Risk Based Product Selection in a Central Kitchen Supply Chain

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Keywords: Central kitchen, Product selection, Risk, Supply chain.

Abstract. In a certain food consumption market, a central kitchen and a retailer form a decentralized supply chain. As the demand is uncertain, the investment on the central kitchen project is under financial risks. For risk reduction of the supply chain, we investigate product portfolio selection of the central kitchen project. Firstly, in two scenarios of the supply chain: coordination and non-coordination, mathematical modeling is used to analyze price decisions of the retailers with respect to different quality products provided by the central kitchen. Secondly, we develop the product portfolio selection model, where the goal is to minimize the risk under certain conditions. Finally, a numerical example is used to illustrate the impact of bargaining power of the central kitchen on the risk taking, industry quality, profit and consumer surplus. The results show that the supply chain coordination can produce high industry quality, low risk and low profit.

Introduction

Central kitchen is an organization that provides finished products and semi-finished products of food to its catering service retailers. Product diversification is important for a central kitchen to meet the market demand and realize the growth of project profit. Also, the quality control and service efficiency of the central kitchen products showed a positive reaction to the product diversification [1].

Due to the diversity of market character and the uncertain demand, central kitchen products may have different risk exposure and expected return. Volatility of demand causes financial risk to a central kitchen supply chain. As a consequence, in a central kitchen supply chain with multiple products to release, the selection of central kitchen products with minimal risk exposure is significant in the supply chain management.

Portfolio selection, originates from the well known Markowitz optimization approach, is an efficient tool for risk reduction. Markowitz demonstrated how stock investors could select an efficient set of portfolios that would minimize the standard deviation (risk), subject to a particular portfolio return (expected return) [2]. In this way, investors could reduce their exposure to the unique or unsystematic risk associated with individual securities immensely [3].

Product portfolio planning has been recognized as a critical decision facing all companies across industries. Aiming at the selection of a near-optimal mix of products and attribute levels to offer in the target market, [4] develops a heuristic genetic algorithm for solving the product portfolio planning problem more effectively. [5] considers a portfolio of products in which each product probabilistically transitions through various life cycle stages. They use an infinite-horizon Markov Decision Process (MDP) to find the optimal decisions to coordinate the operations and finance depending on the composition of the portfolio. In addition, [6] establishes how risk modeling can be applied to supply chain management, specifically to supply portfolio procurement decisions of a firm.

In this study, for risk reduction of central kitchen project investment, we investigate product portfolio selection from a supply chain perspective. Firstly, in two scenarios of the supply chain:
coordination and non-coordination, mathematical modeling is used to analyze price decisions of the retailers with respect to different quality products provided by the central kitchen. Secondly, we develop the product portfolio selection model, where the goal is to minimize the risk under certain conditions. Finally, a numerical example is used to illustrate the influence of bargaining power of the central kitchen on the risk taking, profit, consumer surplus and social welfare.

Description of the Problem

In the following sections, we quantitatively analyze the price decision and portfolio selection of the products in two supply chain strategies. The variables in the model are as follows:

- \( s \): Supply chain strategy between the central kitchen and the retailer (\( s = N, C \));
- \( N \): The non-cooperative Nash equilibrium game strategy is implemented between the central kitchen and the retailer;
- \( C \): Coordination is realized between the central kitchen and the retailer;
- \( c_k \): Quality related fixed cost of the \( k \)th product provided by the central kitchen, \( k = 1, 2, \ldots, l \);
- \( x_k \): Quality of the \( k \)th product provided by the central kitchen;
- \( p^s_k \): Price of the \( k \)th product offered by the retailer with supply chain strategy \( s \);
- \( t_k \): Decision variable of the \( k \)th product, where \( t_k = 1 \) means selected and \( t_k = 0 \) means not selected.

Here, \( x_k \) is an exogenous variable, while \( p^s_k \) is an endogenous variable.

**Assumption 1.** \( p^s_k > w_k + v_R \) and \( w_k > v_c \). Both quality \( x_k \) and price \( p^s_k \) decide the demand, which has a positive correlation with the quality of the product but a negative correlation with the price of the product.

**Assumption 2.** Quality of products from the retailer is decided by that of products or semi-finished products offered by the central kitchen.

**Assumption 3.** The demand for products with different quality is independent of each other in the market segments.

Referring to [7-9], we obtain the demand function of the \( k \)th product as follows:

\[
D_k = a_k + \alpha x_k - \beta p^s_k. \tag{1}
\]

where \( a_k \) is potential intrinsic demand, and demands of products are independent with each other. Furthermore, in order to capture the uncertainty in market demand resulting from changes in economic and business conditions, we assume that \( a_k \) is a random variable as

\[
a_k = \bar{a}_k + \varepsilon_k. \tag{2}
\]

Here, \( a_k \) is the mean of the potential intrinsic demand and \( \varepsilon_k \) follows a normal distribution that \( E(\varepsilon_k) = 0 \) and \( Var(\varepsilon_k) = \sigma^2 \). The fixed cost of the \( k \)th product is expressed as

\[
f_k = f + c(x_k)^2. \tag{3}
\]

Price Decision

In this section, price decision of the retailer is investigated in two supply chain strategies, including non-coordination (\( s = N \)) and coordination (\( s = C \)). When \( s = N \), the retailer makes pricing decision to maximize its own profit, and its expected profit function is:

\[
E(\Pi^N_k) = (p^N_k - w_k - v_R)(\bar{a}_k + \alpha x_k - \beta p^N_k). \tag{4}
\]

Accordingly, the expected profit function of the central kitchen is
\[ E(\Pi_k^N) = (w_k - v_C)(\bar{\alpha}_k + \alpha x_k - \beta p_k^N) - f - c(x_k)^2. \]  

(5)

Here, \( k = 1, 2, \ldots, l \). For the \( k \) th product, Proposition 1 can be derived as follows:

**Proposition 1** When the non-cooperative Nash game is implemented between the central kitchen and the retailer, \( s=N \), the retailer makes price decision for the maximization of its own profit as follows:

\[ p_k^N = [(\bar{\alpha}_k + \alpha x_k) + \beta(w_k + v_R)] / (2\beta). \]  

(6)

When supply chain coordination is realized between the central kitchen and the retailer, \( s=C \), price decision is made to maximize the expected profit of the supply chain, which is as follows:

\[ E(\Pi^C_k) = (p_k^C - v_C - v_R)(\bar{\alpha}_k + \alpha x_k - \beta p_k^C) - f - c(x_k)^2. \]  

(7)

Then Proposition 2 can be derived for the \( k \) th product as follows:

**Proposition 2** When coordination is realized between the central kitchen and the retailer, \( s=C \), the price of the \( k \) th product is made for the maximization of whole supply chain profit as follows:

\[ p_k^C = [(\bar{\alpha}_k + \alpha x_k) + \beta(v_C + v_R)] / (2\beta). \]  

(8)

In the next section, we further investigate risk based portfolio selection of products in a supply chain with one central kitchen and one retailer.

**Risk Based Portfolio Selection of Products**

Also, risk based models for the selection of product portfolios are developed in the two supply chain strategies: \( s=N \) and \( s=C \) as follows.

When \( s=N \), the central kitchen and the retailer take risk from uncertain demand separately. The expected profit of the central kitchen from the \( k \) th product is

\[ E(\Pi_k^N) = (w_k - v_C)(\bar{\alpha}_k + \alpha x_k - \beta p_k^N) - f - c(x_k)^2. \]  

(9)

Accordingly, retailer’s expected profit from the \( k \) th product is

\[ E(\Pi_k^N) = (p_k^N - w_k - v_R)(\bar{\alpha}_k + \alpha x_k - \beta p_k^N). \]  

(10)

When \( s=N \), risk taking policy is decided by negotiation between the central kitchen and the retailer. The objective of the supply chain is to select product portfolio that would minimize the risk, i.e. volatility of profit, subject to particular constraints as follows

\[
\text{Min } \sum_{k=1}^{l} [\theta(w_k - v_C) + (1 - \theta)(p_k^N - w_k - v_R)]\sigma_{k}t_k \]  

(11)

s.t.

\[
\sum_{k=1}^{l} [(w_k - v_C)(\bar{\alpha}_k + \alpha x_k - \beta p_k^N) - f - c(x_k)^2]t_k \geq I_C, \]  

(12)

\[
\sum_{k=1}^{l} (p_k^N - w_k - v_R)(\bar{\alpha}_k + \alpha x_k - \beta p_k^N)t_k \geq I_R, \]  

(13)

\[
\sum_{k=1}^{l} [f + c(x_k)^2]t_k \leq I_0, \]  

(14)

\[ t_k \in \{0,1\}, \]  

(15)

where \( \theta \) also represents the power of the central kitchen in risk based selection of products.
After the product portfolios are determined in the supply chain, the risk taken by the central kitchen and the retailer can be obtained respectively as follows:

\[ RE_{C}^{N} = \sum_{k=1}^{l} (w_{k} - v_{C})\sigma_{k}t_{k}, \]  

\[ (16) \]

\[ RE_{R}^{N} = \sum_{k=1}^{l} (p_{k}^{N} - w_{k} - v_{R})\sigma_{k}t_{k}. \]  

\[ (17) \]

Then, the risk taken by the whole supply chain is

\[ RE^{N} = \sum_{k=1}^{l} (p_{k}^{N} - v_{C} - v_{R})\sigma_{k}t_{k}. \]  

\[ (18) \]

The industry quality of products provided by the central kitchen is

\[ \bar{x}^{N} = \frac{\sum_{k=1}^{l} x_{k}D_{k}^{N}t_{k}}{\sum_{k=1}^{l} D_{k}^{N}t_{k}}. \]  

\[ (19) \]

The expected profit of the central kitchen is

\[ E(\Pi_{C}^{N}) = \sum_{k=1}^{l} [((w_{k} - v_{C})(\bar{\alpha}_{k} + \alpha \alpha_{k} - \beta p_{k}^{N}) - f - c(x_{k})^{2}]t_{k}. \]  

\[ (20) \]

Accordingly, the expected profit of the retailer is

\[ E(\Pi_{R}^{N}) = \sum_{k=1}^{l} (p_{k}^{N} - w_{k} - v_{R})(\bar{\alpha}_{k} + \alpha \alpha_{k} - \beta p_{k}^{N})t_{k}. \]  

\[ (21) \]

The expected industry profit is

\[ E(\Pi^{N}) = E(\Pi_{C}^{N}) + E(\Pi_{R}^{N}). \]  

\[ (22) \]

The consumer surplus is

\[ E(CS^{N}) = \sum_{k=1}^{l} x_{k}(\bar{\alpha}_{k} + \alpha \alpha_{k} - \beta p_{k}^{N})t_{k}. \]  

\[ (23) \]

The social welfare is

\[ E(SW^{N}) = E(\Pi^{N}) + E(CS^{N}). \]  

\[ (24) \]

When \( s = C \), risk is taken by the central kitchen and the retailer together. The expected profit of the supply chain from the \( k \)th product is

\[ E(\Pi_{k}^{C}) = (p_{k}^{C} - v_{C} - v_{R})(\bar{\alpha}_{k} + \alpha \alpha_{k} - \beta p_{k}^{C}) - f - c(x_{k})^{2}. \]  

\[ (25) \]

Then the objective of the supply chain is to select product portfolio that would minimize the risk, i.e. volatility of profit, subject to particular constraints as follows

\[ \text{Min} \quad \sum_{k=1}^{l} (p_{k}^{C} - v_{C} - v_{R})\sigma_{k}t_{k} \]  

\[ \text{s.t.} \quad \sum_{k=1}^{l} [(p_{k}^{C} - v_{C} - v_{R})(\bar{\alpha}_{k} + \alpha \alpha_{k} - \beta p_{k}^{C}) - f - c(x_{k})^{2}]t_{k} \geq I_{C} + I_{R}, \]  

\[ (27) \]
\[
\sum_{k=1}^{l} [f + c(x_k)^2] t_k \leq I_0,
\]
(28)

\[t_k \in \{0,1\}.\]  
(29)

After the product portfolios are determined, the risk taken by the supply chain is

\[RE^C = \sum_{k=1}^{l} (p_k^C - v_c - v_r) \sigma_k t_k.\]
(30)

The industry quality of products provided by the central kitchen is

\[z^C = \sum_{k=1}^{l} x_k D_k^C t_k / \sum_{k=1}^{l} D_k^C t_k.\]
(31)

The expected profit of the central kitchen is

\[E(\Pi^C) = \sum_{k=1}^{l} \left[ (p_k^C - v_c - v_r)(\bar{a}_k + \alpha x_k - \beta p_k^C) - f - c(x_k)^2 \right] t_k.\]
(32)

The consumer surplus is

\[E(CS^C) = \sum_{k=1}^{l} x_k (\bar{a}_k + \alpha x_k - \beta p_k^C) t_k.\]
(33)

The social welfare is

\[E(SW^C) = E(\Pi^C) + E(CS^C).\]
(34)

In the following section, a numerical example is used to illustrate the influence of \(\theta\) on product selection, project investment risk of the central kitchen, industry quality and profit, consumer surplus and social welfare.

**A Numerical Example**

After the preliminary investigation, we analyze the investment feasibility of a central kitchen project. Here, \(v_c=2, v_r=3, \alpha=80, \beta=50, f=1000, l=12.\)

The results show that when \(s=N\), the industry quality increases in the bargaining power \(\theta\) of the central kitchen, while the risk taking, profit, consumer surplus and social welfare decrease in \(\theta\). Compared with \(s=N\), \(s=C\) can lead to high industry quality, low risk taking and low profit.

**Conclusions**

In this study, we investigate product portfolio selection of a central kitchen from the perspective of a food supply chain. Firstly, in two scenarios of the supply chain: coordination and non-coordination, mathematical modeling is used to analyze price decisions of the retailers. Secondly, risk based selection models of product portfolios are developed. Finally, a numerical example is used to illustrate the impact of bargaining power of the central kitchen on the risk taking, industry quality, profits and consumer surplus.

The results suggest that both supply chain strategies and the bargaining power of the central kitchen have significant impact on product selection, industry quality, risk, profits and consumer surplus. When non-cooperative Nash equilibrium game is implemented between the central kitchen and the retailer, the stronger the bargaining power of the central kitchen is, the higher the industry quality is, but the lower the risk taking, profit, consumer surplus and social welfare may be. However, compared with non-cooperative Nash equilibrium game, supply chain coordination can lead to high industry quality, low risk taking and low profit.
Acknowledgement
This work was supported by the National Natural Science Foundation of China (71372176, 71390331).

References