1. Introduction

1.1. Problem description

Recent years have witnessed increased interest on the part of retail and manufacturing companies in investigating innovative pricing strategies in order to boost their operations and bottom line. In the past, e.g. grocery, drug or fashion apparel stores would fix a product’s price over a relatively long time period and mainly focus on their inventory management in order to obtain a better match between supply and demand. This static pricing strategy was mainly due to the lack of information about their customers’ taste, willingness to pay and the fact that high transaction costs - so-called menu costs - were associated with changing prices. Driven in large part by advances in information technology and e-commerce, a more sophisticated approach of changing a product’s price found its way into retail and manufacturing industries. Here, the seller changes prices dynamically over time, based on factors like demand information, supply availability, production schedules and the time of sale. With the goal of balancing demand and supply, dynamic pricing methods were first applied by industries where the short term capacity is hard to change, such as airlines, hotels, cruise ships, etc. (see Talluri and van Ryzin (2004) for more detail). Nowadays, the business model of dynamically changing the prices of a product is an important revolution in retail and manufacturing industries and is already strongly practiced by e.g. Dell Computers and Amazon. There is growing understanding that both pricing as well as replenishment decisions are essential for increasing a firm’s profitability and thus should be coordinated. Nevertheless they are traditionally mostly determined by separate functional areas of a company’s organization: the marketing department sets prices, the market determines the quantity demanded, and the logistics unit produces the quantity demanded. However, research work such as Whitin (1955) has already shown that the simultaneous determination of price and ordering or production quantity can yield substantial revenue increases. The coordination of price decisions and other aspects of the supply chain such as production and distribution is thus not only useful, but also essential. Coordinating these decisions means optimizing the system rather than its individual elements and not only potentially increases profits but also reduces variability in demand or production, resulting in more efficient supply chains. Enabled by powerful IT systems that can store and estimate thousands of demand models and compute integrated optimal policies today, reengineering efforts are being initiated in many companies to eliminate the organizational barriers between distinct functional areas within the same enterprise by creating new entities with such designations as ’Revenue Management’, ’Dynamic Pricing’ or ’Smart Pricing’.
1.2. Research intention

Looking at the state-of-the-art methodological literature, we find that relevant work divides into two rather distinct streams: The operations oriented stream (see chapter 2) and the marketing oriented stream (see chapter 3). Eliashberg and Steinberg (1993) give a nice comparison of the two streams: Operations management (or production management) deals with organizing and controlling the direct resources to produce the goods and services provided by an organization to customers. Marketing in contrast deals with the process of planning and executing pricing, promotion and distribution of goods and services in order to create exchanges that satisfy individual and organizational objectives. The interface between marketing and operations management is being recognized as a legitimate research domain and has experienced increased emphasis in the past. Nevertheless, as already stated above, in most firms the marketing and production functions are organizationally separate. A possible explanation could be that marketing is typically concerned with revenue maximization by setting prices and advertising policies. Here, relatively realistic demand models are being used, which for example account for intertemporal demand correlations by incorporating both current price and reference price, which is formed on the bases of past purchases. However, they underlay a rather simplistic cost structure which does not account for supply chain management interactions by e.g. assuming stationary variable costs. Operations management is typically concerned with cost minimization, meaning that production is required to produce the needed output at minimum costs. Thus rich cost models, well describing a firm’s possible cost structure, are being used. Costs are assumed to be non-stationary, which means that they can vary over time and fixed costs can be in included in the model. Furthermore, production decisions are integrated in the model (not only pricing but also inventory decisions), which is not the case in purely marketing-orientated work. The limitation of these models is that they rely on rather simplistic demand assumptions. Demand is, for example, modeled as a function of the current price only. In any case, both prevalent research streams consider only a partial picture of the relevant system. Typically, a coordinated decision-making problem results in better performance of the system. The magnitude of the improvement depends on how the objective functions are defined for the two separate departments and which department is assumed to act first.

Identifying this prevailing research gap leads us to address the problem of simultaneously determining a pricing and inventory replenishment strategy by combining these two literature streams described above: we want to take the rich and non-stationary cost models commonly used in operations research and combine them with demand models, which account for intertemporal demand correlation and so far have been mainly applied by marketing. Both price and ordering quantity are to be dynamically adjusted according to the prevailing inventory, the consumers’ willingness to pay and the remaining length of the finite selling horizon. The integration of reference price effects with inventory control models has not been reported so far in literature. Hence, by developing such an integrated inventory control and pricing model, we will probe into the issue of whether using a reference price model to describe demand will significantly increase the benefits of integrating marketing and logistic
decisions and when it makes sense to apply such models. In this thesis we generally focus on linear demand models, which are detrended and seasonally adjusted. Furthermore, we only consider monopolistic pricing, ensuring mathematical tractability. These assumptions are not unrealistic, because price optimization by a firm is only possible in imperfect markets. In the case of monopolistic competition a firm faces a range of prices where competitors do not react. The linear demand function is a local approximation conditional on competitor's prices which remain unchanged if the price stays within this permissible range (see Phillips (2005), Chapter 1). Not only are these models important in retail, where price-dependent demand plays a significant role, but also in manufacturing environments with a different underlying cost structure, in which production and distribution decisions can be complemented with pricing strategies in order to improve the firm's bottom line. Within this work we are going to examine how the additional dynamics affect an optimal policy and whether variants of a simple policy such as a base-stock-list-price policy still hold in such a setting. Furthermore, we are going to find conditions under which it is possible to show analytically the existence of a unique optimal solution. We want to state here that the main focus of this dissertation is a mathematical analysis, which justifies that most problem definitions are taken from literature. However, we will still try to motivate an economic understanding of dynamic market models and supply chain decisions, wherever possible. Via numerical simulation we shall explore the size of potential benefits of such models, as well as how optimal policies evolve over time and how optimal solutions vary with changes in the model parameters.

1.3. Structure of the thesis

We will here give a short outline of the structure of this thesis. Chapter 2 and chapter 3 are devoted to a brief review of the current state-of-the-art literature, relevant to this work, as well as some minor new results. The main new results will be presented in chapters 4 to 6.

Chapter 2 gives an overview of the models used in operations research so far. For didactical reasons we first introduce the theory of solely inventory control models in section 2.2, which are then expanded to the multi-period setting in section 2.3. For each of the two sections, we first focus on one-period models, which are then extended to the multi-period setting. We not only present the well known critical fractile solution for the classical lost-sales version of the newsvendor problem, but also adapt the solution to the backlogging case including inventory holding and backlogging costs. Furthermore, the base-stock-list-price policy is introduced in chapter 2 and shown to be optimal for the most commonly used demand models. We also provide a steady-state solution for the joint pricing and inventory control model in subsection 2.3.3, which has not been seen in literature so far.

Chapter 3 is devoted to marketing models that mainly focus on price optimization. The concept of reference price effects is introduced and structural properties of the optimal solutions are given for loss-neutral and loss-averse customer behavior. We show by a numerical example that for loss-seeking customer behavior, the optimal solution does not converge and thus a cycling pricing policy is optimal. As in chapter 2, we provide a steady-state solution
for the case of non-zero proportional ordering costs, which is an extension to the solution found by Popescu and Wu (2007).

In chapter 4 we combine the two models presented in chapter 2 and chapter 3 and introduce an integrated model including reference price effects, which will lay the foundation for the rest of this work.

Chapter 5 is dedicated to an analytical analysis of the model introduced in chapter 4. This chapter consists of three parts: the one-period case, the two-period case and the multi-period case. For the one-period case in section 5.1, we can prove the optimality of a base-stock-list-price-policy and provide implicit solutions for the optimal price and stocking quantity with respect to reference price under very general conditions. However, it is not so easy to extend this property to a multi-period setting. By integrating the solution of the one-period case into section 5.2, we find that for the linear demand a base-stock-list-price policy also holds for the two-period case. The mathematics behind this result is extensive and tedious, which is why we chose to present purely the technical results in the appendix A. In section 5.3 we prove the optimality of a base-stock policy under rather restrictive assumptions. Adjusting the proof technique for a more general setting is definitely worthwhile considering for further research.

Chapter 6 is devoted to simulations and numerical investigations. By the means of numerical optimization, in section 6.1 we extend the results from section 5.2 to the multi-period setting for the special case of linear demand and loss-neutral customer behavior. We furthermore investigate the influence of different demand distributions and coefficients of variations. In section 6.2, we study the potential increase of profit by simultaneously determining optimal prices and stocking quantities compared to a sequential optimization, where prices are set first by the marketing department of a company and then the production unit decides on the optimal stocking quantity, without being able to change prices. In section 6.3, we provide some numerical results for loss-averse and loss-seeking customer behavior and the case of non-zero fixed ordering costs.

The last and concluding chapter 7 of this thesis provides an overview of conclusions and recommendations for further research.