because the number of order plans is finite, the procedure is finite and must converge to an optimal price.

Gilbert [16] considered a multiple product lot sizing problem with shared but time-invariant production capacities and a time-invariant price for each good. Deng and Yano [10] and Geunes, Merzifonluoğlu, and Romeijn [14] subsequently considered the integrated pricing and lot sizing problem with production capacities. Merzifonluoğlu, Geunes, and Romeijn [27] considered a class of aggregate planning problems in which capacities, prices, and subcontracting levels served as decision variables.

2.4 Knapsack Problems with Nonlinear Objectives

This section describes a class of continuous knapsack problems in which a set J of n demands exists, as in our discussion of knapsack problems in Chap. 1. In this class

[2] We define an interval of uncertainty as an interval which is known to contain the optimal price, although the precise value of the optimal price remains unknown.

of knapsack problems, however, the variable x_j no longer corresponds to a binary variable that determines whether or not demand j is selected. Instead, x_j denotes a variable corresponding to the percentage of some maximum level, D_j, at which demand j may be satisfied. For example, D_j might correspond to the maximum level of sales effort that may be applied in a market j or the maximum amount of advertising expenditures that may be dedicated to product j. In each of these cases, the activity level consumes part of a finite resource with capacity b (in the former case this resource may be a salesperson's time in a period, while in the latter this resource may be a limited budget).

Associated with demand j is a revenue function $R_j(x_j)$, which depends on the activity level for demand j. We can formulate this nonlinear revenue maximizing knapsack problem as follows:

$$\text{[NLKP]} \quad \text{Maximize} \quad \sum_{j=1}^{n} R_j(x_j) \tag{2.16}$$

$$\text{Subject to} \quad \sum_{j=1}^{n} D_j x_j \leq b, \tag{2.17}$$

$$0 \leq x_j \leq 1, \quad j = 1, \ldots, n. \tag{2.18}$$

Clearly if each $R_j(\cdot)$ function is linear in x_j, then NLKP corresponds to the continuous relaxation of the knapsack problem KP defined in Chap. 1. If each $R_j(\cdot)$ function is convex in x_j, then an extreme point optimal solution also exists (as in the relaxation of KP). It is straightforward to show that extreme point solutions for NLKP contain at most one x_j variable that takes a value strictly between zero and one (moreover, for such extreme solutions, the resource capacity constraint (2.17) is tight). Using this fact, [4] provides a pseudopolynomial time algorithm under convex revenue functions that runs in $\mathscr{O}(Un^2b)$ time in the worst case, where U denotes the maximum value of D_j over all $j \in J$ (assuming that b and all D_j are integer). When all revenue functions are concave, the NLKP is a convex program and can therefore be solved using standard nonlinear optimization solvers. More general so-called S-curve return functions are considered in [2] and [17]. These functions arise in numerous marketing contexts such as advertising, where small levels of investment provide increasing returns to scale, and larger investment levels lead to decreasing returns to scale. Such S-curve functions are convex from zero to an inflection point, and then are concave thereafter. Analysis of the special structure of these revenue functions leads to pseudopolynomial time solution methods (see [2, 17]).

Additional classes of generalized knapsack problems with demand flexibility will arise in our study of decomposition methods for assignment and location models in Chap. 8. Moreover, in our analysis of EOQ models in Chap. 3 and in our discussion of newsvendor models in Chap. 4, several interesting nonlinear and nonseparable knapsack problems will arise.

2.5 Location and Assignment Problems with Flexible Demand

Location theory has been well studied in the economics and operations research literature under a number of assumptions. Much of the literature on location theory with price effects applies game-theoretic analysis in competitive settings. This body of literature simultaneously considers the objectives of multiple competing organizations, each of which wishes to maximize its profit based on its location and market-supply decisions. A discussion of the models and approaches for this class of problems may be found in [11] and [34]. The models we consider, and which are most relevant to the work considered throughout this book, are more appropriate for a single firm who is a monopolist, and thus wishes to make location decisions based on response to a price–demand curve for its product (and independent of other firms' decisions).

Wagner and Falkson [36] provided perhaps the earliest model for a facility location problem facing a single monopolistic producer of a good with price-sensitive demand. This model considered the location of public facilities under the maximization of social welfare and several different assumptions on the level of service that must be provided to customers. Hansen and Thisse [19] then provided a model for a private firm seeking to simultaneously determine price and location decisions in order to maximize profit when demand is price-dependent. Erlenkotter [12] generalized their approach to account for the profit maximization objectives of private and public firms within a single model. He provided a heuristic algorithmic approach based on Lagrangian relaxation and explicitly considered situations in which the revenue in a customer market is a quadratic function of price. The models we have discussed thus far permit charging different prices to individual markets, where the optimal price in a market depends on which facility serves the market at optimality. Hansen, Thisse, and Hanjoul [20] modeled the problem when the delivered price must be the same for all markets. Hanjoul et al. [18] later provided models that allowed different methods of consistent pricing among customers (that is, they considered the case in which the delivered price is the same for all customer markets, as well as the case in which all customers pay the same *mill price*, i.e., the price before bearing transportation costs from the supply point).

Although work on the generalized assignment problem (GAP) with pricing is quite limited, a rich set of models exists in the marketing literature for determining the optimal amount of limited salesforce effort to exert in different territories (see, e.g., [26, 40]). In these models, a salesperson's time corresponds to a limited resource, and sales territories must be assigned to sales personnel. Given an assignment of territories to a salesperson, the time the salesperson spends in each territory must also be determined, where the sales response (or revenue function, as in the NLKP) in a territory is a nonlinear function of the time spent in the territory (or the effort exerted). Thus, the sales level within each territory (i.e., the demand) effectively serves as a decision variable that is determined via the level of sales effort.

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