THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ECONOMICS

# MULTIMARKET CONTACT AND COLLUSION IN THE BETA CAROTENE AND THIAMINE CARTELS: LESSONS FROM ASYMMETRIC AUCTION THEORY

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SPRING 2010

A thesis
submitted in partial fulfillment
of the requirements
for baccalaureate degrees
in Mathematics and International Studies
with honors in Economics

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**Abstract**

It is rare for a cartel that employs a market share allocation scheme to allow a member firm to gain market share at the expense of another member. Nevertheless, this was the case when Hoffman-La Roche, the leading producer of the vitamin beta carotene, accommodated the growth of the smaller firm BASF at direct cost to its own market share. Using a novel extension of an asymmetric first-price auction model, it is found that the Roche-BASF accommodation cannot be explained by single-market contact alone. Moreover, it is found that multimarket contact with the thiamine industry may explain Hoffman-La Roche's unorthodox behavior. Applications to anti-trust enforcement are discussed.

# Contents

**Acknowledgments**

Sincere thanks to Dr. Marshall for his insightful and challenging feedback throughout the entire process. Without his guidance, this thesis would have never come into being. Sincere thanks also to Dr. Shapiro, whose direction helped shape the project invaluably.

# CHAPTER 1

# Introduction

## 1.1 Vitamins Background

### 1.1.1 Biological Importance

Vitamins are essential molecules necessary for the growth and maintenance of living organisms. Functioning as enzymes, coenzymes or precursors to coenzymes, vitamins are essential to the regulation of metabolic activity in both animals and humans. Human needs for vitamins are complex - some can be synthesized by the body, sometimes in response to environmental stimulus such as sunlight, while others must be ingested from outside sources, such as foods or dietary supplements (Medline Plus, 2010). Lack of essential vitamins can cause a variety of chronic diseases in both humans and animals, so a balanced intake is essential to healthy growth and development. While balanced intake of vitamins is possible from diet alone, modern diets consisting of heavily processed foods often are deficient in some vitamins - these must be supplied by either supplements or by the fortification of foods. Fortification of foods and cosmetics and the production of supplements are multi-million dollar industries (Connor, 2001).

### 1.1.2 Industrial Production

#### 1.1.2.1 Feed-grade

Feed-grade vitamins are some of the most important types of vitamins by turnover. Feed-grade vitamins are commonly blended with proteins and minerals in set proportions to form so-called "premixes," which are then added as supplements to animal feed. While cattle, sheep and other ruminants can synthesize many vitamins from grains within their first stomach, animals with a single stomach must ingest vitamins as part of their diet, and in artificial environments, are reliant on pre-mixes to meet their nutritional needs (Connor, 2001). Even for ruminants, farm-raised animals have non-trivial vitamin requirements due to the stress from artificial confinement as well as the loss of vitamins in products such as milk (DSM, 2010b). Premixes therefore are precisely engineered to match the specific dietary requirements of animals at various times in their development, resulting in efficient growth with better meat production (DSM, 2010b). For all vitamins with the

exception of C, B1 (thiamine), and B6 (pyridoxine), animal feed is the largest market (Connor, 2001). For example, riboflavin usage from 1990-1998 was 60% for animal feed, 15% for human food consumption, and 25% for pharmaceutical usage (Connor, 2001).

#### 1.1.2.2 Production for Human Use

Vitamins produced for human use differ greatly from those produced for animal feed. Vitamins for human use must meet higher standards established by separate regulatory bodies - in the United States for example, vitamins for human use must meet guidelines established by the U.S. Pharmacopeia (U.S. Pharmacopeia, 2010). As a result of the enhanced quality, pricing for human grades, labeled 'USP', is often higher than those for animals. Vitamins produced for human use are used for the fortification of foods, the production of vitamin supplements, as well as for cosmetics, such as skin creams, with the majority of the human vitamin market concentrated in foods (Connor, 2001).

### 1.1.3 Manufacturing Technologies

Modern production techniques are distinguished into two categories: production by chemical synthesis and production by biotechnologies. As synthetic techniques produce high-quality products and offer economies of scale, they have been historically favored over natural harvesting methods (Connor, 2001). Nevertheless, modern biotechnologies have challenged the supremacy of chemical synthesis in many vitamin markets. One of the most prominent biochemical techniques is fermentation, which harnesses the natural metabolism of bacteria to produce vitamins in a one-step process. Genetically engineered bacteria are often used in this process, and the species of bacteria can be fine-tuned to match the production requirements of specific vitamins (Shimizu, 2001). In the 1990s, vitamins E, B2 (riboflavin), B5, H (biotin), and D3 were all produced via bioengineering techniques (Connor, 2001). Nevertheless, chemical synthesis is still a competitive production method for many vitamins for which bioengineering pathways have not been discovered.

### 1.1.4 Market Characteristics, 1989-2002

Throughout the late 1980s and 1990s, the vitamins market was characterized by maturity. In fact, in the 1990s, the average growth rate for all vitamin markets was only 2.4% (Connor, 2001). Nevertheless, while the growth rate was small, due to collusion and the entry of outsider firms, vitamin prices changed greatly over the 1990s (see Figures 1.1 on page 13 and 1.2 on page 15).

Each vitamin market has unique characteristics. First, families of vitamins have different costs of entry and production, which lead to different barriers to entry. Due to the costly investment required to develop synthetic processes as well as obstacles created by existing patents barriers to entry are high in many vitamin markets (Connor, 2001). The beta carotene market in the 1990s - which was controlled almost exclusively by Hoffman-La Roche and BASF - is a good example of this type of market. Some markets, however, have much lower barriers to entry - for example, the thiamine market in the 1980s and 1990s, in which Chinese entry was strong enough to depress prices by over thirty percent over thirteen years (Bernheim, 2002) [1].

Secondly, within each family of vitamin products each grade of vitamin is priced differently. As human-grade vitamins must comply with much higher quality standards, they can command a much higher price than feed grade, by even as much as 1600% (Connor, 2001).

### 1.1.5 Market Players, 1989-2002

The vitamins market in the 1990s was dominated by the market leader Hoffman-La Roche, with BASF the second-largest firm in many markets. Japanese firms such as Takeda and Daiichi were also major players in this time period. Smaller Chinese firms began entering several vitamins markets, including thiamine and riboflavin, in the late 1980s and the 1990s, eventually commanding a dominant market share in those groups (The Commission of the European Communities, 2001). A

[1] Bernheim (2002) was submitted as exhibit number 243 in In re: Vitamins Antitrust Litigation, case No. 99-0197 (TFH) filed in the District Court of the District of Columbia. The document was originally obtained through a request by Bates White L.L.C. to the law clerk to Chief Judge Thomas F. Hogan. The document was made available based on D.C. Local Civil Rule 79.2 and the United States District Court for the District of Columbia's policy of not retaining exhibits that are admitted into evidence at trial in civil cases. The price data used in this thesis was reversed engineered from the graphs in the document and is used here with permission.

brief introduction to each firm or groups of firms appears below:

#### 1.1.5.1 Hoffman-La Roche

Headquartered in Basel, Switzerland, Hoffman-La Roche was the largest player in vitamins in the 1990s and continues its dominance today. Hoffman-La Roche (also known as Roche), initially found success in the synthesis of Vitamin C in 1933, and expanded later to Vitamins A and E (Hoffman La-Roche, 2010). By 1970, Hoffman-La Roche had a global market share of around 50 to 60 percent of the global market, a position that was challenged in the late 1980s and 1990s by Chinese entry (Connor, 2001). Nevertheless, despite Chinese entry, from 1987 to 1998, Roche had the largest average worldwide vitamins market share, at 46% (Bernheim, 2002).

#### 1.1.5.2 BASF AG

Headquartered in Ludwigschafen, Germany, BASF AG is a leading producer of chemicals and significant player in the vitamins market as well. Together with Hoffman-La Roche, BASF controlled the majority of the vitamins market in the 1960s and 1970s, dominance that continued throughout most of the 1990s, when BASF posted a 17% share in the worldwide vitamins market (Bernheim, 2002). In 1989, although the vitamins division continued to post profits, the greater BASF faced a sharp decline in sales (Connor, 2001). After laying off large numbers of workers, divesting properties and increasing its emphasis on health and nutrition products - including vitamins - BASF later returned to profitability, with profits reaching around 8% of sales in 1997 (Connor, 2001).

#### 1.1.5.3 Takeda

Headquartered in Osaka, Japan, Takeda is the largest research-based pharmaceutical company in Japan (Takeda, 2010). In addition to introducing new pharmaceutical products, Takeda aggressively expanded its market shares in a number of vitamins throughout the 1990s. As a result of

this expansion, in some vitamins, such as thiamine, Takeda became the single-largest firm in the market (Bernheim, 2002). Overall, however, Takeda was still comparatively small; from 1987 to 1998, Takeda controlled only 7% of the worldwide vitamin market (Bernheim, 2002).

#### 1.1.5.4 Chinese Manufacturers

Beginning in 1980s, small Chinese manufacturers began entering several vitamin markets. In some markets, Chinese entry was driven by innovations in the production processes, as in the introduction of a new fermentation technology in the vitamin C market (Bernheim, 2002). In most cases, however, Chinese companies were also heavily subsidized by the Chinese central government (Connor, 2001). Around 1994, Chinese pressure had grown so strong that Roche and other traditional market leaders were forced to lower their prices to remain competitive with Chinese producers, and, in some cases, dissolve the cartels that had been formed (The Commission of the European Communities, 2001). From 1987 to 1998, Chinese producers commanded an average aggregate worldwide market share of 8% (Bernheim, 2002).

### 1.1.6 Selected Vitamins

#### 1.1.6.1 Thiamine (B1)

Thiamine is an important vitamin for growth and metabolism. In the body, it is found predominantly in coenzymes which metabolize carbohydrates, and may have important roles in insulin synthesis and nerve impulse transmission (Bernheim, 2002). It also has a role in enzyme systems which are involved in decarboxylation and transkeletalation (Linus Pauling Institute, 2010b). As B1 is incapable of being synthesized by the body, it must be ingested on a regular basis from plant or animal sources (Connor, 2001). Thiamine deficiency results in severe symptoms, including beriberi - a disease of the peripheral nervous system - as well as Wenicke-Korsakoff Syndrome, characterized by lesions in the central nervous system (Itokawa, 1996).

**Commercial Function**

Thiamine is an important vitamin used in the fortification of breads, cereals, pastas and whole grains (New York Times, 2010). Thiamine is also used in some injection solutions, and is included in small volumes in premixes (Connor, 2001 and Bernheim, 2002). Approximately 46% of thiamine produced is used for feed, in comparison to 22% for food and 32% for pharmaceuticals (Connor, 2001).

**Production Process**

The dominant method of production of thiamine is chemical synthesis. As this process uses ethylene cracking[2], it is produced by similar synthetic pathways as those that produce vitamins A, E and niacin (Bernheim, 2002).

**Global Market**

While thiamine turnover is small (see Table 2.1 on page 27) , the vitamin is an essential component of many premixes and as result, is an important vitamin in the animal feed business. Throughout the 1990s, the global market was dominated by Roche and Takeda, with a combined share of 80% in 1988 (Bernheim, 2002). BASF was also a minority player in the market until 1989, when it exited thiamine production and entered into a 5-year supplier agreement with Roche, later extended to last until 1998. From 1989, Chinese producers using low-cost production technologies posted dramatic gains in market share, expanding from 12% share in 1988 to 40% by 1994 (Bernheim, 2002).

#### 1.1.6.2 Beta carotene

A member of the carotenoids[3] family, beta carotene is a provitamin for Vitamin A - an important molecule involved in the synthesis of glycoproteins. Deficiencies of Vitamin A can result in serious disorders including abnormal bone development and xerophthalmia, as well as disorders of the reproductive system (National Institutes of Health, 2010). Beta carotene is also a strong antioxidant, neutralizing cancer-causing free radicals and possibly helping extend mental health in

[2]Ethylene cracking uses steam at high temperatures to break hydrocarbons into smaller molecules (Zimmerman and Walzl, 2010)

[3]Carotenoids are highly pigmented, fat soluble molecules such as beta carotene, canthaxanthin and astaxanthin

men (Bakalar, 2007).

Beta carotene is found naturally within orange vegetables such as carrots, sweet potatoes, squash and apricots, as well as within some green vegetables, including spinach and green pepper (PR Newswire, 1989).

**Commercial Function**

Beta carotene has a variety of commercial functions. First, it is used as a natural colorant for orange-tinted baked goods, beverages and dairy products (DSM, 2010a). Secondly, beta carotene is used a source of Vitamin A in pharmaceutical products (Miller, 2001). While Vitamin A itself can be toxic in high dosages, excess beta carotene is not toxic, making it an safe additive to foods (Linus Pauling Institute, 2010a). As a result, beta carotene is often added to food and pharmaceutical products, as well as animal feed to a marginal extent.

**Production Process**

Throughout the 1990s, beta carotene was almost exclusively produced via chemical synthesis (Bernheim, 2002). Throughout the 1990s, Roche and BASF were the sole producers of beta carotene, implying that beta carotene at that time had high barriers to entry (Bahner, 1993).

**Global Market**

Market turnover is presented within Table 2.1 on page 27. As with the other carotenoids, throughout the 1990s, Roche and BASF were the only two major players in the market (Bernheim, 2002).

#### 1.1.6.3 Astaxanthin

Like beta carotene, astaxanthin is a member of the carotenoids family. Astaxanthin functions as natural antioxidant, and is thought to be up to 10x more powerful than beta carotene (Algatech, 2010). Astaxanthin occurs naturally in many seafoods, included salmon, trout, shrimp, crabs and lobster (Bernheim, 2002).

**Commercial Function**

As a recently characterized carotenoid, in the U.S., astaxanthin was only approved for use in

animal nutrition products in 1995 (Bernheim, 2002). Astaxanthin was first approved for human products in 1999 (Cyanotech, 2010).

**Production Process**

In chemical synthesis, astaxanthin can be produced via the oxidation of canthaxanthin or from a common intermediate (Bernheim, 2002). Astaxanthin can also be produced from algae in aquaculture, a predominant method of production today (Cyanotech, 2010).

**Global Market**

In comparison with other markets, the market for astaxanthin was quite small during the 1990s, amounting to only $1,380,737 in turnover over 5.5 years (Bernheim, 2002). During this period, Roche enjoyed close to a monopoly on the production of astaxanthin.

#### 1.1.6.4 Canthaxanthin

As with astaxanthin, canthaxanthin is a strong antioxidant and natural colorant (Bernheim, 2002). Canthaxanthin is found naturally in some mushrooms, algae and crustaceans (European Commission: HCP Directorate-General, 2002) .

**Commercial Function**

As a carotenoid, canthaxanthin is used to provide color to white-meat poultry, as well as fish raised under aquaculture (U.K. Food Standards Agency, 2010). In addition, canthaxanthin is used to color foods directly (European Commission: HCP Directorate-General, 2002).

**Production Process**

Canthaxanthin is produced via chemical synthesis. Initially, canthaxanthin was produced by the oxidation of beta carotene, however in 1994, Roche and BASF introduced new technologies to produce canthaxanthin from a 15-carbon intermediary (Bernheim, 2002).

**Global Market**

Canthaxanthin turnover in the United States over 5.5 years was $54,927,563 or approximately $9,986,820 per year. As with the other carotenoids, the primary players within the market were Roche and BASF (Bernheim, 2002).

## 1.2 Cartel Background

### 1.2.1 The Vitamins Markets As Suitable for Price Fixing

In late 1980s and into the 1990s, many of the markets for vitamins fulfilled many of the ideal characteristics for collusive markets according to collusion theory.

First, the markets had high concentrations of producers, a condition which facilitates oligopolistic conduct (Stigler, 1964). In fourteen of the major vitamin markets, the top three producers had an average of a combined 59% market share, and 11 out of these markets, the Herfindhal Index was above 1800, indicating a highly concentrated market in which collusion is likely (Connor, 2001). In some markets - such as beta carotene - there were even only 2 producers in the entire market (The Commission of the European Communities, 2001). Roche was a market leader in many of the markets, making it natural for Roche to take the role as cartel leader.

In addition to having a high concentration of producers, the markets also had regular information about list prices, a condition which deters cheating in a cartel (Porter, 2005). In the United States, the *Chemical Marketing Reporter*, a weekly trade publication, published (and continues to publish as the *Chemical Market Reporter*) weekly list prices for a wide variety of vitamins. The reporter also documented capacity expansions and new plants by the colluding members (Chemical Marketing Reporter, 1993). This information would have aided in the detection of cheating by member firms, encouraging collusion.

Finally, collusion in most of the vitamins markets was facilitated by high barriers of entry. As discussed previously, the engineering expertise required to produce vitamins is substantial, and some techniques are protected under patent and therefore unusable. While entry by new competitors was not impossible, and indeed, some vitamins markets experienced disruptive entry by lower-priced competitors, competition was inherently limited by this structural barrier (The Commission of the European Communities, 2001).

### 1.2.2 The Global Vitamins Cartels

#### 1.2.2.1 Overview

Beginning in the 1980s, the major vitamin producers began organizing what would become one of the largest ever ring of cartels. Spearheaded by a highly profitable collusion in vitamins A and E, within several years, collusive agreements had been established within 12 major vitamin markets (The Commission of the European Communities, 2001). The arrangements, coordinated and enforced by the leader Hoffman-La Roche, lasted in some cases up to 11 years, even despite ongoing anti-trust investigations in the latter years. Ultimately, the vitamins cartel was fortuitously discovered by U.S. authorities, and the details of the cartel mechanisms described in depth in multi-million dollar court cases in the United States and Europe (Connor, 2001).

In many markets, cartel arrangements were successful in raising prices and generating unprecedented profits. By 1997, Roche's Vitamins and Fine Chemicals Division was posting an incredible 18.5% profits of revenue (Connor, 2001). Although ostensibly insisting that price increases were due to changes in demand, capacity, exchange rates and factor inputs, in reality none of these factors sufficiently explain the indicated price increase (Bernheim, 2002). Over the course of the Vitamin A cartel, for example, the price of producing Vitamin A ranged from $15.37/kg to $15.60/kg, while its list price leapt from $25.40 to $45.62 (Bernheim, 2002).

The success of the cartels was due to both their size and precise reporting systems. All told, 18 manufacturers of vitamins were involved in at least one cartel, with the largest market players Hoffman-La Roche, BASF and Rhone Poulenc in collusion in almost all of the vitamin markets (Connor, 2001). With the support of the largest producers, the firms often had market power to punish deviations; Roche and BASF, for example, had average combined shares of 54% of all vitamins markets from 1987 to 1998 (Bernheim, 2002). Also, the reporting structure was sophisticated and afforded firms comprehensive information about other firms' sales. While coordination structure varied from cartel to cartel, in general at least three levels of organization were involved, including yearly top-level meetings with executives, yearly meetings with vitamins division presidents and global marketing managers and finally quarterly meetings between regional managers,

who exchanged sales data (Connor, 2001). Oversellers were traditionally required to compensate undersellers by buying products at cost (Connor, 2001).

#### 1.2.2.2 Cartel Agreements without frozen market shares or with firm exit

During the period of collusion, there arose several unique cartel arrangements. While cartel market shares are traditionally frozen at the beginning of a cartel, all of carotenoid markets (beta carotene, astaxanthin and canthaxanthin) show accommodation of a smaller firm's growth at the expense of shares of a larger firm. Moreover, the thiamine market shows exit of a former producer, which henceforth becomes a re-seller of thiamine. Each of these cartels displays unique characteristics which suggest multimarket contact.

#### 1.2.2.3 Thiamine cartel

According to the EC decision, the thiamine cartel ostensibly lasted from 1991 to 1994, eventually ending under competitive pressure from low-cost Chinese manufacturers. The major firms in the cartel were Roche, Takeda and BASF, with 1989 global market shares of 44%, 31% and 13%, respectively (The Commission of the European Communities, 2001). During the duration of the cartel, the cartel was able to successfully raise the price of thiamine in the European Community from 27 ECU/kg to 32 ECU/kg, however, as a result of competition from Chinese firms, prices returned to pre-cartel levels and continued to drop even lower after the cartel was ended (The Commission of the European Communities, 2001). The timeline of important events in the B1 cartel is presented in Figure 1.1 on the following page, with a historical market shares for Roche and BASF appearing in Figure 1.2a on page 14.

The thiamine cartel was marked by a unique arrangement between Roche and BASF. According to the EC decision, in 1989, BASF exited production of thiamine and entered into the thiamine market as a reseller for Roche. During the duration of its 5-year supply contract, BASF continued to appear as a "bidder" at procurements, however, all of its contracts would be fulfilled by Roche

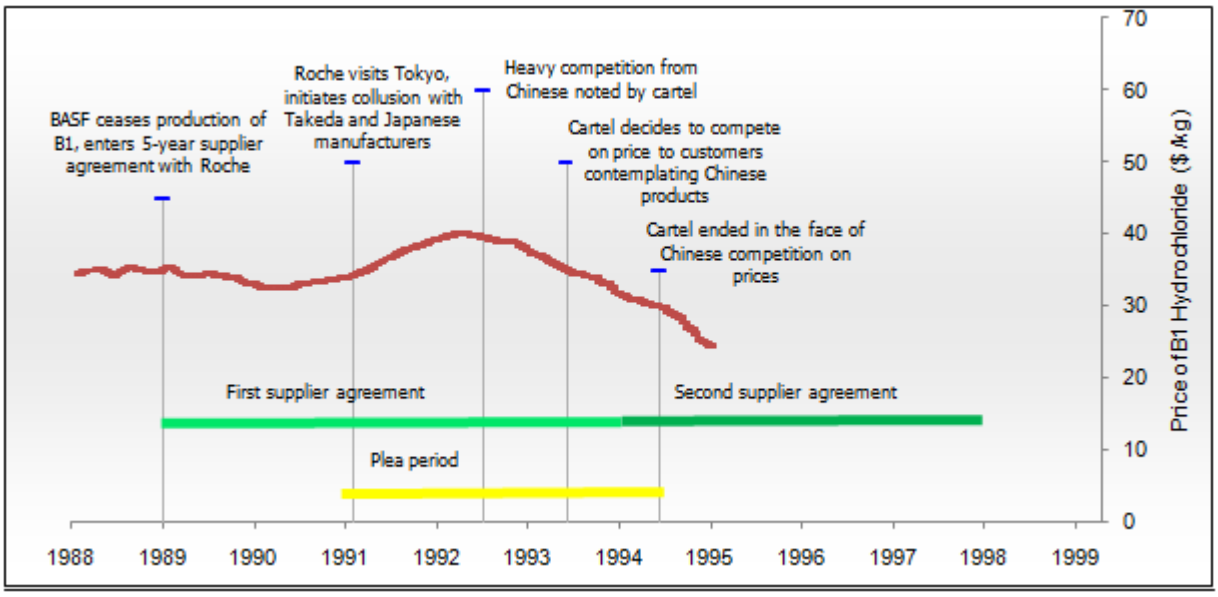
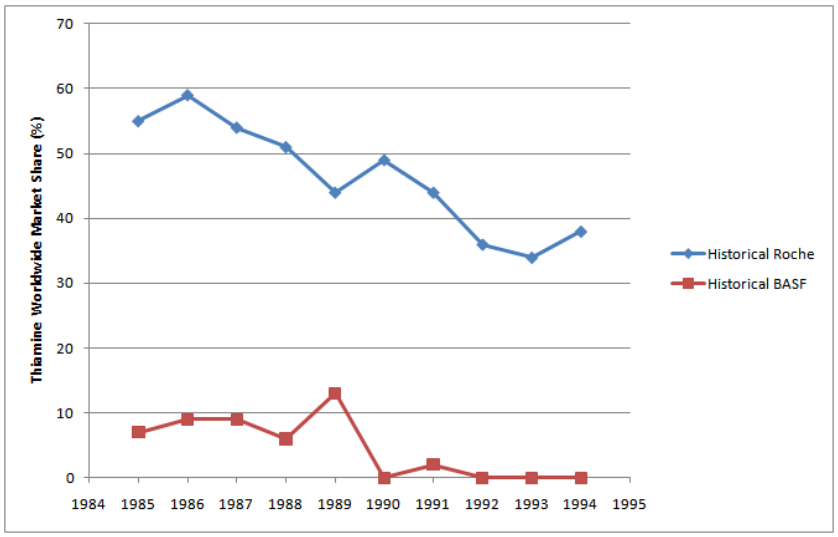



Figure 1.1: Timeline of B1 Cartel According to EC decision
Source: Prices from Bernheim (2002), cartel events from (The Commission of the European Communities, 2001)

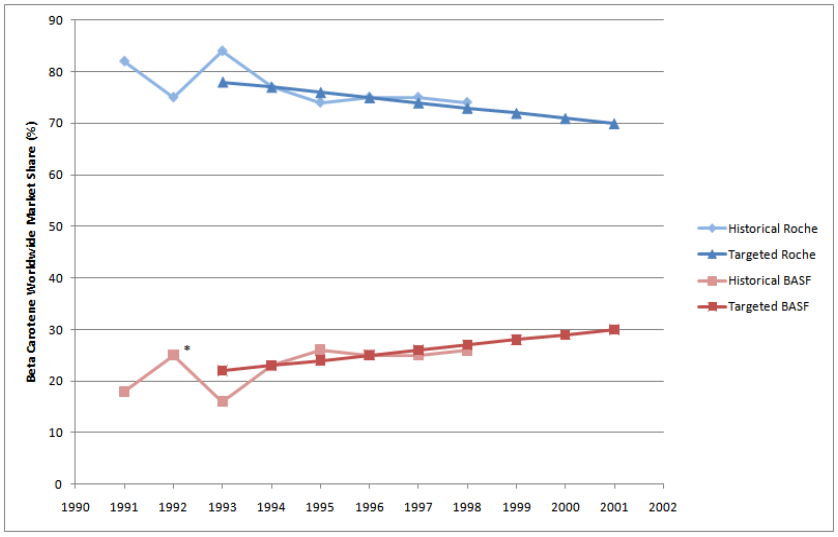
(The Commission of the European Communities, 2001). Despite distancing itself from production, however, BASF remained aware of the collusive agreement, and, according the EC decision, had designated Roche to represent itself in cartel negotiations and reporting of shares. BASF's initial supply agreement was extended after 5 years, and continued to remain operative at least until 1998 (The Commission of the European Communities, 2001).

#### 1.2.2.4 Beta carotene cartel

According to the EC decision, the beta carotene cartel began in 1991 and concluded in 1998 under threat of anti-trust legislation (The Commission of the European Communities, 2001). Composed of the two dominant firms in the beta carotene market, Hoffman-La Roche and BASF, the cartel controlled nearly 100% of the beta carotene market during its existence and as a result, the cartel




(a) B1 Historical Market Shares
Source: Bernheim (2002)




(b) BC Historical and Targeted Market Shares
Source: Bernheim (2002), the Commission of the European Communities (2001)

*Bernheim (2002) reports 25% in 1992, however, the Commission of the European Communities reports 21% in 1992. To maintain consistency with the EC decision, this report uses the 21% figure in all calculations, however, the 25% figure is presented here to maintain consistency with Bernheim's historical shares, presented for reference in the above graph

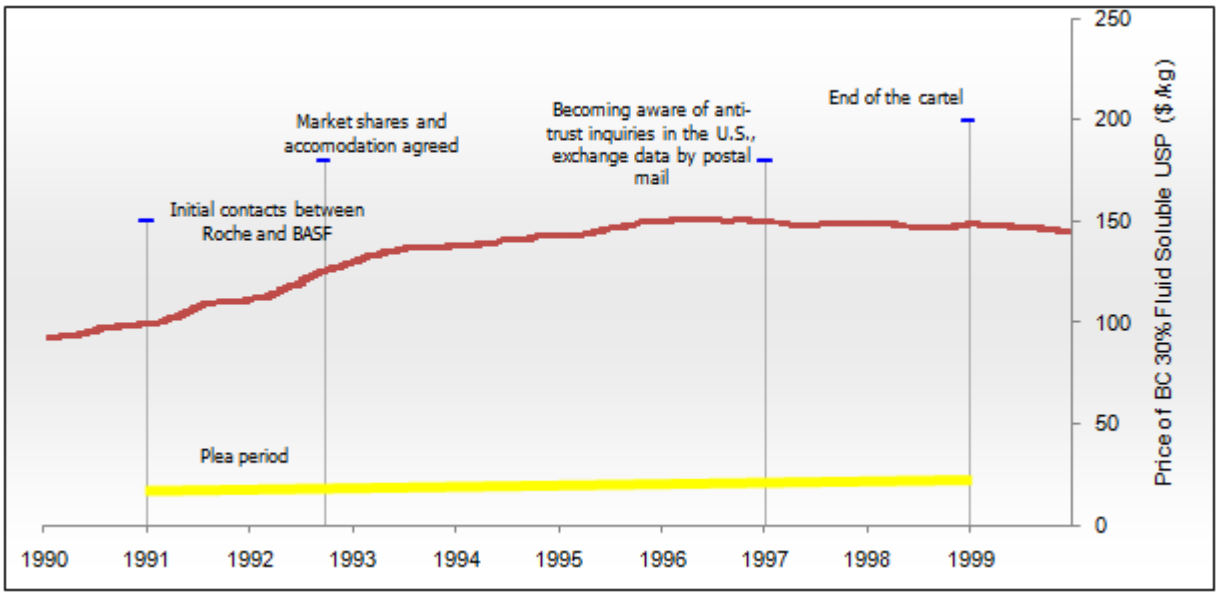



Figure 1.2: Timeline of BC Cartel According to EC decision
Source: Prices from Bernheim (2002), cartel events from the Commission of the European Communities (2001)

was able to successfully raise price levels for beta carotene to an average overcharge of 31.7% (Bernheim, 2002). The timeline of important events in the BC cartel is presented in Figure 1.2, with achieved and targeted market shares presented in Figure 1.2b on the previous page.

Interestingly, unlike many other contemporary cartels, market shares in the beta carotene cartel were allowed to vary. According to the EC decision, Roche agreed to accommodate BASF's growth from a 1992 share of 21% by 1% per year, eventually reaching a maximum share of 30% (The Commission of the European Communities, 2001). While actual market shares diverged from the agreement, they appear to be similar - in 1998 for example, BASF achieved a market share of 26% in comparison to a targeted share of 27% (The Commission of the European Communities, 2001, and Bernheim, 2002). Because Roche and BASF were the only two producers in the market, BASF's growth came at the direct expense of Roche's market share.

#### 1.2.2.5 Canthaxanthin/Astaxanthin Cartel

In addition to the beta carotene market, Roche and BASF also entered into a collusive agreement within several other carotenoids - canthaxanthin and astaxanthin. The arrangement, beginning in May 1993, would have BASF restrict its market share in castaxanthin exchange for an accommodated entry into the astaxanthin market (The Commission of the European Communities, 2001). According to the EC decision, BASF agreed to restrict its market share from 33% to 29% in 1994, after which point it would be permitted to increase its market share by 1-2% per year until 2002, when the market share would be capped (The Commission of the European Communities, 2001). In compensation, Roche would allow BASF to enter the astaxanthin market according to the schedule depicted in Figure 1.3 on the following page. During the time leading up to the opening of its plant, Roche would supply BASF with astaxanthin for marketing purposes (The Commission of the European Communities, 2001).

Historical reality, however, was different from the agreed plan. Although initially slated to be operational in 1996, the astaxanthin plant's opening was delayed until 1999, and as a result the astaxanthin carotenoid agreement was never implemented (The Commission of the European Communities, 2001). While achieved market share data is not available for astaxanthin, the agreement on canthaxanthin was at least in place until 1998, when it was abandoned at the same time as the beta carotene agreement.

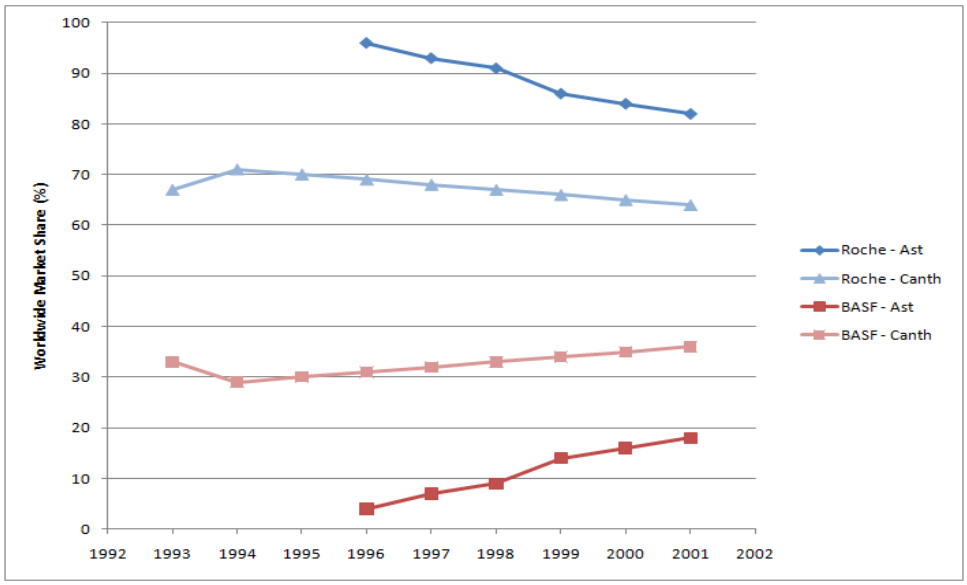



Figure 1.3: Astaxanthin/Canthaxanthin Swap (Targeted Shares)
Source: the Commission of the European Communities (2001)

## 1.3 Collusion in Asymmetric Auctions Background

Asymmetric auction models are fundamental tools of auction and procurement theory. They are designed to calculate the expected revenue[4] for each bidder or auctioneer in an auction. The fundamental problem of auction models is calculating the bid function of each bidder, which maps valuations to bids based on strategic considerations of bidders at auction. As per auction theory, valuation distributions are taken to be correlated to the underlying market share of firm; as a result, auction models can be calibrated to simulate firms with different underlying market shares.

Auction models were initially restricted to symmetry of valuations and beliefs. Equilibrium bids were first documented by Vickrey (1961), with assumptions of identical intervals of support relaxed under Griesmer et al. (1967). Riley and Samuelson (1981) provide a proof of the existence of an equilibrium, as well as a well-defined set of equilibrium strategies. Their work was subsequently extended by Milgrom and Weber (1982) as well as Plum (1992), who established necessary and sufficient conditions for the existence of an equilibrium in a two-bidder case.

[4] Revenue is difference between a winner's valuation of the good and their bid price

Asymmetric auction models have made great strides over the past two decades. Previously limited to restrictive cases of symmetry of beliefs and values, auction models were expanded to include cases of asymmetry under the pioneering model of Marshall et al. (1994), which explicitly assumed stochastic dominance. Existence theorems were established under relatively mild conditions by Lebrun (1996, 1999, 2006), as well as Maskin and Riley (2000b,a). Finally, Gayle and Richard (2008) implement Marshall et. al's original model in FORTRAN code, allowing for the modeling of arbitrary distributions of values.

Asymmetric auction models have historically been used to model cases of collusion. Pioneering efforts in this area include Graham and Marshall (1987), who demonstrated that expected revenue to colluders tends to be higher within an open auction. McAffee and McMillan (1992) expand and describe the bidding strategies, as well as Marshall and Marx (2007), who define a variety of profit-sharing and bidding mechanisms used in collusive rings.

## 1.4 Central Question: Was There an Exit/Accommodation Swap?

Considered in isolation, BASF's accommodation within the beta carotene cartel is hard to understand. In nine out of the twelve cartels from the EC decision, the cartel agreement specified that market shares would be frozen. Moreover, of the other three cartels with changing market shares, the beta carotene cartel is the only one with no obvious cause for volatility. In the riboflavin cartel, for instance, increases in market share were largely the result of Takeda's aggressive policies of overselling and demanding increased share (The Commission of the European Communities, 2001). Moreover, in the canthaxanthin/astaxanthin cartel, BASF traded market share in canthaxanthin for growth in astaxanthin (The Commission of the European Communities, 2001). In contrast, however, the EC decision does not describe the rationale for the beta carotene accommodation. There is no record of BASF acting aggressively, nor is there a record of any kind of explicit compensation agreement within a related market (The Commission of the European Communities, 2001). While Miller (2001) suggests that the capacity expansion may have provided BASF with a credible threat against Roche's defection, the large value of the beta carotene market and rapid growth of BASF suggest that there may be other explanations for the accommodation.

In addition to the beta carotene cartel, the thiamine cartel is also difficult to understand in isolation. For BASF, the decision to exit thiamine production and become a reseller for Roche appears to have disadvantages. First, by becoming a reseller, BASF must have yielded to Roche a portion of its profits from any transaction. Secondly, by placing control of its production firmly in Roche's hands, BASF made itself more vulnerable to Roche's whims - should Roche desire, it could punitively stop shipping product to BASF. As a result, BASF was placed at a disadvantage as a result of its exit of the thiamine market.

Although these two events appear disconnected from a single-market perspective, multimarket theory suggests that they may be linked. Indeed, in conditions of differing costs of production and economies of scale, as was the case with Roche and BASF, multimarket contact facilitates collusion, especially through trading output (Bernheim and Whinston, 1990). As a result, it is possible that rather than being isolated, these two markets were linked, and that Roche and BASF

traded output in the two markets as a way to improve chances of successful collusion.

In the following sections, the hypothesis that a exit/accommodation swap improved profits is examined. Revenues under collusion are compared to those under non-cooperative bidding using asymmetric procurements software. Chapter 2 describes the assumptions of this model and introduces the software. Chapter 3 then presents the resulting revenues under non-cooperative bidding and various scenarios of collusion. Chapter 4 analyzes the revenues from each scenario, finding that an accommodation/exit swap does not improve profits for Roche, and suggesting that there may be other explanations for the exit and accommodation, such as creating a mechanism for side payments or allowing Roche to increase the stability of its cartels. Finally, the results of the work are summarized in Chapter 5, which also discusses implications for anti-trust enforcement and future research.

# CHAPTER 2

# Methodology

## 2.1 Why Use An Asymmetric Procurements Model?

Gayle and Richard's (2008) asymmetric auctions and procurements software is an excellent tool to calculate revenues for the vitamin cartels. Within both the beta carotene and thiamine markets, sales are made by competitive procurement for a single object, a process modeled in Gayle and Richard's code. Furthermore, the software can be calibrated to simulate changing market shares, as was the case in the beta carotene market. The only limitation is that the software does not take into account total market size or a discount rate for revenues over time, both of which are required to use the revenues in a multimarket, parametric context. To overcome this problem, the expected revenues from the asymmetric procurement software are scaled by both a market size multiplier and a discount factor (see Appendix B for details).

The implementation of the software is based on standard asymmetric procurement models. Within the software, bids for an object are modeled as randomly drawing a valuation from a beta distribution and mapping this valuation to a bid. Each firm is assumed to draw valuations from non-identical distributions, with collusion modeled as one firm out of the cartel submitting the minimum of independent bids from each of the cartel members. Cartel members who do not have the lowest bid do not bid in the procurement, and revenue from the procurement is distributed instantaneously to cartel members in proportion to in-cartel market shares. Under these rules, expected revenue for each independent bidder or cartel is calculated, and after scaling, can be compared across different markets.

## 2.2 Scenarios

Using Gayle and Richard's code, revenues for non-cooperative bidding, collusive bidding without exit/accommodation, and collusive bidding with exit/accommodation are compared. The revenue for each scenario is affected primarily by three factors, including the length of the scenario, the presence of the cartels and the market shares of each firm. The following section first lays out these factors for each scenario, and then defines scaling parameters such as market size multipliers and

discount factors.

### 2.2.1 Beta carotene

The beta carotene scenarios are constructed using information from both historical market shares and cartel agreements. The length of each of following scenarios is taken from the length of the accommodation agreement, that is, from 1993 to 2001 (Bernheim, 2002). Market shares and cartel composition are based on this timeframe, and specified as follows:

**1. Non-cooperative bidding**

Under non-cooperative bidding, market shares are frozen at 79% and 21% for Roche and BASF, respectively, in accordance with the reported market shares for 1992 (The Commission of the European Communities, 2001). These are depicted graphically in series S1 in Figure 2.1a on page 26).

**2. Collusion without accommodation**

Under collusion without accommodation, market shares are also assumed to be frozen, as was occurring in other vitamin cartels at this time (The Commission of the European Communities, 2001). Roche and BASF form an all-inclusive cartel.[1]

[1] To model expected revenue of the beta carotene cartel, which is a single-bidder cartel and therefore intractable in Gayle and Richard's model, Roche and BASF are assumed to earn the expectation of their joint valuation in proportion to their in-cartel market share. This is in accordance with standard practice for asymmetric auctions modeling.

**3. Collusion with accommodation**

Under collusion with accommodation, market shares are assumed to be those targeted in the accommodation agreement. Hence, BASF grows by 1% per year until 2002, while Roche loses 1% market share per year (The Commission of the European Communities, 2001). This growth is depicted in series S2 in Figure 2.1a. As with scenario 2, BASF and Roche are assumed to be the only firms in beta carotene market and the only members of the all-inclusive cartel.

### 2.2.2 Thiamine

As with beta carotene, the parameters for the thiamine scenarios are based on historical data. Nevertheless, the assumptions are less straightforward than for beta carotene.

First, the duration of the scenarios for thiamine requires significant consideration. For the thiamine market, the duration of the first supplier agreement was five years, from 1989 to 1993 (The Commission of the European Communities, 2001). Nevertheless, after 1993, the agreement was extended until 1998. For the purposes of this model, however, only the first supplier agreement is analyzed, as from the viewpoint of a 1989 cartel, Roche had no credible promise that the agreement would continue after 1993. Furthermore, although the firms entered plea statements admitting to collusion only after 1990, Bernheim (2002) indicates that the thiamine cartel had begun colluding as early as 1985. As a result, it is assumed that collusion was ongoing throughout the duration of the supplier agreement. Therefore, the duration of the thiamine scenarios is assumed to be five years, from 1989 to 1993.

The thiamine market shares also require careful consideration. Unlike the beta carotene cartel, BASF and Roche were not the only firms operating within the thiamine market, as Takeda, Chinese producers and a fringe of small producers also produced thiamine. However, as there is no evidence that BASF or Roche had anticipated changes in other producers' market shares, other producers' shares are assumed frozen at 1989 levels. Shares therefore are 31%, 9% and 2%, for Takeda, Chinese producers and fringe producers, respectively (The Commission of the European

Communities, 2001). The market shares for Roche and BASF are the only shares that are vary, as specified in the following scenarios:

**1. Non-cooperative bidding**

Under non-cooperative bidding, Roche and BASF's market shares are frozen at their 1989 levels of 44% and 13%, respectively, for all five years (see series S1 in 2.1b on the following page). All firms are assumed to be playing non-cooperatively.

**2. Collusion without exit**

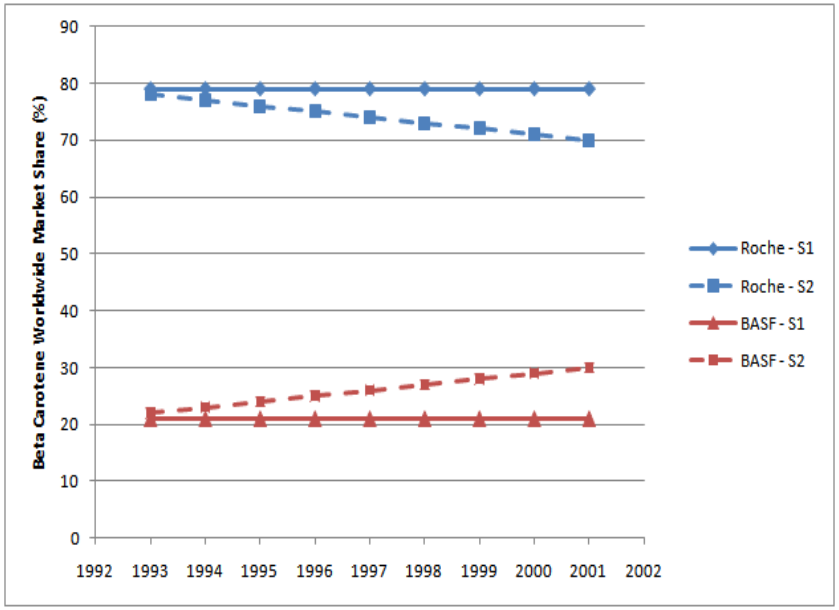
Under collusion without exit, Roche and BASF's market shares are again frozen at their 1989 levels, as occurred in many vitamin cartels in this period (The Commission of the European Communities, 2001). Collusion is assumed to involve a single cartel of Roche, Takeda and BASF, as documented in the EC decision (The Commission of the European Communities, 2001).

**3. Collusion with exit**

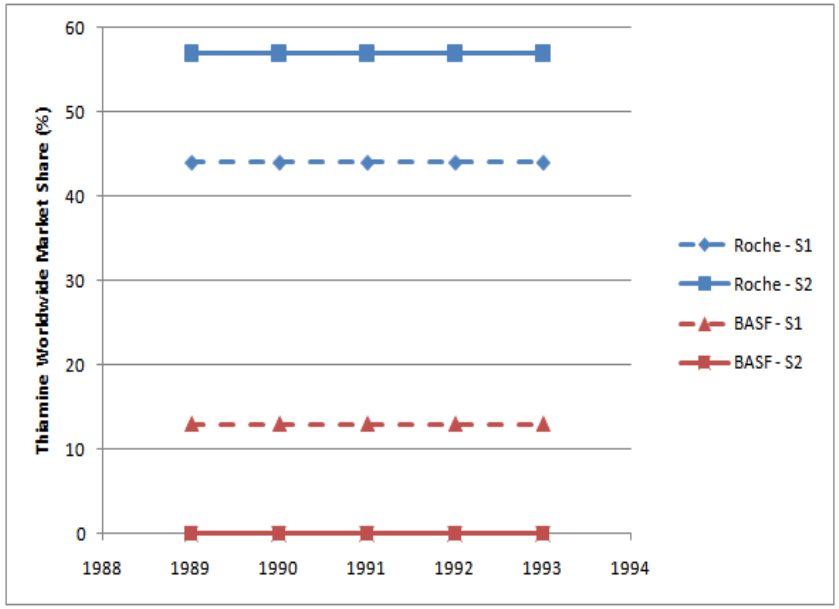
Under collusion with exit, all of BASF's market share is allocated to Roche (see series S2 in 2.1b on the next page). This scenario provides an upper bound on the revenue that Roche could have earned from the exit agreement. As a result, in any scenario of collusion, Roche's revenue must have fallen between the revenue from this scenario and the revenue from collusion without exit.

## 2.3 Scaling Parameters

In addition to the specific scenarios, scaling parameters are defined for comparison between multiple scenarios:




(a) BC Market Shares




(b) B1 Market Shares

| Key | Description | Source |
|---|---|---|
| $S_1$ | Shares fixed | Fixed 1992 (EC) |
| $S_2$ | Shares under accommodation | EC Shares |

(c) BC Key

| Key | Description | Source |
|---|---|---|
| $S_1$ | Shares frozen at 1989 values | Bernheim |
| $S_2$ | Shares frozen at 1989 values; BASF shares allocated to Roche | Bernheim |

(d) B1 Key

### 2.3.1 Discount Rate

The exit/accommodation agreement is hypothesized to have begun in 1989, and as a result the discount rate is taken from the market yield of a 2-year U.S. treasury constant maturity bond for that year (U.S. Federal Reserve, 2010). From a rate of 8.57, the discount rate is $\frac{1}{1+0.0857} = 0.921$ to 3 significant digits. This figure is additionally supported by Bernheim (2002), who states that over the time period of the cartel, the average prime rate was 8.3%.

### 2.3.2 Market Size

No expectations of market growth are included in the model in accordance with the maturity of the markets at this time, which experienced little to no growth during the 1990s (Connor, 2001). Market turnover rates during the plea periods are taken as estimates of the market size multiplier $\mathbf{r}_t$ (see Table 2.1).

| **Vitamin** | **Turnover (USD)** | **Duration of Turnover Data** | **Turnover rate (USD/year) ($\mathbf{r}_t$)** |
|---|---|---|---|
| BC | 392,361,806 | 8 | 49,045,226 |
| B1 | 49,541,957 | 3.5 | 14,154,845 |

Table 2.1: Turnovers for BC and B1 markets during the plea period
Source: Bernheim (2002)

## 2.4 Calibration

Beta distributions used in calculating revenue were calibrated by matching the preceding market shares to expected probabilities of winning in Gayle and Richard's model, in accordance with standard practice for asymmetric auctions and procurements. This process was automated by extending Gayle and Richard's code in object-oriented form. Parameters for these beta distributions appear in Appendix A as well a calibration to market shares.

# CHAPTER 3

# Results

## 3.1 Beta carotene

For the beta carotene cartel, Table 3.1 reviews the scenarios under consideration, with the revenue for each scenario reported in Figure 3.1.

| Scenario | Type of Bidding | Cartel Firms* | Market Shares |
|---|---|---|---|
| 1 | Non-cooperative | - | 1992 market shares |
| 2 | Collusive | R,B | 1992 market shares |
| 3 | Collusive | R,B | Accommodation |

Table 3.1: BC Scenarios
* R = Hoffman-La Roche, B = BASF

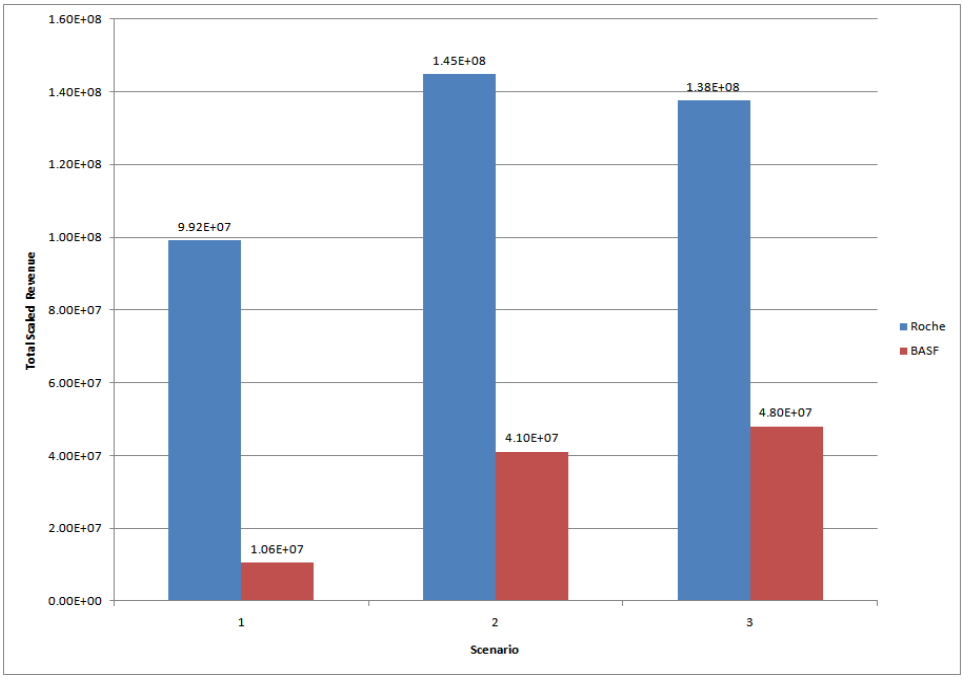



Figure 3.1: BC Revenue by Scenario

## 3.2 Thiamine

For the thiamine cartel, Table 3.2 on the following page reviews the scenarios under consideration, with the revenue reported in Figure 3.2.

| Scenario | Type of Bidding | In-Cartel Firms* | Market Shares |
|---|---|---|---|
| 1 | Non-cooperative | - | 1989 market shares |
| 2 | Collusive | R,T,B | 1989 market shares |
| 3 | Collusive | R,T,B | 1989 market shares, BASF exits and Roche takes BASF's market share |

Table 3.2: B1 Scenarios
* R = Hoffman-La Roche, B = BASF, T = Takeda

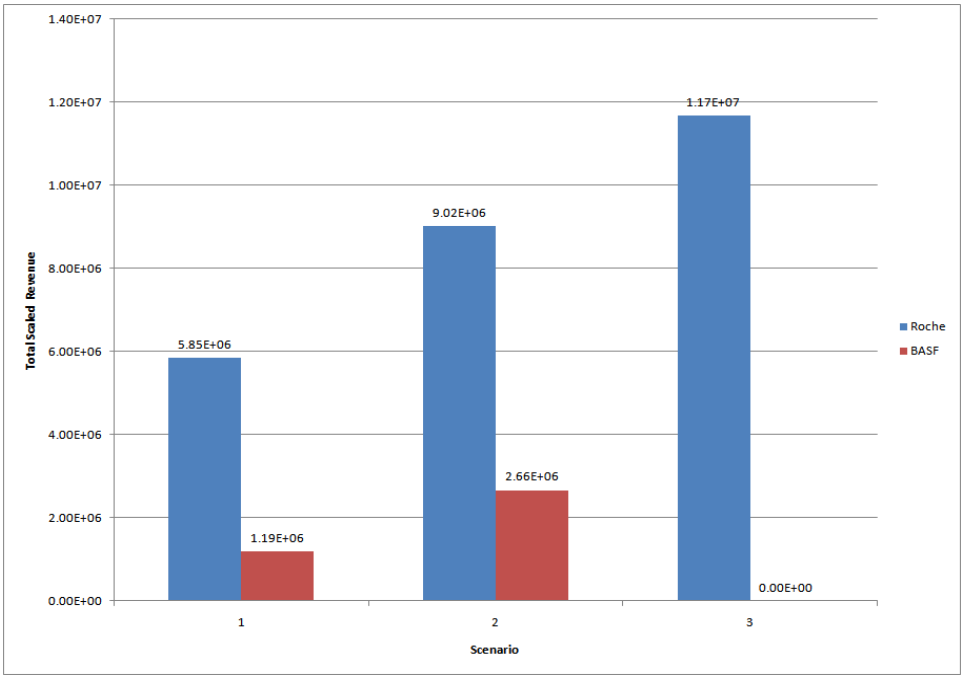
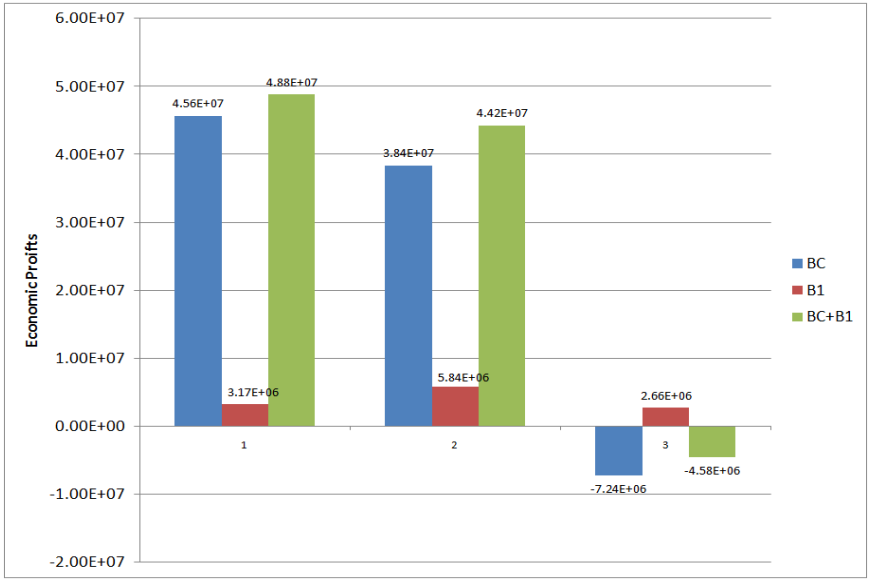


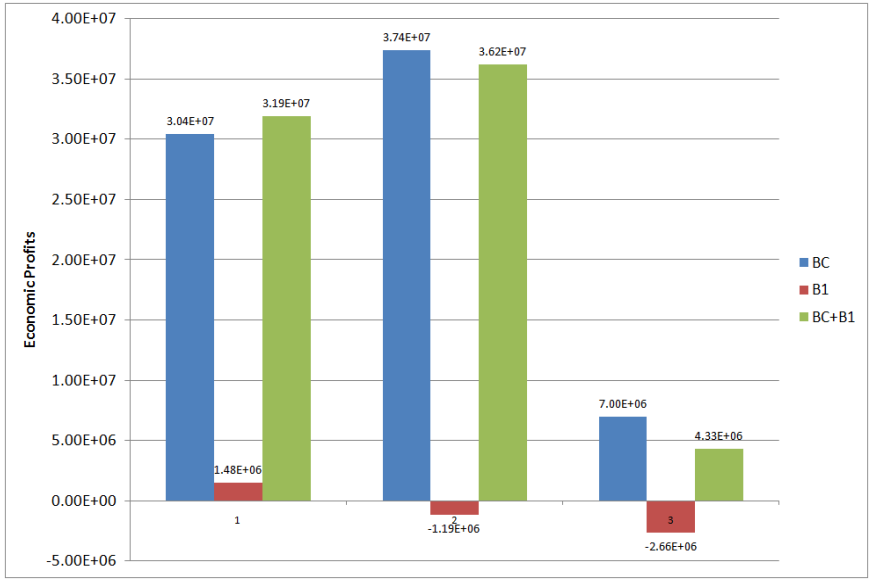

Figure 3.2: B1 Revenue by Scenario

## 3.3 A B1/BC Swap

Assuming non-cooperative revenues as opportunity cost, the profits from collusive agreements are depicted in first two sets of columns on the following page. For each set, the first column depicts the profits in beta carotene, the second the profits in thiamine and the third the sum of profits in both markets. The third set of columns depicts the profits from an exit/accommodation swap, taking as opportunity cost the revenues under collusive bidding without exit/accommodation.




(a) Roche Profits




(b) BASF Profits

| Code | Interpretation |
|---|---|
| 1 | Profit from entering collusive agreement without exit/accommodation |
| 2 | Profit from entering collusive agreement with exit/accommodation |
| 3 | Profit from accommodation/exit |

(c) Profits Key

# CHAPTER 4

# Analysis

It is important to note that because Gayle and Richard's algorithm only produces unitless values of expected revenue, revenue and profit figures reported do not have real-world units. Nevertheless, the ratio between revenues as well as their signs can be used to make comparisons between different scenarios.

## 4.1 Beta Carotene

The beta carotene revenues in Figure 3.1 are similar to what is expected by the procurements model. First, Roche's revenue decreases from scenarios 2 to 3, as Roche accommodates BASF's growth.[1]

Both Roche and BASF gain a large amount - approximately $4.56\text{x}10^7$ and $3.17\text{x}10^6$, respectively - from entering the cartel (scenarios 2 vs. 1). However, accommodating BASF's growth (3 vs. 2) incurs a cost to Roche of $-7.24\text{x}10^6$. Despite this fact, even with accommodation, at $3.48\text{x}10^7$, revenue for Roche is still more in collusive bidding than in non-cooperative bidding. Therefore, Roche has incentive to collude, even if collusion includes accommodation. However, collusion without accommodation remains the best result for Roche.

## 4.2 Thiamine

The revenues for the thiamine markets are also in line with auction theory (see Figure 3.2 on page 30). For Roche, entering collusive bidding causes revenue to increase from $5.85\text{x}10^6$ to $9.02\text{x}10^6$. BASF also gains from joining the cartel, growing from $1.19\text{x}10^6$ to $2.26\text{x}10^6$. Therefore,

[1] Interestingly, the sum of BASF and Roche's revenue also decreases under accommodation. In a real-world interpretation, this may arise from changes in the underlying costs of production for the firms as Roche reduces its output and BASF adds capacity and increases its production. As costs of production factor into the underlying valuations of the firms, then the revenue reported by the model also changes in correspondence to the changes in underlying valuation.

both Roche and BASF gain from collusion. Interestingly, Roche gains much more than BASF ($3.17x10^6$ versus BASF's $1.48x10^6$); this may be indicative of Roche's larger existing stake within the thiamine market which would let it benefit more from collusion.

The supplier agreement, however, only generates a gain for Roche. Entering the supplier agreement costs BASF an estimated $2.66x10^6$, which is instead allocated to Roche.

## 4.3 A B1/BC Swap

Considering both the BC and the B1 market together (Tables 3.3a and 3.3b on page 31), it is found that both Roche and BASF expected to gain from collusion in both markets, gaining additional profits of $4.88x10^7$and $3.19x10^7$, respectively. However, the addition of a accommodation/exit swap is beneficial only to BASF. While BASF gains $4.33x10^6$ from the arrangement, Roche stands to lose $4.58x10^6$, or, that is, 9.39% of the profit from entering collusion.

From these figures, it is found that even if Roche takes all of BASF's thiamine market share, the loss from the beta carotene accommodation is still greater than the gain from thiamine. This is not unexpected due to the size of the beta carotene market (approximately 3.4x the thiamine market), as well as the longer duration of the beta carotene cartel (9 years versus 5 years) (Bernheim, 2002). Nevertheless, this is still an interesting result, as it indicates that Roche's beta carotene accommodation cannot be explained by a swap as hypothesized. To explain the accommodation, an expanded definition of a swap must be considered, one which takes into account not only profits from each market but also considerations of cartel stability across multiple markets.

## 4.4 What Advantages From A Swap?

### 4.4.1 A B1/BC Swap to Avoid Cartel Detection

In addition to profits, a swap may have been also been motivated by a desire to avoid detection by anti-trust authorities. Although constant market shares themselves are not necessarily indicative of collusive conduct, frozen market shares within all of the vitamin markets at the same time that prices were rising may have looked suspect (Porter, 2005). As a result, Roche and BASF may have had a desire to simulate non-cooperative volatility of market shares in the beta carotene and thiamine markets.

### 4.4.2 The B1 Exit as a Mechanism for Side Payments

Another rationale for the deal would be to develop stable cartels via the creation of a mechanism for side payments. As documented before, both Roche and BASF gain immense profits from collusive agreements within these two markets, and even more so from their collusive agreements within other markets (Bernheim, 2002). As a result, both companies had a strong incentive to develop stable cartels. However, from basic theory of collusion, a cartel's stability depends on its ability to correct deviation from agreed market shares, either by punishment (in the case of overselling) or by making side payments to an under-performing member of the cartel. Furthermore, the ability to take these actions is hampered by the need to avoid detection by anti-trust authorities. In the case of under-performance, for example, undisguised side payments provide direct evidence to court prosecutors, and thus are avoided by firms, who then seek alternative mechanisms to transfer funds (Porter, 2005).

In the case of the Roche/BASF cartels, the supplier agreement would have provided a mechanism for side payments hidden from anti-trust authorities. By buying thiamine product from Roche at non-market price, BASF could effectively correct an imbalance of achieved shares in any of the other markets under collusion. Although purchases above or below market price may be suspect if examined in detail, on the surface, it would have been a non-cooperative transaction.

The circumstantial evidence supporting the B1 arrangement as a mechanism for side payments is substantial. In the same year that the B1 supply agreement was being negotiated, the greater A and E cartel was also being initiated (The Commission of the European Communities, 2001). This cartel, operating in two of the largest vitamin markets, included provisions for the redistribution of funds. According to the EC decision, "If at the end of the year a producer was substantially ahead of its quota, it had to purchase vitamins from the others in order to compensate them for the corresponding shortfall in their allocation" (p. 19). Moreover, although the greater B1 collusive agreement was dissolved around 1995 as a result of Chinese entry, the Roche/BASF B1 supply agreement continued until 1998, when BASF re-entered the thiamine market in a joint venture with a Chinese partner (Bernheim, 2002). From this timeline, it is easily visible that the supplier agreement was in place throughout the duration of many of the collusive agreements between BASF and Roche.

In addition, during the duration of the beta carotene cartel, a thiamine side payment mechanism might have been used to allow volatile market shares in beta carotene. Pesendorfer (2000) argued that the presence of side payments allows volatility in market shares in cartels, whereas lack of side payments requires frozen market shares. The same pattern may have occurred here, in which side payments through the supplier agreement compensated for gains in beta carotene, thus maintaining the appearance of non-cooperative bidding in beta carotene while balancing profits between both firms.

### 4.4.3 The B1 Exit As a Method of Monitoring Premix Production

In addition to facilitating side payments and maintaining the appearance of non-cooperative behavior in beta carotene, BASF's exit from thiamine may have assisted Roche in monitoring the production of premix. With worldwide sales averaging on the order of $109 million per year from 1989 to 2001, premix was a product important to Roche's business (Bernheim, 2002). Moreover, thiamine is a small but essential component of many premixes, and was mixed in announced proportions with the other chemicals (Bernheim, 2002). As a result, if BASF abided by the supplier

agreement, then any premix that BASF sold during the supplier agreement must have included Roche-produced thiamine, and so Roche could produce a reliable estimate of how much premix BASF was producing.[2] As a result, the supplier agreement gave Roche an reliable, independent survey of BASF's production of premix, as well as BASF's production of all vitamins used in premix, including Vitamins A, E, B5, B2, B3 and H (Bernheim, 2002). In essence, the supplier contract would have provided independent monitoring of BASF's output over a wide range of vitamins and vitamin products.

Independent monitoring of premix production would have been a keystone to many of Roche's and BASF's collusive agreements. For Roche, the information provided by the supplier agreement would have made it easier to detect BASF defections, an important condition for maintaining cartel stability (Porter, 2005). This arrangement also would have benefited BASF - as demonstrated in Section 4.3, the gains from a trusted collusive relationship with Roche were larger the cost incurred from market exit.

As a result, although the thiamine market was small, it may have played a key role in maintaining stable collusive agreements, and would be therefore more valuable to Roche than profit calculations indicate. While an exit/accommodation swap is not proven by this data, such a swap may have indeed been reasonable for both Roche and BASF.

[2] While BASF could have cheated and purchased thiamine from other suppliers, the supplier agreement would have given Roche recourse to punitively constrain BASF's production of premix by cutting off its supply of thiamine. Roche could even seek legal action against BASF for breaching its supplier contract. Therefore, cheating for BASF would have been difficult.

# CHAPTER 5

# Conclusion

## 5.1 Summary

From calculations of profits, it appears that a hypothesized Roche/BASF accommodation/exit swap would result in net gain for BASF, and a net loss for Roche. As a result, it is unlikely that such a swap would have been executed only for purposes of gaining revenue within these isolated markets. A swap may however have been executed for the purpose of maintaining stable and undetected cartels. First, the thiamine supplier agreement could have been used as a mechanism for side payments which would have created the appearance of non-cooperative bidding in beta carotene, thus making it harder for authorities to detect the cartel. Secondly, the thiamine exit may have also given Roche a powerful independent method of monitoring premix production, therefore enabling it to maintain stable cartels. In both cases, in accordance with multimarket contact theory, multimarket contact may have been used to help sustain collusion (Bernheim and Whinston, 1990).

## 5.2 Implications for Cartel Detection

The detection of contemporary cartels is difficult at best. Although many collusive environments are characterized by frozen market shares, some markets show changes in market share and even firm exit while under collusion, as occurred in these two cartels. Such activities are difficult to distinguish from normal market activity, and can lead authorities to erroneously conclude that markets are competitive.

While markets may appear to be non-cooperative, if examined in detail, there may emerge signs of collusion. As is suggested in the beta carotene and thiamine markets, changes in market share may be balanced by side payments between colluding firms. Such payments may be channeled through a supplier agreement, which is made possible by market exit. In some cases, the existence of such a mechanism of side payments may also create the opportunity for a firm to disguise its collusion in another market.

Detection of cartels, therefore, should focus closely on supplier agreements. First, inter-firm transaction prices in supplier agreements should be examined for evidence of side payments, as

evidenced by unreasonably high or low prices. Such transactions should be examined especially if market shares within related markets appear to be volatile, as in non-competitive bidding. While inter-firm transaction prices may be protected data, firms should be required to disclose this data to authorities. Supplier agreements should also be considered more closely in cases of multimarket contact. As supplier agreements for an intermediate product such as thiamine can improve potential for collusion in multiple markets, they will likely be particularly attractive to large firms operating in multiple markets.

## 5.3 Further study

### 5.3.1 Examine B1 transaction prices for evidence of side payments

Further study of the thiamine and beta carotene markets should be conducted to determine whether the thiamine market acted as a mechanism for side payments, as evidenced by payments over or under market value. In particular, correlations between B1 supplier transaction prices and BC market share changes should be examined. In order to procure this data, more detailed data about transaction prices in the B1 supplier agreement should be procured.

### 5.3.2 Examine the astaxanthin/canthaxanthin swap arrangement

Additionally, the balance of profits within the astaxanthin/canthaxanthin swap should be examined for insight into Roche and BASF's collusive style. Studying this system will allow greater insight into the processes of multimarket collusion, and in particular, the hypothesized B1/BC swap arrangement.

# Appendix A: Parameters & Calibration to Market Shares

Each of the following markets were modeled with 10,000 data points and a 10th-order Taylor series.

## Beta Carotene

The beta carotene cartel is simulated by drawing valuations from beta distributions which are parametrized for $0 \leq t \leq 8$ in Table A.1. The estimated market shares (probabilities of winning) generated from these distributions appear in Table A.2, and a comparison to the targeted market shares appears in Figure A.1. The maximum error in calibration is small, at 0.7%. From empirical investigations, this appears to be within the inherent variation of Gayle and Richard's model (the sum of all market shares can reach up to ~101% in normal modeling).

| Firm | $\alpha$ | $\beta$ |
|---|---|---|
| Roche | 2 | 0.55+0.05t |
| BASF | 0.5 + 0.1t | 2 |

Table A.1 Parameters for BC Cartel

| t | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Roche Share | 0.781 | 0.769 | 0.757 | 0.746 | 0.735 | 0.724 | 0.714 | 0.703 | 0.693 |
| BASF Share | 0.221 | 0.233 | 0.244 | 0.255 | 0.265 | 0.276 | 0.287 | 0.297 | 0.307 |

Table A.2 Estimation for BC Cartel

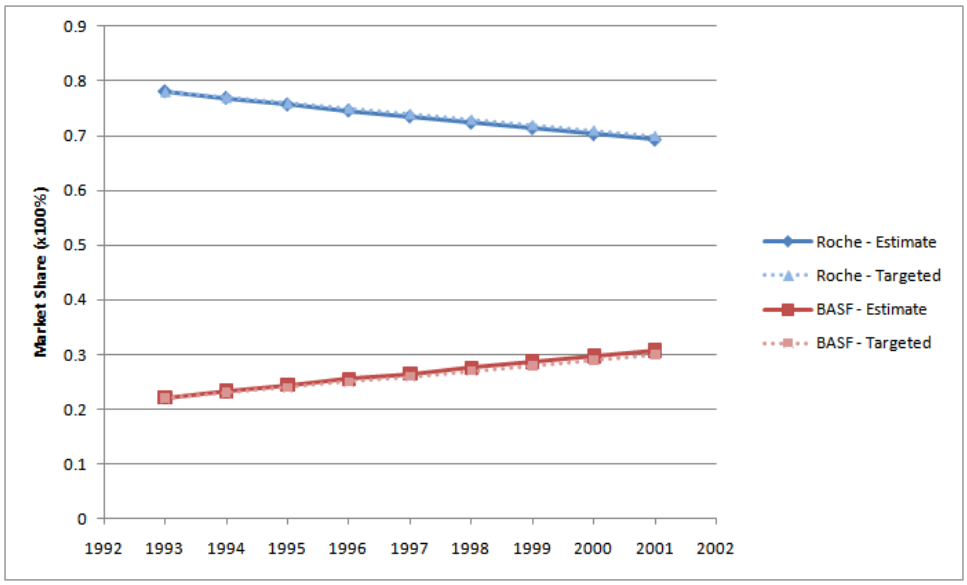



Figure A.1 BC Calibration

## Thiamine

As with the beta carotene market, firms within the thiamine market are parametrized in beta distributions with parameters appearing in Table A.4. A comparison with the historical market shares is described in Figure A.2. As with the beta carotene cartel, the maximum error of the estimated market shares is small, at 0.535%.

| Firm | $\alpha$ | $\beta$ | Calculated Share |
|---|---|---|---|
| Roche | 2.22 | 1 | 0.438465 |
| Takeda | 1.25 | 1 | 0.308554 |
| BASF | 1 | 1.6 | 0.133290 |
| Chinese | 1 | 1.95 | 0.091662 |
| Others (fringe) | 1 | 3.2 | 0.027980 |

Table A.4 Parameters for B1 Cartel

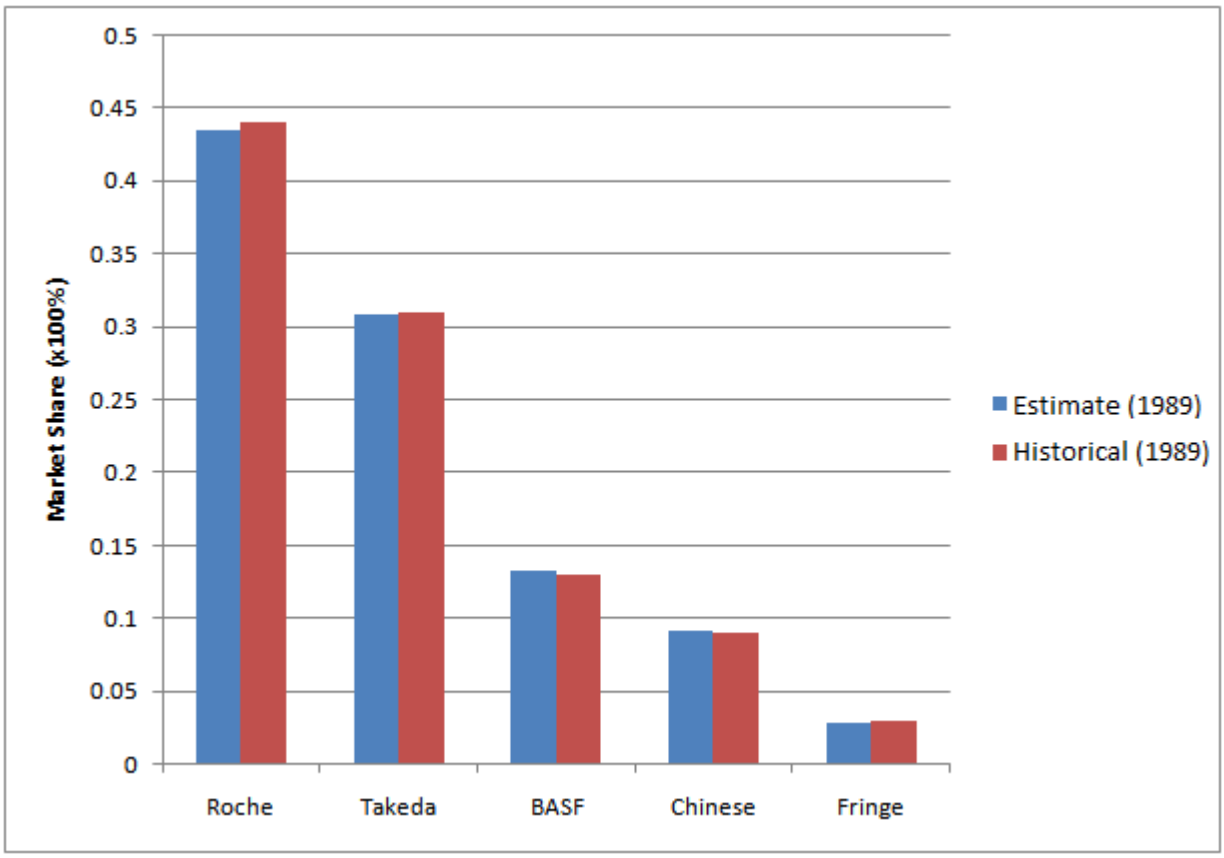



Figure A.2 B1 Calibration

# Appendix B: Adapting Expected Revenue to the Multimarket Case

Consider a firm $f \in F = \{R, B\}$, where $F$ is the two-element set of firms Roche and BASF. Furthermore, consider a market $m \in M = \{BC, B1\}$, where $BC$ is the beta carotene market and $B1$ is the thiamine market. Take a sequence of revenues for firm $f$ indexed by time $t$, $t_0 \leq t \leq T$, to be defined as $\{p_t\}_f \in P_m$ where $P_m$ to be the set of all sequences of revenues[1] for market $m$. Notice that for firms in a cartel, in accordance with instant distribution of cartel revenue, $\{p_t\}_f = \{(p_t)'(s_t)_f\}$ where $\{(p_t)'\}$ is the sequence of the cartel's total revenues and $\{s_t\}_f$ is the sequence of firm $f$'s in-cartel market shares. Taking:

1. $\{\{p_t\}_f\} \in P_m$ to be a sequence of revenues for all firms in market $m$ indexed by time $t$, $t_0 \leq t \leq T$,
2. $\delta$ to be the prevailing discount rate in market $m$

then define a "market scenario", $sc$, as the collection $sc := (\{\{p_t\}_f\}, \delta, t_0, T)$, where $sc \in SC_m$, the set of all market scenarios for market $m$.

Define the total revenue for a firm $f$ under market scenario $sc$ as:

$$(E\pi_f)_{sc} = (\sum_{t=t_0}^{T} \delta^t (p_t)_f)_{sc} \tag{5.1}$$

which for firms in cartels can also be represented as:

$$(E\pi_f)_{sc} = (\sum_{t=t_0}^{T} \delta^t p_t' s_{t,f})_{sc}$$

[1] Revenues here are expected revenues over an infinitely repeated procurement implemented in Gayle and Richard's software

Now, scale the total revenue by the market size. Taking $((r_t)_{sc})_m$ to be a sequence of sizes of market $m$ over the duration of a scenario $sc$, then the total scaled revenue for a firm $f$ under market scenario $sc$ is given by:

$$(E\pi_f)'_{sc} = (\sum_{t=t_0}^{T} r_t \delta^t (p_t)_f)_{sc} \tag{5.2}$$

or for a firm in a cartel:

$$(E\pi_f)'_{sc} = (\sum_{t=t_0}^{T} r_t \delta^t p'_t s_{t,f})_{sc}$$

Notice that because Gayle and Richard's algorithm produces unitless numbers between 0 and 1 (eg. 0.70), this total scaled revenue has no real units. Nevertheless, the ratio between total scaled revenues as well as the sign of the total scaled revenues can provide information over whether one scenario would be favored over another.

Now calculate the opportunity cost. Defining a pair of market scenarios as $u = (i, j)$ and taking $(E\pi_f)'_i$ to be the (total scaled) revenue of firm $f$ in a "deal scenario" $i$ (for example, a scenario of accommodated growth), and $(E\pi_f)'_j$ to be firm $f$'s (total scaled) revenue in a "baseline scenario" $j$ (for example, a scenario of frozen market shares), then the economic profit of scenario $i$ for firm $f$ is given by:

$$\Delta_f^u := (\Delta E\pi_f)_u = (E\pi_f)'_i - (E\pi_f)'_j = (\sum_{t=t_0}^{T} r_t \delta^t (p_t)_f)_i - (\sum_{t=t_0}^{T} r_t \delta^t (p_t)_f)_j$$

Finally, compare across two different markets. Take two scenario pairs from different markets, $u = (i, j)$, $v = (k, l)$,where $i, j \in SC_{m_1}$, $k, l \in SC_{m_2}$ for markets $m_1, m_2$. A "deal" is defined as $D^{(u)_{m_1},(v)_{m_2}} = ((u)_{m_1}, (v)_{m_2})$. For a "deal" to be rational for firm $f$, it will be sufficient to show that, for the identified scenario pairs that the individual rationality condition $(IR_f)_{(u)_{m_1},(v)_{m_2}}$ is satisfied, namely:

$$(IR_f)_{(u)_{m_1},(v)_{m_2}} := (\Delta_f^u)_{m_1} + (\Delta_f^v)_{m_2} \geq 0$$

where $((\Delta E\pi_f)_u)_{m_1}$ represents the economic profit[2] of firm $f$ in the $m_1$ market and $((\Delta E\pi_f)_v)_{m_2}$ represents the economic profit of firm $f$ in the $m_2$ market.

[2]In this paper, for simplicity, "revenue" and "profit" refer to "total scaled revenue" and "economic profit", respectively, as defined in this Appendix

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