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A modelling framework for shelf space allocation of fresh produce at a local retailer

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Abstract

Retailers may gain a competitive advantage through the efficient management of shelf space, which is considered to be one of the most valuable resources in a supermarket. Several mathematical models have in the past been proposed to assist with the allocation of shelf space to the various products on offer. The most basic of these models appeared during the 1960s, but since then several variations, enhancements and improvements to these models have appeared. Products may, however, be classified into different categories according to a variety of characteristics. Considering a product's shelf life, for example, it can be categorised as perishable or non-perishable. Shelf space allocation decisions become more complicated in the area of fresh produce, due to the seasonality of these products, their short shelf lives and freshness-dependent demand. A modelling framework is proposed in this paper which may be used as the basis for practical decision support in respect of shelf space allocation for fresh produce at a local retail outlet.

Key words: Shelf space allocation, Retailing.

1 Introduction

South Africa has a competitive retailing industry. The expansion of this industry during the past two decades may be attributed to factors such as trade liberation after 1994 and extensive recent urbanisation [14]. Five top-performing retailers in South Africa were among the 250 largest retailers in the 2015 Global Powers of Retailing report [13].

Store managers in the retailing industry are faced with complex periodic decisions related to shelf space allocation and display periods for fresh produce. The complexity of these decisions may be attributed to the short shelf lives and seasonality of fresh produce, as well

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as their freshness-dependent demand. A competitive advantage may be gained through the efficient management of shelf space in the fresh produce department of a retail outlet.

The research in this paper forms part of an ongoing project at Stellenbosch University in which the aim is to propose a fresh produce shelf allocation modelling framework and to incorporate this framework into a flexible, user-friendly decision support system which may be used as a practical support tool in respect of shelf space allocation decisions related to fresh produce within the South African retailing industry. The study is performed in collaboration with one of the top five South African retailers, which prefers to remain anonymous. A specific outlet of this retailer has been selected as the focus of a case study demonstrating workability of the decision support tool and underlying modelling framework.

The remainder of the paper is organised as follows. Literature on topics related to perishable products and shelf space allocation decisions in respect of these products is reviewed in Section 2. In Section 3, we propose a modelling framework for fresh produce shelf space allocation at the local retailing partner. Section 4 contains a brief conclusion, and some ideas with respect to possible future work is outlined in Section 5.

2 Literature review

Fresh produce exhibits certain characteristics that make it a unique type of product, but which also complicate decisions related to its inventory control and shelf space allocation. Due to its short shelf life, fresh produce is generally considered a perishable product, a class of products which is the topic of discussion in Section 2.1. Certain notions related to the mathematical modelling of perishable products are discussed in Section 2.2. Two shelf space allocation models which have inspired our proposed modelling framework are finally presented in Section 2.3.

2.1 Perishable products

The thousands of products in a supermarket may be classified into different categories based on a variety of characteristics. Contributing to the earliest shelf space allocation research, Brown and Tucker [5] reportedly partitioned products into three classes based on their responsiveness to changes in the amount of shelf space allocated to them. Products that are sold at a rate that is independent of how much shelf space is allocated to them (such as spices) are classified as *unresponsive products*, whereas products whose sales rates are slightly dependent on shelf space allocation (breakfast cereals, canned food, *etc.*) form part of the class of *general use products*. Finally, *occasional purchase products* are only sold when a large amount of shelf space is allocated to them so as to increase their visibility (sardines and nuts, for example). Classification with respect to product shelf life is often also observed when managing products in a store. Products are then categorised as either perishable or nonperishable.

Typical perishable products are meat, seafood, dairy products, eggs and fresh produce (fruit and vegetables). Perishable products exhibit certain characteristics which may influence shelf space allocation decisions. Compared to nonperishable products, the most prevalent characteristic of a perishable product is its short shelf life [17]. In order to slow down the process of their deterioration, perishable products also require special storage conditions. Deterioration occurs quicker in higher temperatures [16], which is generally avoided by displaying products on refrigerated shelves. Frozen products are not categorised as perishable products, because freezing reduces the deterioration process rate significantly [17].

The quality and variety of perishable products displayed contribute to a customer's perception of the store quality and may be the primary reason why a customer prefers a certain store above another [11]. Fresh perishable products also portray an efficient supply chain and a high demand for the specific products. Often, new perishable products are procured to replenish shelves before all the products on display have been sold. This poses a decision as to whether new and old stock should be displayed together, which is a decision unique to perishable products [11]. Some retailers separate old and new stock, preferring to sell the older products at a discounted price. Products can be sold separately in the same store in order to prevent products of poor quality from affecting fresh ones. Alternatively, older products can be sold from a different retail outlet in a lower income area [10]. Stores which choose not to separate old and new stock do so to minimise administration related to product prices and to minimise the amount of shelf space allocated to a specific product [11].

Other product characteristics that have been identified as contributing toward distinguishing between perishable and nonperishable products include average weekly sales, the coefficient of variation in weekly sales, delivery frequency, case pack size and minimum inventory [17]. Higher weekly sales and less variation in average weekly sales are typically associated with perishable products. The minimum inventory level of perishable products is higher, deliveries of perishable products are made more often and perishable products' case packs typically contain fewer units.

The supply chain of perishable products is referred to as a cold chain, and consists of several processes followed to maintain special conditions from the time of harvest until products reach the end customer [9]. A well-managed, temperature-controlled supply chain is normally associated with a competitive advantage [2]. Although several advanced technologies exist for improving temperature control, factors such as delays in deliveries are difficult to control and negatively influence product quality [1]. An inefficient cold chain leads to waste [9], which is an unnecessary expense that should be avoided as far as possible.

2.2 Mathematical modelling of perishable products

For mathematical modelling purposes, perishable products are generally classified into three categories, namely products with fixed shelf lives, products whose quality decays proportionally over time, or products with random shelf lives [18]. Products with fixed shelf lives have predetermined expiry dates and an entire batch of products (of the same age) perishes at the same time [12]. Medicines and most food items form part of this category [7]. The second category refers to perishable products which decay at a rate that is directly proportional to the amount of the product present (also known as exponential decay). Examples of this category are radioactive materials and chemicals [8]. Perishable products have random shelf lives when the time to spoilage is not known beforehand and differs from product to product. Fresh produce generally forms part of this last category [7].

2.3 The shelf space allocation problem

Several mathematical models have been proposed since the 1960s to assist with the allocation of shelf space at retail outlets. One of the most cited models, proposed by Corstjens and Doyle [6] in 1981, takes into account a product's contribution towards profit, its responsiveness to changes in the amount of shelf space allocated to it (space elasticity), cross-elasticities among products and costs associated with displaying the product. Constraints in this model include the total amount of shelf space available, and upper and lower display size limits per product. The aim of the model is to maximise overall profit as a result of product exposure to consumers. A literature review on the shelf space allocation problem revealed twelve models that are based specifically on the model developed by Corstjens and Doyle. Other models that follow different approaches are, however, also abundant in the literature.

Bai and Kendall [4] proposed a particularly useful model for the shelf space allocation of fresh produce by combining a deteriorating inventory model with a shelf space allocation model. Their assumptions differ from those underlying previous attempts at modelling shelf space allocation in the literature. In previous attempts, fresh produce had traditionally been considered a special class of perishable products, which implies a fixed deterioration rate and that all products have the same value unless they have expired. Bai and Kendall claimed that it is possible to predict the expiry dates of fresh produce, by using advanced cooling technology in the fresh produce supply chain. Their model is built on the assumption that the freshness condition of fresh produce decreases continuously although the value is not entirely lost by the time the products expire. They also assume that the demand for fresh produce depends on the volume and the freshness of the products displayed. Freshness is a consumer measurement of quality. In other models it has typically been assumed that demand depends on inventory as a whole, but due to the scarcity of shelf space, only a fraction of inventory can usually be displayed. In the model of Bai and Kendall, an ordering policy is determined for fresh produce as well as the amount of shelf space to be allocated to each product. They used the generalised reduced gradient method to solve instances of the model. Bai, Burke and Kendall [3] also used a metaheuristic and a hyperheuristic to solve instances of the same model approximately.

Although numerous models have been proposed for both shelf space allocation and inventory control, none of them was developed specifically for fresh produce prior to the model of Bai and Kendall [4]. Only one other similar model appears in the literature. Piramuthu and Zhou [15] proposed an extension to the model of Bai and Kendall in 2013. They drew into question Bai and Kendall's assumption that all the displayed items of the same product are of the same quality. According to Piramuthu and Zhou, items are exposed to varying environmental conditions and therefore advanced technologies should be employed to track individual item deterioration. In contrast to the approach of Bai and Kendall, they modelled demand as a function of both item freshness and allocated shelf space. Furthermore, they computed the effective amount of shelf space allocated to items of a specific product, which is less than the actual allocated shelf space because of the influence of deteriorated items on the product demand. The rest of their model is similar to that of Bai and Kendall.

3 Model development

The local retail partner wishes to gain a competitive advantage by improving operations in its fresh produce department as a result of streamlining decisions related to order quantities, display periods and shelf space allocation. The general nature of operation at an outlet of the local retailer in question is described in Section 3.1. The development of our modelling framework tailored for the specific retailer is presented in Section 3.2, and the model is finally proposed in Section 3.3.

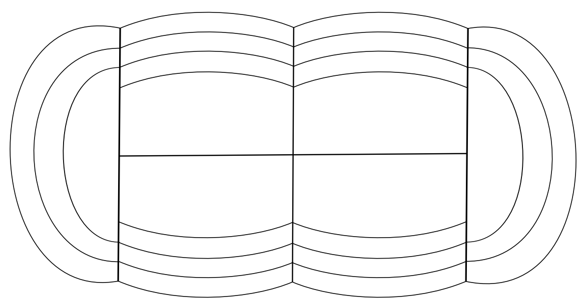

Figure 1: *Top-view layout of a fruit and vegetable boat at the local retailer.*

3.1 The local retailer

As in most retail outlets, the layout of the fresh produce department at the local retail partner varies significantly from those employed in other aisles and shelves. Fresh produce is displayed in a single loose-standing produce display, also referred to as a fruit and vegetable boat, as well as in refrigerated shelves. Figure 1 contains a simplified top-view representation of the fruit and vegetable boat of the outlet considered. The only calculations incorporated in the current shelf space allocation method is the products' rates of sale. Products which sell the fastest are given the most shelf space, and the most popular products are displayed on the semi-circular sides. The products are displayed in compartments, which may be shared by more than one product or may be reserved for one type of product.

With respect to lead time, products are either on a 2-day or a 3-day delivery roster. Some products are delivered from the distribution centre two days after having been ordered and some three days. Product orders are, however, placed on a daily basis. Once the delivery process reaches a steady state, products are delivered whenever necessary. Products are ordered in multiples of a so-called pack size, which is the number of units that are packaged together at the distribution centre.

The local retail outlet identified for case study purposes operates with minimal backroom

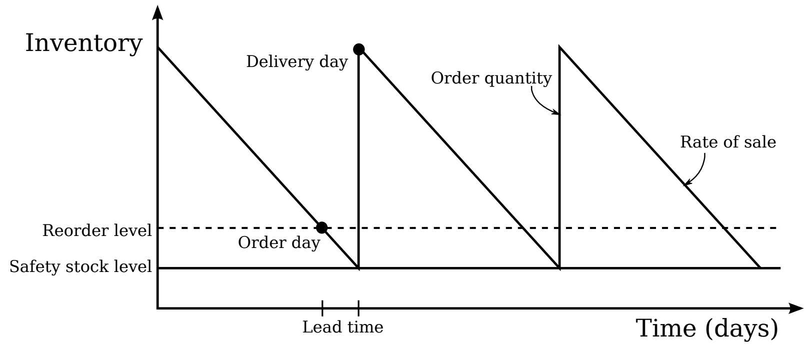

Figure 2: *The inventory control policy adopted at the local retailer.*

inventory. Only 20 percent of the outlet floor space is dedicated to inventory storage, with no space to store additional fresh produce. The entire fresh produce inventory is therefore displayed on the shelves. As in most inventory control systems, the local retail partner incorporates the notion of a safety stock in inventory replenishment decisions. The method is illustrated in Figure 2. In order to prevent stock-outs and increase customer satisfaction, the retailer focuses on placing orders in time so that the safety stock is never compromised.

In Figure 2, the relationship between order quantity, lead time and rate of sale can be seen. Rate of sale describes how the products leave the store, while the lead time and order quantity together describe the replenishment of the products. Shelf space allocation decisions are influenced by this relationship as well as the expected shelf life of a specific product.

The local retailer seeks to gain a competitive advantage by improving stock turnover, eliminating (or at least minimising) product waste and not having too much capital tied up in stock. In respect of inventory control, the main focus is on maintaining the safety stock level, the second most important aspect is the replenishment of products and almost as important as this are decisions related to the actual display of products in the store.

A shelf space allocation model will typically be solved twice per year in order to determine the allocation of the available shelf space for an entire season (summer or winter). The model of Bai and Kendall [4], described in Section 2.3, may be applied to form the basis of decision support for the retail partner. The model is therefore used as a foundation from which we develop a modelling framework tailored for specific use by the retail partner. Some model adaptations are, however, required in order to better represent requirements at the local retailer's outlets. These adaptations are described in the following section.

3.2 Suggested model adaptations

In the model of Bai and Kendall [4], two factors are accounted for that are not present at the local retail outlet, namely backroom inventory and a second, discounted selling period. The associated variables are therefore excluded in the adapted model. Some of the modelling assumptions adopted by Bai and Kendall are also not valid for the local problem. For example, lead time is considered to be zero in the model of Bai and Kendall.

Some expressions in the model of Bai and Kendall will, on the other hand, have to be simplified due to data unavailability constraints and to decrease the complexity of their modelling framework. This section contains a systematic discussion of how we adapted the model of Bai and Kendall to suit the situation at the local retailer.

Instead of calculating the demand for fresh produce from scale parameters, elasticity values, decaying rates and inventory levels, the rates of sale will be used instead. These rates are a good representation of demands for the different fresh produce products. This is the preferred approach because trends exist in the rate of sales data and because all the parameters present in the Bai and Kendall demand formula are not available.

The model of Bai and Kendall does not account for safety stock, but it does allow for the possibility of surplus inventory at the end of a decision cycle. Such surplus inventory should be sold at a discounted price. The local retailer currently does not have this option. Therefore, the incorporation of a surplus inventory value into the model should be replaced by a constant representing the safety stock, which can be determined from the lead time and daily demand of a product.

The other two types of decision variables calculated in the model of Bai and Kendall, procurement quantity and number of facings, are relevant to the local retailer. The number of facings will, however, be taken as the number of product units allocated to a compartment of the fruit and vegetable boat — not only the number entirely visible to the customer, as the name might suggest. The number of facings will, however, be equal to the sum of the procurement quantity and the safety stock, because there is no backroom inventory. The procurement quantity will be the quantity ordered from the retailer's distribution centre. The quantity must be in multiples of the pack size, as mentioned. To account for this requirement, an additional constraint should be added to the model.

Due to the shelf layout of the fresh produce department at the local retailer's outlets, the total shelf space available has to be measured in number of compartments. The amount of shelf space required for a facing of a product unit will then be taken as the portion of a compartment taken up by one item (one divided by the number of items that fit into a compartment).

We have confirmed that the selling prices (neglecting the use of discounted selling prices), unit costs and fixed costs are available from the local retailer. Data on product shelf lives, and lower and upper bounds on the number of product facings are also available. A simplified formula will be used for determining the holding cost during a decision cycle at the local retailer. Only one type of period occurs during each decision cycle at the local retailer, as opposed to the normal period and discounted period in the model of Bai and Kendall [4]. The holding cost per decision period may be determined from the average inventory cost and the acquisition cost per product.

After affecting all these model adaptations, the total profit can still be calculated as the sum of all the individual product profits. The objective of the model for the local retailer will remain the same as that of Bai and Kendall. The local retailer does, however, not merely want to make as much profit as possible — it also values customer satisfaction. Because customer satisfaction is not easily measured, the way in which it will be accounted for in the model will vary from outlet to outlet, based on customer segmentation. For example, a retail outlet in a neighbourhood with many school children should be able to provide for weekly purchases of lunchbox snacks put together by mothers on Sunday evenings. Customer segments of other retail outlets may, on the other hand, exhibit a need for specific products to be sold together.

3.3 Model formulation

As mentioned, the objective in our model is to maximise the overall profit as contributed by the individual product profit functions. Let $\mathcal{P} = \{1, \ldots, |\mathcal{P}|\}$ be the set of fresh produce products to be displayed at the outlet, and define the decision variable q_i as the order quantity of product $i \in \mathcal{P}$ for a decision cycle.

Let d_i denote the average daily demand for product $i \in \mathcal{P}$. From Figure 2, the expression for the length of the decision cycle is deduced as a function of the order quantity and is represented by $T_i = q_i/d_i$ for all $i \in \mathcal{P}$. Let L_i denote the lead time of product $i \in \mathcal{P}$. Then $s_i = L_i d_i/2$ is the safety stock level of product $i \in \mathcal{P}$. Furthermore, let a_i denote the acquisition cost of product $i \in \mathcal{P}$ and let $h_i = a_i(\frac{q_i}{2} + s_i)$ be the holding cost of product $i \in \mathcal{P}$ during a decision cycle. The number of items of product $i \in \mathcal{P}$ displayed on the shelves may therefore be denoted by $f_i = q_i + s_i$.

In addition, let the characteristics of product $i \in \mathcal{P}$ be denoted by p_i (the selling price), o_i (the fixed ordering cost), e_i (the amount of shelf space taken up by one unit of the product), ℓ_i and u_i (the lower and upper limits on the number of product facings), t_i (the expected shelf life), and k_i (the pack size). Furthermore, let S denote the total amount of shelf space available and let c_s be the cost of shelf space per unit of space. Then the average profit of product $i \in \mathcal{P}$ per unit time may be expressed as $P_i = \frac{1}{T_i}[(p_i - a_i)q_i - o_i - h_i] - c_s f_i e_i$ and the objective of the model is to

$$\text{maximise} \quad \sum_{i \in \mathcal{P}} P_i(q_i)$$

subject to the constraints

$$\begin{aligned}
\sum_{i \in \mathcal{P}} f_i e_i &\leq S, && (1)\\
\ell_i \leq f_i &\leq u_i, \quad i \in \mathcal{P}, && (2)\\
q_i &> s_i, \quad i \in \mathcal{P}, && (3)\\
0 < T_i &\leq t_i, \quad i \in \mathcal{P}, \text{ and} && (4)\\
\frac{q_i}{k_i} &\in \{1, 2, 3, \ldots\}, \quad i \in \mathcal{P}. && (5)
\end{aligned}$$

Constraint (1) ensures that the allocated shelf space does not exceed the available amount of space, while constraint set (2) limits the number of facings allocated to product $i \in \mathcal{P}$ between its minimum and maximum values. Constraint set (3) furthermore ensures that the order quantity is more than the safety stock level, while constraint set (4) restricts the length of the decision period to be shorter than the expected product shelf life. Constraint set (5) finally ensures that the order quantity is a multiple of the pack size.

4 Conclusion

Upon reviewing the literature related primarily to perishable products, a modelling framework for the shelf space allocation of fresh produce at a local retail partner was proposed in this paper. This framework was based on a model by Bai and Kendall [4], but included several adaptations to better represent the situation experienced at the local retail partner. The objective of the model is to maximise overall profit subject to a number of constraints developed according to the situation at the local retail partner.

5 Further work

Developing the modelling framework here in order to portray the operation of the retail partner more realistically is an ongoing process. The model proposed is currently still in a basic form, and more detail will be added as our understanding of the requirements of and processes followed by the local retail partner deepens over time. After a sufficient level of model detail has been achieved, the modelling framework will be verified and validated in the context of the case study outlet mentioned in Section 1, using real data.

It is envisaged that the modelling framework may eventually be incorporated into a computerised decision support system. Although the modelling framework and decision support system will be developed specifically for the local retailer, it is anticipated that many of the requirements and specifications identified at the case study retail outlet are commonly experienced at local supermarkets. The proposed framework and system are therefore expected to be generic to some extent.

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