Three Essays on Product Management

How to Offer the Right Products at the Right Time and in the Right Quantity

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To my parents Marion and Gerolf,

and my beloved Julia

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Summary

How to Offer the Right Products at the Right Time and in the Right Quantity

Jochen Schlapp

Across virtually all industries, firms share one common objective: they strive to match their supply with customer demand. To achieve this goal, firms need to offer the right products at the right time and in the right quantity. Only firms that excel in all three dimensions can provide products with a high customer value and achieve extraordinary profits. This thesis investigates specific challenges that a firm has to overcome on its way to a good match between supply and demand. The first essay investigates how a firm can already select the right products during the product development phase. To make good resource allocation decisions, the firm needs to collect valuable information, and incentivize information sharing across the entire organization. The key result is that the firm needs to balance individual and shared incentives to achieve this goal. However, such compensation schemes come at the cost of overly broad product portfolios. The second essay examines how uncertain customer demand patterns affect seasonal products. Specifically, the timing of the product's availability is crucial. Too early, and high opportunity and inventory costs may devour profits. Too late, and the firm loses its customers. In short, the firm has to balance a product's market potential with the costly market time. This tradeoff may induce a firm to stock more inventories to satisfy a smaller market potential. Lastly, the third essay investigates how customer substitution influences the inventory decisions of different supply chain members in the presence of upstream competition. We find that customer substitution has a non-monotonic effect on the supply chain members' decisions, and that left-over inventories may decline even when initial inventories are raised.

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Chapter I

Introduction

Across virtually all industries, firms share one common objective: they strive to match their supply with customer demand (Cachon and Terwiesch, 2009, p. 2). This is a demanding task even for the most successful firms since customer demand is, in general, hard to predict. However, the rewards of outperforming rival firms on this challenge are substantial. By better matching supply with demand a firm can reduce costs and increase revenues. Thereby, the firm can operate more profitably and ultimately create a sustainable competitive advantage. For any firm, the key to a better match between supply and demand is to offer the *right products* at the *right time* and in the *right quantity* (Lee, 2004; Slone, 2004). Only firms that excel in all three dimensions can provide products with a high customer value and achieve extraordinary profits. Interestingly, already falling short of one of these three dimensions is sufficient for products to fail in the market place. As the following examples illustrate, evidence for this phenomenon abounds in practice.

For instance, choosing the right products is of utmost importance in the pharmaceutical industry, where product development costs are tremendous. As reported in DiMasi et al. (2003), the total drug development costs for a single product can easily reach $800 million. Naturally, when making such huge investments in bad products that later "flop" on the market or do not receive approval due to adverse side effects, firms eventually suffer from eroding profits. "Blockbuster" products, in contrast, boost firm profits, as these products can easily generate annual revenues exceeding $1 billion (Girotra et al., 2007). As such, in the pharmaceutical industry, firm performance is closely related to top management's ability to reliably select the right products for development.

Yet, simply offering the right product is not enough. In 2009, the swine flu pandemic spread all over Europe. To reduce the number of infections and to avoid a presumed high mortality rate in the population, government agencies together with the pharmaceutical industry intended to provide vaccination that should help immunize the population. In Germany, such a vaccine was made publicly available at the end of October 2009.

By this time, however, the number of new infections had already peaked and people were realizing that the adverse effects of the swine flu were rather weak (Seuchen-Info, 2010). Due to this observation, the population considered the vaccination as unnecessary, and vaccine demand dropped dramatically. This development had disastrous financial implications. From the overall production of 34 million doses, 29 million doses remained idle and had to be destroyed at the end of the flu season. The total costs of this mistimed market introduction were estimated to surpass $300 million (Briseño, 2011).

Cisco Systems Inc. is a famous example for a company that experienced the severe repercussions of offering the right products at the right time but in the wrong quantity. Due to unexpectedly strong demand, Cisco faced a $3.8 billion backlog in customer orders in October 2000 (Lakenan et al., 2001). Because this inventory shortage clearly limited Cisco's profitability, Cisco heavily expanded production capacities to build sufficient stocks to meet future customer demand. During this adaptation of the desired inventory levels, however, customer demand massively dropped. Eventually, Cisco was forced to write-down $2.25 billion in inventories in 2001 due to excessive stocks.

The above examples clearly demonstrate that a firm has to overcome manifold challenges on its way to a good match between supply and demand. Importantly, these challenges evolve dynamically over time as a product matures. At the very beginning, the firm's most important task is to choose the *right products* and to allocate scarce resources across multiple product ideas. Then, once a product is fully developed, the firm has to decide on the *right time* to make the product available on the market. Finally, after the product's introduction, the firm has to keep the *right quantity* of inventories on stock to best satisfy customer demand. Moreover, firms also have to account for the mutual interdependencies between these fundamental decisions. This dissertation examines specific challenges that a firm experiences during these three different stages of a product's life, and provides explicit guidance on how to efficiently manage the tradeoffs involved.

The first essay (joined work with Nektarios Oraiopoulos and Vincent Mak), presented in Chapter II, investigates a significant organizational challenge that is inherent to many R&D projects: How can a firm get informed opinions about a product's future market value when the people with the best information are the ones who most want to see their product succeed? This problem is particularly relevant when the different units who run these R&D projects compete among each other for scarce resources. Given the high uncertainty embedded in R&D projects, firms struggle to detect the most promising projects early on. To overcome these difficulties and to make good resource allocation decisions, the firm needs to collect valuable information. However, information sharing among the different units cannot be taken for granted. Instead, individual units need to be incentivized to not only evaluate their projects thoroughly, but also to truthfully reveal their findings. The former requires an emphasis on individual performance, while the latter relies on the existence of a common goal across the organization. Motivated by this commonly observed tension, we address the following question: How can a firm incentivize individual project teams to exert effort to improve the evaluation of their own projects, and at the same time achieve cooperation and information sharing across the different teams?

To answer this question, we develop a game-theoretic model that combines moral hazard during the product evaluation stage with adverse selection during the information revelation stage. In essence, the firm needs to design an incentive scheme that induces project managers to exert effort ex-ante, and to truthfully disclose their findings ex-post. Our analysis reveals that such a contract must incorporate a combination of individual and shared incentives, i.e., a bonus for the manager's own performance and a bonus for the firm's overall performance. Interestingly, we find that managerial compensation decreases in the manager's quality of information: the more precise a manager can determine his product's future market value, the lower his expected compensation. Our study also explores how the incentive misalignment between the managers and the firm affects the firm's evaluation strategy. The firm's limited ability to infer the managers' private information can lead to an under- or over-investment in information. Yet, the firm always spreads its resources into too many products.

Chapter III (joined work with Moritz Fleischmann) looks at two different sources of uncertainty that a firm is confronted with when offering seasonal products. Specifically, for many seasonal products, firms do not only experience uncertainty in the magnitude of customer demand, but also in the timing of the product's actual selling season. This is particularly true for products that are heavily affected by exogenous factors such as weather conditions or the spread of diseases. For these products, a fundamental challenge for each firm is to determine how much inventory to stock, and equally importantly, when to make the products available for sale. Too early, and high opportunity and inventory costs may devour profits. Too late, and the firm loses its customers. Given the need to balance these two adverse effects, we answer the following research question: For a seasonal product, what inventory timing and scale should a firm choose to best satisfy uncertain customer demand over an uncertain selling season?

To address this question, we build an analytical framework that allows a firm to simultaneously choose its inventory scale and timing in order to effectively manage both sources of demand uncertainty. Our results establish that the firm's optimal inventory strategy aims at resolving two intertwined tradeoffs. While the demand scale uncertainty gives rise for the classical newsvendor tradeoff, the timing uncertainty creates a tension between the product's market potential and its market time. In combination, these two tradeoffs create a subtle interaction between the firm's inventory scale and the inventory timing. Surprisingly, we find that the firm may raise its inventory levels when the product's market potential decreases. This happens because the firm can at the same time shorten the product's availability period, and a shorter selling season is cheaper to serve. Importantly, we also show that the timing uncertainty has more severe repercussions on a product's profitability than an unknown demand scale. The reason for this finding is that the firm is not able to lower the product's inventory costs without at the same time reducing the product's market potential.

The study presented in Chapter IV (joined work with Moritz Fleischmann) takes a different perspective by focusing on a specific coordination issue arising in supply chains. In particular, we investigate how customer substitution influences the inventory decisions of different supply chain members in the presence of upstream competition and vertical information asymmetry among the supply chain partners. Our study is motivated by our observations in the agrochemical market. This market is shaped by two key characteristics: customers have a high willingness to buy substitute products in case of stock-outs, and manufacturers initiate their production long before the wholesalers commit to their final order quantities. As a result, making good inventory decisions is a challenging task for both manufacturers and wholesalers. This is true because manufacturers have only limited information about the wholesaler's future order quantities, and they need to anticipate their rivals' behavior and the indirect effects of substituting customers. The wholesaler, in turn, is restricted in his decision by the manufacturers' inventory decisions. Additionally, the wholesaler has to balance inventories across products in order to successfully manage the direct effects of customer substitution. Inspired by these observations, we study the following question: Given customer substitution and a finite selling season, what are the optimal inventory decisions of different members of a supply chain?

To answer this question, we study a two-stage supply chain in which potentially multiple manufacturers sell partially substitutable products for a single season through a monopolistic wholesaler. Our analysis establishes the wholesaler's optimal inventory decision. We find that inventory levels are non-monotonic in the manufacturers' production decision and customer substitution rates. Interestingly, the wholesaler may increase inventories for a product although customers are more willing to substitute away from this product. We find that these counter-intuitive results are the more prominent, the more heterogeneous the products and the higher the customers' willingness to buy substitute products. We also explore a manufacturer's optimal inventory decision. Surprisingly, our study reveals that inventories may decrease under competition. This happens because a monopolistic manufacturer can coordinate the availability of all products, while such an availability tradeoff is impossible under competition. Moreover, we show that a manufacturer's left-over inventories at the end of the selling season may decline even when initial inventories are raised.

Chapter II

Resource Allocation Decisions under Imperfect Evaluation

with Nektarios Oraiopoulos and Vincent Mak[1]

2.1 Introduction

Launching new products has always been a daunting task even for the most successful organizations. Scholars early on highlighted that given the high uncertainty embedded in such projects, identifying the "winners" upfront is rather unlikely, and as such, committing substantial resources early on may not always be the most prudent strategy. Instead, scholars suggest that a firm should engage in parallel pursuits, and refine its resource allocation decisions as more information becomes available (Nelson, 1961). A parallel search approach allows a firm to explore a much broader set of ideas (Kornish and Ulrich, 2011), develop a much more robust and adaptable business strategy (Beinhocker, 1999), and gain a competitive advantage in environments characterized by unforeseeable uncertainty and complex performance landscapes (Sommer and Loch, 2004). Despite these indisputable benefits, the management of parallel projects involves substantial challenges. A fundamental one stems from the fact that these projects often co-exist within a product portfolio, and therefore, compete with each other for the same scarce resources. This challenge is widespread in companies that manage parallel projects and is nicely summarized in Sharpe and Keelin (1998, p.45): *"how do you make good decisions, in a high-risk, technically complex business when the information you*

[1]The research presented in this chapter is based on a paper entitled "Resource Allocation Decisions under Imperfect Evaluation and Organizational Dynamics", coauthored with Nektarios Oraiopoulos and Vincent Mak.

need to make those decisions comes largely from the project champions who are competing against one another for resources?" This is the primary question we address in this essay.

This question is particularly relevant in industries where tough resource allocation decisions need to be made. For example, given its skyrocketing costs and its highly uncertain nature, the pharmaceutical industry has been struggling to improve its decision making processes. Consider the recent restructuring of GlaxoSmithKline (GSK) discussed in Huckman and Strick (2010). When GlaxoWellcome and SmithKline Beecham merged in 2000, the new company announced the creation of six independent Centers of Excellence for Drug Discovery (CEDD) focused on different therapeutic areas, a unique concept that sought to bring the entrepreneurial culture of a biotech R&D to the gigantic new company. If a compound progressed through Phase IIa, the leadership of the CEDD unit would present the compound to the centralized Development Investment Board (DIB) which would ultimately decide whether the compound would receive the substantial resources required to progress to Phase IIb. A key aspect of this restructuring was the incentive scheme which, in an effort to promote decentralization and mimic small biotech companies, offered substantial rewards to scientists and executives for progressing compounds that originated from their own CEDD. Naturally, this policy raised serious concerns about the emergence of ferocious competition among the different CEDDs.

A diametrically opposite reward structure was adopted by Wyeth Pharmaceuticals (Huckman et al., 2010). The fundamental premise of Wyeth's restructuring efforts was to motivate scientists to look beyond their departmental "silos" and strengthen synergies across the various therapeutic areas, and as such, the bonuses of all eligible scientists in R&D were based on the degree to which the entire organization achieved its objectives. In general, promoting such synergies is perceived to be beneficial for organizations, but in the case of running parallel projects it is often considered absolutely vital as such shared incentives facilitate better communication across the organization. This is stressed in Loch et al. (2006, ch. 6) who argue that the successful implementation of running parallel projects critically relies on the ability of top management to elicit credible information from their product development teams, and subsequently disseminate this information to the rest of the organization. This information, in turn, is the key to efficient resource allocation decisions that strengthen "star" projects and abandon "flops". Under this collective reward policy, however, a key concern at Wyeth was that it failed to reward exceptional achievements by specific project teams.

The goal of this essay is to understand how a firm should design its incentive schemes in order to balance these two opposing forces: to incentivize individual project teams to exert effort to improve the evaluation of their own projects with the need to achieve cooperation and information sharing across the different project teams. Specifically, and given the information-intensive nature of such resource allocation decision processes, we address the following question: how can a firm balance individual and shared incentives, so that its product managers are willing to acquire the necessary information, and equally importantly, to share it with the rest of the organization?

It is worth noting that in such highly technical and complex environments as the ones faced in the pharmaceutical industry, neither the acquisition nor the dissemination of reliable information can be dictated by traditional top-down management approaches. As Sharpe and Keelin (1998) explain, traditional top-down approaches are ineffective because no single executive could know enough about the highly complex projects that the company is considering. Moreover, even the most sophisticated quantitative approaches have limited value given that it is impossible for senior management to see the *"quality of thinking"*[2] behind those valuations. As a result, project funding decisions were primarily driven by the advocacy skills of project champions. The following quote by one of the executives highlights quite vividly his perception regarding the lack of transparency in the evaluation process: *"Figures don't lie, but liars can figure."* (Sharpe and Keelin, 1998, p. 46). To capture these two key aspects of the decision making process, we develop a game-theoretic model that combines moral hazard ex-ante (at the information acquisition stage) with adverse selection ex-post (at the information revelation stage).

Our study makes three contributions to the existing literature. First, we show that by offering a combination of individual and shared incentives, the firm can incentivize managers to undertake highly accurate evaluation efforts and to truthfully disclose their findings. Interestingly, more accurate information leads to lower pay-performance sensitivity for both the individual and shared incentives. This highlights a key difference between incentivizing information acquisition and inducing higher efforts in a moral hazard setting where an agent's effort (stochastically) improves the outcome of the project. For the latter, standard principal-agent theory suggests that pay-performance sensitivity increases as the effort has more influence on the final outcome, i.e., as the environment

[2]This term was used by one of the executives in Sharpe and Keelin (1998) to illustrate that senior managers could not rank these recommendations with respect to their rigor or robustness.

becomes less noisy (e.g., Holmstrom, 1979). In contrast, we show that if the agent can obtain a less noisy signal about the outcome, his pay-performance sensitivity decreases. Moreover, the total wage of a project manager decreases as the accuracy of his information increases. The reason behind this counter-intuitive finding is that, through the incentive mechanism, more accurate information leads to a better alignment between the managers' and the firm's interests, thereby reducing the managers' information rents.

Second, we show that the misalignment of incentives (hereafter referred to as decentralization) between the firm and its product managers has a non-uniform effect on the firm's product evaluation strategy (i.e., the decision on how much information to acquire ex-ante). As we would expect, decentralization increases the effective cost of such information, and therefore, for a wide range of parameters, the firm under-invests in information acquisition. However, for intermediate information acquisition costs and very reliable information, decentralization may lead the firm to over-invest in information. This result is driven by top management's inability to distinguish informative signals from uninformative ones when project managers possess private information. Importantly, this has implications for the firm's product portfolio scope: decentralization is driving the firm to spread its resources into too many products. Lastly, our analysis identifies under what conditions higher information accuracy and acquisition costs might amplify or mitigate the firm's profit losses and the total welfare losses due to decentralization.

2.2 Related Literature

The challenges associated with resource allocation processes have been central in the new product development (NPD) literature. A thorough review of this literature can be found in Kavadias and Chao (2007). Recently, an emerging stream has accounted for the decentralized nature of modern NPD processes (Terwiesch and Xu, 2008; Siemsen, 2008; Chao et al., 2009; Sommer and Loch, 2009; Mihm, 2010; Mihm et al., 2010; Xiao and Xu, 2012) and the reality that incentive mechanisms play a central role in such processes. The effect of incentive schemes on the effectiveness of resource allocation processes is more explicitly studied in Chao et al. (2009), Hutchison-Krupat and Kavadias (2013), and Chao et al. (2013). Chao et al. (2009) compare a policy in which a senior manager empowers the divisional manager to adapt the innovation budget to the divisional sales versus a policy in which the senior manager directly controls the division through a fixed budget. Hutchison-Krupat and Kavadias (2013) characterize optimal funding decisions across different resource allocation processes such as top-down, bottom-up, and strategic buckets. Lastly, Chao et al. (2013) study incentive schemes in a stage-gate process where senior management has to rely on a privately informed project manager in order to make go/no-go decisions. They emphasize the role of uncertainty regarding the quality of the project idea, and show how it might make an organization overly conservative in its project selection process, i.e., projects that would have been profitable do not get approved. We contribute in the above stream of resource allocation processes by capturing the dynamics arising when multiple product managers compete for the same resources. All of the aforementioned papers are concerned with the level of resources allocated to a single product, and as such, they do not address the challenges associated with managing a portfolio of projects.

To our knowledge, the only other paper that analyzes incentives for parallel projects is Ederer (2013). By combining both a theoretical and experimental analysis, he shows that when workers can freely learn the best practices from each other, the firm can only incentivize innovation by establishing group incentives. This happens because individual pay-for-performance incentive schemes encourage imitation and free-riding on the successful ideas of others. While we also highlight the importance of group incentives for an organization developing new products, our work differs from Ederer (2013) in several aspects. Most notably, in our setting the outcome of the product evaluation is not public information, and thus, the firm needs to incentivize the managers to reveal their information truthfully. Another recent stream of work in NPD has studied parallel search in the context of innovation tournaments (Terwiesch and Xu, 2008; Kornish and Ulrich, 2011; Boudreau et al., 2011), but the tradeoffs involved in these settings are considerably different than the resource allocation decisions within a single firm. As such, despite the extensive discussion in the NPD community about the necessity of running parallel projects (see Loch et al., 2006, and references therein) we know very little about how to manage such a process within the boundaries of the firm.

Our work also touches upon a central question in the capital budgeting literature in corporate finance. The stream most related to our setting begins with the seminal work of Stein (1997) which focuses on the role of corporate headquarters in allocating resources among competing projects. In particular, he compares the efficiency of internal capital markets with respect to the external ones. In a series of follow-up papers, Bernardo et al. (2001), Stein (2002), and Inderst and Laux (2005) examine the role of incentives in mitigating agency costs, and specifically, the potential private benefits that agents enjoy from controlling more capital, thereby reflecting a preference for "empire building". Closer to our work, Friebel and Raith (2010) develop a model in which pay-for-performance incentives create an endogenous empire building motive, which in turn, might prevent a manager from truthfully communicating his private information. They show that the firm can induce truthful communication by using shared incentives, and they compare the benefits and costs of integration once such information rents are taken into account.

All of the above papers assume that information regarding the type of the project is perfect and freely available to the agent, but not to the principal. On the contrary, in our setting, acquiring reliable information is associated with substantial costs incurred privately by the agent, and thus, the agent will only exert that effort if he is incentivized to do so. To the best of our knowledge, the only other paper that studies project selection when the agent is incentivized to acquire costly information is Lambert (1986). Our model, however, differs in a number of ways. Most notably, Lambert (1986) considers a single-agent setting, and as such, his model does not address the issues that we discussed earlier regarding competition for resources among parallel projects.

2.3 Model Setup

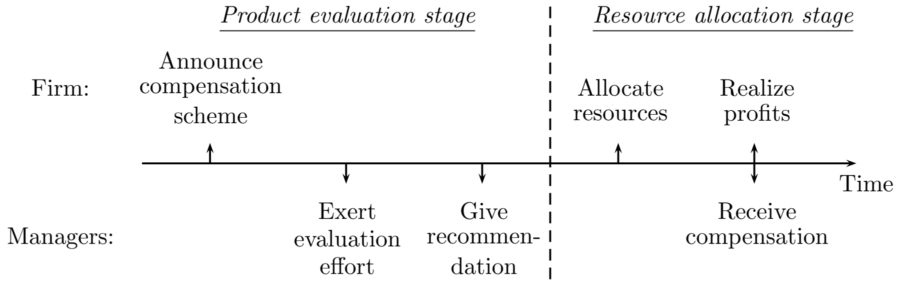
Consider a firm that is faced with the decision of allocating its resources across multiple projects. The key decision for the firm is whether to choose a narrow product portfolio scope or a broader one. To capture this tradeoff in a mathematically tractable way, we assume that the firm is contemplating two projects, and we examine under what conditions the firm decides to allocate all of its resources in a single project (narrow scope) versus spreading them evenly across both projects (broad scope). The market value that the firm realizes from each project depends on two parameters: (i) the inherent market potential of each project, which is uncertain upfront and can be either good or bad; and (ii) the resources that the firm invests in the project. The firm seeks to maximize its profits by allocating resources to good projects and forgoing investments in bad ones.

A central element of our model is the product evaluation stage in which the firm can acquire costly information regarding each project's potential. This information is acquired through extensive experimentation by each project's respective product manager. Then, upon observing the outcome of this experimentation process, each product manager makes a recommendation to the senior management of the firm (from hereon, the firm), and the firm decides how much resources to allocate in each project. For example, in the case of GSK, the head of each R&D unit (i.e., of each CEDD) would present a compound to the centralized Development Investment Board, and subsequently, the board members would decide about the progress of the compound in the next stage (the extremely resource-intensive Phase IIb). Similarly, at Wyeth there was a centralized Discovery Review Board that was responsible for making funding decisions across all therapeutic areas. As discussed extensively in the aforementioned examples, the "quality of thinking" behind such recommendations by the product managers is very hard to verify, and even less so to contract upon. As such, there can be considerable information asymmetry between the product managers and the firm.

In our setting, the presence of information asymmetry is reflected both in the "quality of thinking" as well as in the truthfulness of the recommendation that the product managers submit to the firm. We model the former by acknowledging that information acquisition (e.g., experimentation) is a costly process and can be done at various levels of quality (e.g., robustness checks may satisfy only some minimum standards, or may be very thorough). In particular, we assume that each product manager can choose between a high-effort and a low-effort evaluation process for his product. The chosen effort level is not observed by the firm. For the manager, high-effort evaluation comes with a private cost, while the cost of low-effort evaluation is normalized to zero. The latter form of information asymmetry aims to capture the fact that not all product managers truthfully communicate the results of their experimentation, especially when they compete for resources with one another. In short, our model incorporates ex-ante moral hazard (at the information acquisition stage) with ex-post adverse selection (at the recommendation stage), and as such, if the firm desires high-effort product evaluation and truthful recommendations, it has to design appropriate incentive schemes. Lastly, upon observing the managers' recommendation, the firm decides on its resource allocation strategy.

To summarize, the sequence of events is as follows (see Figure 2.1): (i) The firm announces the compensation scheme to the product managers; (ii) Each manager chooses his evaluation effort levels and incurs the associated private effort costs; (iii) Then, each manager observes a private and imperfect signal and makes a recommendation to the firm regarding his product's potential; (iv) Based on the managers' recommendations, the firm allocates resources to the products; (v) The products are launched and their market value is realized. The firm receives the corresponding payoffs and compensates its managers. In the following three subsections, we explain our modeling assumptions regarding the above stages in more detail.

Figure 2.1.: Timing of events.



The Product Evaluation Stage

New projects carry significant uncertainty regarding their market potential. We capture this uncertainty by assuming that two ex-ante identical products i and j can either have high ($\theta_i = G$) or low ($\theta_i = B$) market potential.[3] The true potential of each product is unknown to the firm and its managers, and both states are considered ex-ante equally likely.[4] By evaluating his product, manager i receives an imperfect signal $s_i \in \{g, b\}$ which indicates whether product i has high ($s_i = g$) or low ($s_i = b$) market potential. In line with prior work on NPD (Loch et al., 2001; Thomke, 2007), we capture the informativeness of the signal for both products i and j by the parameter q to which we refer to as signal *fidelity*. Mathematically, q represents the conditional probability that the signal is reflective of the true market potential, i.e., $Pr(s_i = g|\theta_i = G) = Pr(s_i = b|\theta_i = B) = q$. Importantly, the fidelity q depends on the chosen effort level e_i which can be high ($e_i = h$) or low ($e_i = l$). High-effort evaluation requires a cost $c > 0$ which is privately incurred by the product manager, and results in a signal of fidelity $q \in \left(\frac{1}{2}, 1\right]$. In contrast, low effort is costless for the product manager, but results in

[3]For notational simplicity, we define explicitly only the parameters for project i. An identical set of parameters applies for product j as well.

[4]This assumption is done for expositional clarity and does not affect qualitatively any of our results.

an uninformative signal, i.e., $q = \frac{1}{2}$. Note that our assumptions cover the full range of product evaluation difficulty. We capture products that are so complex such that high-effort product evaluation only leads to a marginal information gain, and we also capture very simple products for which high-effort evaluation perfectly reveals the product's market potential.

Upon observing the signal s_i, manager i revises his prior belief for his product's market potential to account for the new information. In particular, since both states are ex-ante equally likely, the posterior beliefs are given by $Pr(\theta_i = G|s_i = g) = Pr(\theta_i = B|s_i = b) = q$. Then, manager i submits his recommendation $m_i \in \{g, b\}$ about his product's potential to the firm. If $m_i = s_i$, then a manager truthfully reveals his signal. Thus, manager i's action space is fully characterized by his product evaluation effort, e_i, and his subsequent recommendation, m_i.

The Resource Allocation Stage

Once the firm receives the managers' recommendations, then it has to decide on whether to allocate all of its resources to a single product or split them evenly between products i and j. The market value to the firm generated by product i, denoted by ν_i, depends on both, its inherent potential θ_i as well as the amount of resources invested in it.

More specifically, we assume that if product i has a bad market potential ($\theta_i = B$), then it generates zero market value regardless of the resources invested into it. Similarly, a product that has a good potential ($\theta_i = G$), but does not receive any resources for development, also generates zero market value. In contrast, for products of good potential that receive resources, their generated value increases as more resources are allocated to them because more resources improve a product's quality and thus its market value. In particular, if the firm splits resources evenly across two products, then each *good* product's market value is $v_1 > 0$. If the firm allocates all resources to a single good product, then this product's market value is $v_2 > v_1$. The above mathematical expressions imply that resources create value when they are allocated to products with good potential, while resources are wasted when they are allocated to products of bad market potential.

Note that if the firm realizes increasing returns, i.e., $v_2 > 2v_1$, then the choice of product portfolio scope becomes a trivial question as it is always optimal to allocate all resources to a single project. Therefore, in the remainder of this essay, we focus on the more interesting case where the marginal value of investing more resources in a product is decreasing, i.e., $2v_1 > v_2$. In other words, all else being equal, allocating one unit of resources to two good products yields higher profits that allocating both units into a single good product. This assumption is also in line with recent empirical work that shows that firms with a broader product portfolio scope experience higher performance (Klingebiel and Rammer, 2014).

The Compensation Scheme

As discussed in our motivating examples companies often struggle to strike a balance between individual incentives (e.g., rewarding a specific CEDD for its performance in the case of GSK) and shared incentives (e.g., as in Wyeth where divisions were rewarded based on the R&D performance of the entire organization). While the former is typical in agency relationships and requires little justification, our model also illustrates why, in many settings, the latter might be equally important. In particular, it can be readily seen that, if a manager's payoff depends only on the performance of his own product, then the manager is always better off by communicating a positive recommendation for his product, so that he receives more resources from the firm. Thus, information becomes unreliable, and therefore, irrelevant for the resource allocation decisions of the firm. However, once shared-incentives are included in the compensation scheme, a manager who observes a bad signal, and anticipates that his product is likely to fail, becomes more likely to "step aside" and allow his peer's product to receive more resources.

In line with prior literature on shared-incentives (Rotemberg and Saloner, 1994; Siemsen et al., 2007; Friebel and Raith, 2010), we focus on compensation schemes of the following structure: $\hat{w}_i = k_0 + k_s\nu_i + k_p\nu_j$, where k_0 is a fixed wage, k_s is the self-product sensitivity that determines the manager's share from the performance of his own product, and k_p is the respective peer-product sensitivity.[5] Our compensation scheme is mathematically equivalent to $\hat{w}_i = k_0 + (k_s - k_p)\nu_i + k_p(\nu_i + \nu_j)$. Intuitively, $(k_s - k_p)$ determines the share that each manager receives from his own product's value, and k_p determines the share that the managers receive from the firm's overall performance. Consistent with the aforementioned papers, we restrict attention to linear compensation contracts that are symmetric between the two agents.

[5]Where appropriate, we use the notation $\hat{x}$ to denote a random variable, and distinguish it from its expected value which, for notational convenience, we denote by x.

We employ a linear compensation scheme for three reasons. First, under fairly general conditions, Holmstrom and Milgrom (1987) have shown that optimal compensation schemes are linear in the aggregated outcome when agents influence outcomes through a series of actions. Based on this fundamental result, linear compensation schemes have become pervasive in the academic literature when studying, e.g., incentive design (Siemsen et al., 2007), relative performance evaluation (Aggarwal and Samwick, 1999), optimal organizational forms (Friebel and Raith, 2010), or sales force management (Caldieraro and Coughlan, 2009). Second, contract linearity allows us to derive analytical results in a complex setting that combines ex-ante moral-hazard with ex-post adverse-selection, and facilitates the required mathematical exposition. Lastly, linear schemes are intuitive and easily implementable, and thus, widely found in practice. For example, at Wyeth employees received shares of an overall bonus pool.

Our focus on symmetric contracts is based on the theory of equity (Adams, 1963). In the words of Akerlof and Yellen (1988, p.45): *"All textbooks consider it self-evident that the most important aspect of a compensation system is its accordance with workers' conceptions of equity"*. A more detailed discussion about the numerous studies that provide support for this theory can be found in Akerlof and Yellen (1990), Fehr and Schmidt (1999), and Bolton and Ockenfels (2000). In our setting, given that managers are ex-ante identical, an asymmetric contract would be hard to put in place without the firm suffering severe repercussions from the managers' sense of unfairness. As such, in the remainder of our analysis we assume a symmetric contract structure. It is worth noting though, that our characterization of the optimal product evaluation strategy holds for asymmetric contract structures as well (the analysis is available upon request from the authors).

Given the compensation $\hat{w}_i$, manager i's utility $\hat{U}_i$ is comprised of $\hat{w}_i$ net his effort cost, i.e., $\hat{U}_i = \hat{w}_i - cI_{\{e_i=h\}}$, where $I_{\{A\}}$ is the indicator function of event A. Following a typical assumption in the principal-agent literature, we assume that the managers have limited liability, i.e., $\hat{w}_i \geq 0$. We also assume that the managers are risk-neutral. As a result, the fixed term k_0 only raises wages without inducing effort, so it is always optimal for the firm to set $k_0 = 0$. Thus, the optimal compensation scheme is uniquely defined by the tuple $k = (k_s, k_p)$. Finally the firm's profit is the sum of the market value of all of its products minus the agents' compensation, which can be written as $\hat{\Pi}(k) = (1 - k_s - k_p)(\nu_i + \nu_j)$. For ease of exposition, we refer to manager i's expected wage and utility, and the firm's expected profit by w_i, U_i, and Π, respectively, where the expectation is taken over the products' market potential, θ.

2.4 Analysis

In this section we characterize the firm's optimal product evaluation and resource allocation strategy. To ensure that the derived equilibrium solution is subgame perfect, we solve our model by backwards induction. Therefore, we first determine the firm's optimal resource allocation policy for any given outcome of the product evaluation stage (section 2.4.1). Then, we characterize the optimal product evaluation strategy (section 2.4.2) given that the firm acts rationally (i.e., maximizes profits) in the resource allocation stage. In doing so, we also derive the optimal contract structure for each type of product evaluation strategy, and thus, account for the information rents that the firm incurs for each strategy.

2.4.1. The Optimal Resource Allocation Strategy

Once the firm receives the recommendations of the two managers, it decides on how much resources to allocate to each product. Clearly, a manager's recommendation is useful to the firm only if the manager reports truthfully his signal, and additionally, he exerted a high-effort product evaluation. When the managers do not report truthfully their signals, their recommendations are not informative to the firm. Consequently, the firm allocates the resources based on its prior beliefs, which implies that resources should be split evenly across products. When the managers report truthfully their signals, the firm needs to consider three different cases for the evaluation stage: (i) both managers exert low effort, $e = (l, l)$; (ii) manager i exerts high effort, while manager j exerts low effort, $e = (h, l)$; and (iii) both managers exert high effort, $e = (h, h)$.[6] Then, an optimal resource allocation strategy maps the managers' product evaluation strategy $e = (e_i, e_j)$ together with the received recommendations $m = (m_i, m_j)$ into the resource allocation strategy that maximizes expected profits. Note that, as we show in the next section, through the design of an appropriate contract, the firm can always anticipate the evaluation strategy of its managers and whether or not they report truthfully their

[6] Throughout, we adopt the convention that in case of asymmetric effort levels, manager i always exerts high effort, while manager j exerts low effort.

signals. Lemma 2.1 fully characterizes the firm's optimal resource allocation for any possible state of e and m. All proofs are provided in Appendix A.

Lemma 2.1. *Define* $q_a \equiv v_1/2(v_2 - v_1)$, $q_b \equiv (3v_1 - v_2)/2v_1$, *and note that* $v_1/v_2 < q_b < q_a$. *Then, for a given evaluation strategy* e, *a signal fidelity* q, *and received recommendations* m, *the firm's optimal resource allocation is summarized in Table 2.1, where "—" indicates that the result holds for any possible realization of the respective parameter.*

Table 2.1.: Optimal resource allocation.

Evaluation Efforts $e = (e_i, e_j)$	Signal fidelity q	Received recommendations $m = (m_i, m_j)$	Optimal resource allocation
(l, l)	—	—	split evenly
(h, l)	$q < q_b$	—	split evenly
	$q_b \leq q < q_a$	$(g, -)$	split evenly
		$(b, -)$	all to product j
	$q_a \leq q$	$(g, -)$	all to product i
		$(b, -)$	all to product j
(h, h)	$q \leq v_1/v_2$	—	split evenly
	$q > v_1/v_2$	(g, b)	all to product i
		(g, g)	split evenly
		(b, b)	

Lemma 2.1 presents some intuitive properties of the firm's optimal resource allocation strategy. First, when both managers exert low effort, the firm does not receive any useful information, so it decides to split resources evenly across the two products. In the case where only manager i pursues high-effort evaluation for his product, then the firm will only direct all of its resource to the most promising product, if the information fidelity is high enough. Otherwise, if $q < q_a$ ($q < q_b$), then the good (bad) signal for product i is discarded, and resources are still split evenly. The last case also highlights the substitution effect between the two products: even if there is no high-effort recommendation for the product at hand (in this case product j), it might still be optimal to invest all resources into it as long as there is reliable information that product i is of low market potential. Lastly, when both managers exert high effort, the optimal resource allocation depends on both managers' recommendations. If the two managers give identical recommendations for the products, then, again, an equal split of the resources is the preferable choice. If, on the other hand, the recommendations are different, then all resources should be directed to the most promising product.

2.4.2. The Optimal Product Evaluation Strategy

Given the firm's optimal resource allocation strategy, we are now ready to derive the firm's optimal product evaluation strategy. Our analysis proceeds in two steps. We begin by establishing the first-best benchmark under the assumption that the product managers and the firm are integrated as a single entity. This allows us to illustrate the key properties of the optimal product evaluation strategy based on the firm's operating environment, namely, the information fidelity, q, and the information acquisition cost, c (Proposition 2.1). Then, we study how a decentralized firm can induce different product evaluation strategies by designing appropriate incentive structures (Propositions 2.2 and 2.3), and subsequently, we derive the optimal product evaluation strategy of a decentralized firm (Proposition 2.4).

The Integrated Firm

The integrated firm's optimal product evaluation strategy solves

$$e^*_{fb} = \arg\max_{e} \Pi^{fb}(e),$$

where $\Pi^{fb}(e) = \mathbb{E}_\theta[\nu_i + \nu_j|e] - c(I_{\{e_i=h\}} + I_{\{e_j=h\}})$ denotes the firm's ex-ante expected profit under the evaluation strategy e.

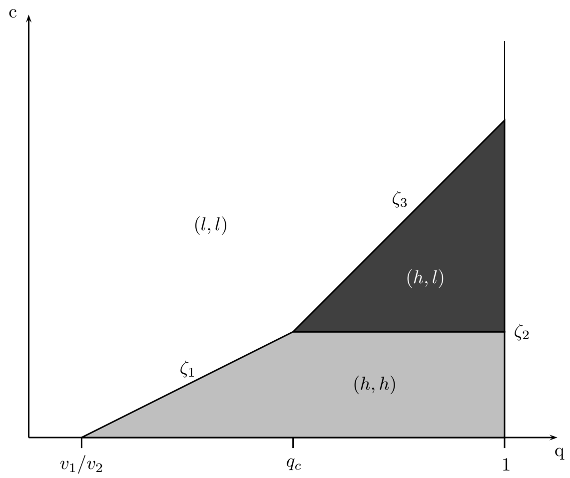
Proposition 2.1. *Let $q_c \equiv (3v_1 - v_2)/v_2$, and define $\zeta_1 \equiv \frac{1}{4}(qv_2 - v_1)$, $\zeta_2 \equiv \frac{1}{4}(2v_1 - v_2)$, and $\zeta_3 \equiv 2\zeta_1 - \zeta_2$. The integrated firm's optimal product evaluation strategy is as follows:*

(i) If $q < q_c$, then, $e^*_{fb} = (h,h)$ for $c \leq \zeta_1$; and $e^*_{fb} = (l,l)$ elsewhere.

(ii) If $q \geq q_c$, then, $e^*_{fb} = (h,h)$ for $c \leq \zeta_2$; $e^*_{fb} = (h,l)$ for $\zeta_2 < c \leq \zeta_3$; and $e^*_{fb} = (l,l)$ elsewhere.

Figure 2.2 visualizes the results of Proposition 2.1 and illustrates the key properties of the first-best evaluation strategy. Firstly, as we would intuitively expect, high-effort evaluation is undertaken only when the information fidelity is sufficiently high, $q > \frac{v_1}{v_2}$, and the evaluation cost sufficiently low, $c \leq \max\{\zeta_1, \zeta_3\}$. Otherwise, the value of information does not justify its cost, and the firm decides to forgo the rather inefficient evaluation process. Remarkably, even if evaluation costs are zero, the firm never exerts high-effort product evaluation if $q \leq \frac{v_1}{v_2}$. In this case, effort is meaningless because the

Figure 2.2.: The integrated firm's optimal product evaluation strategy.



Notes: The firm's optimal product evaluation strategy is (i) $e^*_{fb} = (h,h)$ in the light gray region; (ii) $e^*_{fb} = (h,l)$ in the dark gray region; and (iii) $e^*_{fb} = (l,l)$ in the white area.

information fidelity is so low that product evaluation cannot reliably identify a product's market potential.

Secondly, for moderate q values ($\frac{v_1}{v_2} < q < q_c$), the firm adopts a rather coarse evaluation strategy by either exerting high effort for both products or none. However, for higher q values ($q \geq q_c$) and moderate costs c ($\zeta_2 < c \leq \zeta_3$), the firm finds it optimal to pursue high-effort evaluation for only one of its products. In fact, even if the firm can obtain perfect information, i.e., q approaches 1, it still remains optimal to pursue only low-effort evaluation for the second product. Moreover, if a product's market value is relatively insensitive to the allocated resources, i.e., $v_2 < \frac{3}{2}v_1$, then the asymmetric effort strategy, $e = (h,l)$, is never optimal (i.e., $q_c > 1$). On the contrary, if the market value is very sensitive to the invested resources (v_2 approaches $2v_1$), then pursuing high-effort for only a single product is optimal for a wide range of parameters (as q_c approaches $\frac{1}{2}$).

The Decentralized Firm

In this section, we account for the decentralized nature of modern NPD projects, and the potential misalignment of incentives that stem from it. As such, to elicit the necessary information the firm needs to design appropriate incentive schemes. As discussed earlier, managers can pursue three different evaluation strategies, and to induce each one of them, the firm needs to offer a different incentive scheme. Thus, to derive the firm's optimal product evaluation strategy we first need to account for the managers' information rents that vary across these contracts.

Throughout our analysis, we focus on truth-inducing contracts. Intuitively, non-truth-inducing contracts provide no value to the firm, and therefore, the firm would never reward a manager for providing useless information, i.e., $k_s = k_p = 0$ for any non-truth-inducing contract. Moreover, the next Lemma states that a contract that incentivizes only one product manager to exert high-effort evaluation can never be incentive compatible. Intuitively, given ex-ante identical managers, if the contract terms are such that one of the managers decides to exert high-effort, so does the other.

Lemma 2.2. *No feasible truth-inducing symmetric compensation scheme exists such that, in equilibrium, managers choose different effort levels during product evaluation.*

By Lemma 2.2, to find the firm's optimal product evaluation strategy, we only need to investigate the firm's optimal contract that induces truth-telling and high effort by either both managers or neither. Consider first the simpler case where the firm incentivizes both managers to pursue a low-effort evaluation strategy. In that case, the optimal contract is $k_s = k_p = 0$. This contract is clearly incentive compatible in effort because no manager has an incentive to exert high effort, since then he would incur a cost without receiving any reward. In short, the firm can induce low-effort product evaluation by simply offering no reward to its managers, and in that case, the firm optimally splits resources evenly across products (since $v_2 < 2v_1$) to obtain an expected profit $\Pi(k = (0, 0)) = v_1$.

We now examine the more interesting case where the firm incentivizes both managers to exert high-effort evaluation and to truthfully report their signals. In that case, the firm's objective is to maximize the expected value of both products net the managers' wages. More formally, the firm solves the following optimization problem (the exact derivation can be found in the proof of Proposition 2.2):

$$\max_{k_s,k_p} \; \Pi(k) = (1 - k_s - k_p)\frac{1}{2}(qv_2 + v_1) \tag{2.1}$$

$$\text{s.t.} \; k_s q v_2 + k_p q v_1 \geq k_p q v_2 + k_p(1-q)v_1 \tag{IC-g}$$

$$k_p q v_2 + k_p(1-q)v_1 \geq k_s(1-q)v_2 + k_p q v_1 \tag{IC-b}$$

$$2k_s q v_2 - 8c \geq k_s v_2 \tag{IC-e}$$

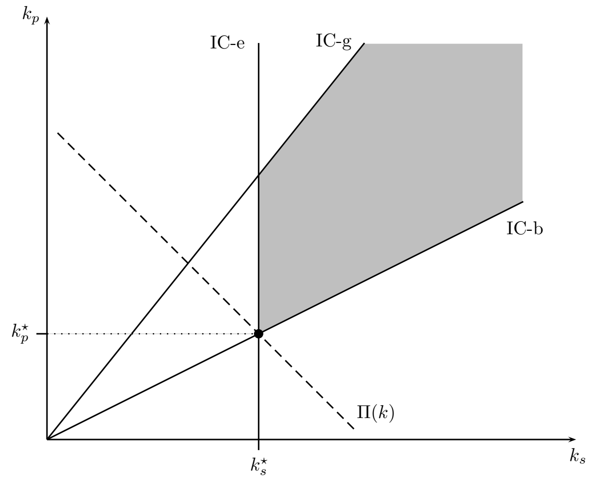
$$k_s, k_p \geq 0. \tag{LL}$$

Constraints (IC-g) and (IC-b) ensure that both managers truthfully reveal a good and a bad signal, respectively. High-effort product evaluation is incentivized by (IC-e), and the limited liability constraint (LL) guarantees that wages are non-negative. Since high effort is costly for the managers, the firm has to pay a strictly positive wage to induce truth-telling and high effort. Thus, (LL) never binds in optimum. In contrast, (IC-e) is always binding because the firm pays just as much as necessary to induce high-effort evaluation. Furthermore, it is harder to motivate a manager to reveal a bad than a good signal. Hence, truthful revelation of bad signals (IC-b) also binds at optimality. Figure 2.3 graphically illustrates the optimization problem and Proposition 2.2 characterizes the optimal contract, $k^\star$.

Proposition 2.2. *The optimal contract that induces truth-telling and high-effort product evaluation by both managers is* $k_s^\star = \frac{8c}{(2q-1)v_2}$ *and* $k_p^\star = \frac{8(1-q)c}{(2q-1)(qv_2-(2q-1)v_1)}$. *Moreover,* $\frac{k_p^\star}{k_s^\star} < 1$ *and the ratio decreases in* q *and* v_2, *while it is invariant in* c.

The optimal contract exhibits several interesting properties. First, with simple algebraic manipulation it can be readily seen that both $k_s^\star$ and $k_p^\star$ decrease in q. In other words, managers who can acquire better information receive a smaller share of each product's value. This counter-intuitive finding can be explained by recalling that the optimal contract is determined by the intersection of constraints (IC-e) and (IC-b) (see Figure 2.3), which ensure high-effort product evaluation ex-ante and truthful revelation of bad signals ex-post, respectively. Consider $k_s^\star$ which is determined solely by constraint (IC-e). From (IC-e) we see that as the fidelity, q, increases, all else being equal, exerting high effort becomes more rewarding for the manager than exerting low effort. This happens because the only reason for the manager to exert high effort is so that he can credibly indicate the product's high potential to the firm, and therefore, request more

Figure 2.3.: The decentralized firm's optimization problem.



Notes: The light gray region indicates the set of all feasible contracts that induce truth-telling and high effort. The optimal contract $(k_s^\star, k_p^\star)$ is at the intersection of (IC-b) and (IC-e).

resources for it. Clearly, the credibility of the manager's recommendations, and thus, his incentive to exert high effort in the first place increase as the information fidelity increases. As such, higher information fidelity makes higher effort more rewarding for the manager. At the same time, the firm realizes that it can now lower the manager's share of his project value, $k_s^\star$, while still ensuring that his effort incentive constraint (IC-e) is satisfied. That is why $k_s^\star$ decreases in q.

To see why $k_p^\star$ decreases in q, recall that the reason why a manager with a bad signal might report a good signal is that he can request more resources for his project. These resources, however, are only beneficial to the manager if his project eventually succeeds in the market. As the information fidelity increases, and given that the manager has observed a bad signal, the likelihood that his project will "defy the odds", and turn into a success, is shrinking. As a result, lying to the firm becomes less rewarding, and all else being equal, the firm can incentivize truth-telling with a lower $k_p^\star$. In fact, if $q = 1$, then $k_p^\star = 0$ (but $k_s^\star > 0$), i.e., the firm completely abandons shared incentives if managers can acquire perfect information. Intuitively, managers always truthfully report their signals, as there is no value in claiming resources for a project that is bound to fail. It is worth noting the stark contrast regarding the effect of a noisier environment on the pay-performance sensitivities (i.e., $k_s^\star$ and $k_p^\star$) between our model and the standard theory on principal-agent models. For instance, Holmstrom (1979) shows that pay-performance sensitivity increases as the effort has more influence on the final outcome, i.e., as the environment becomes less noisy. This comparison highlights the fundamentally different nature of incentives that induce higher effort for information acquisition versus standard moral-hazard settings where an agent's effort stochastically improves the outcome of the project.

Second, both $k_s^\star$ and $k_p^\star$ decrease as v_2 increases, i.e., when allocating all the resources to a single project becomes more rewarding. The former happens because a higher v_2 makes exerting effort more rewarding for the manager: if his project receives the entire resource budget, its market value will be much higher, and so will his share of that value. The latter happens because a higher v_2 makes the manager more willing to disclose a bad signal truthfully: if his peer's product succeeds, he will also receive a share from that high value project. Thus, as v_2 increases, the firm need not pay as high $k_s^\star$ and $k_p^\star$ to incentivize the managers to exert high-effort and report truthfully. Interestingly, $k_s^\star$ is invariant in v_1 while $k_p^\star$ increases in v_1. A higher v_1 erodes the value from ex-post "winner-picking", and therefore, it has the exact opposite effect of v_2 when it comes to incentivizing truth-telling. It has no effect, however, when it comes to incentivizing high effort ex-ante, as due to symmetry the manager might still receive v_1 in either case (i.e., under high or low effort).

Third, the ratio between $k_p^\star$ and $k_s^\star$ decreases in both q and v_2, but it is invariant in c . Figure 2.3 illustrates how $k_s^\star$ ensures high-effort evaluation, while the ratio $\frac{k_p^\star}{k_s^\star}$ ensures truth-telling. To see why the cost c does not affect a manager's truth-telling propensity, note that each manager decides on his recommendation after incurring the effort cost. Hence, effort costs are sunk costs and do not affect a manager's recommendation. To see why $k_p^\star$ is decreasing more steeply in q than $k_s^\star$, note that information of higher fidelity is always more crucial ex-post (i.e., when a bad signal has actually been realized) than ex-ante (i.e., when either a good or a bad signal can be realized). In other words, when choosing his effort level, a manager does not yet know whether a high evaluation fidelity raises or reduces the expected value of his product. Due to this ambiguity, $k_s^\star$ is only moderately decreasing in q. In contrast, when the manager decides whether to truthfully report his bad signal, q has a direct detrimental effect on the value of his project. Therefore, $k_p^\star$ is more sensitive to the manager's information fidelity.

This result bears important managerial implications for the optimal balance between individual and shared incentives. It states that in environments of higher information fidelity (high q) or where "winner-picking" is more crucial (high v_2), the firm needs to shift its focus towards rewarding based on the performance of individual project units rather than on company-wide metrics. So far, our discussion was focused on the pay-performance sensitivities $k_s^\star$ and $k_p^\star$. One might think that even though $k_s^\star$ and $k_p^\star$ decrease in q and increase in c, the total utility of a manager might increase in the fidelity of his information and decrease in his effort costs. Rather surprisingly, Proposition 2.3 shows that this is not the case.

Proposition 2.3. *A manager's expected utility $U_i(k^\star)$ decreases in q and v_2, and increases in c; while the firm's expected profit $\Pi(k^\star)$ increases in q and v_2, and decreases in c.*

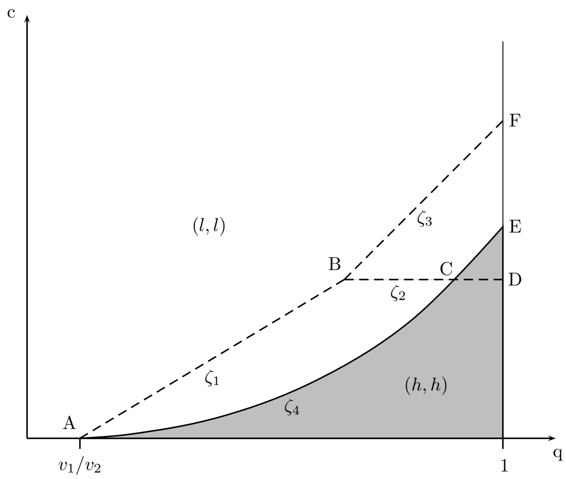
Proposition 2.3 states a counter-intuitive result: a manager's utility decreases in the information fidelity of the evaluation process, that is, when the manager can provide better information to the firm. Similarly, when this information becomes more important (i.e., v_2 increases), the manager's utility decreases as well. Thus, even though a higher q and higher v_2 raise the expected value of each product, the drop in $k_s^\star$ and $k_p^\star$ is so steep that it leaves each manager with a lower expected utility. On the contrary, a manager's utility increases in c as both $k_s^\star$ and $k_p^\star$ increase in c. This can be explained as follows. Recall from our discussion following Proposition 2 that both a higher q and higher v_2 reduce the misalignment in incentives between the managers and the firm. As such, they make the manager more willing to exert high effort and also to disclose his signals truthfully. Conversely, a higher c makes high effort more costly for the manager, and widens the incentive misalignment with the firm. A lower (higher) misalignment in incentives, in turn, results in lower (higher) information rents for the manager, and consequently, to higher (lower) profits for the firm. Having characterized the optimal contract structure, we can now derive the optimal evaluation strategy for the decentralized firm.

Proposition 2.4. *Define $\zeta_4 \equiv \zeta_1 \cdot \frac{2qv_2 - v_2}{2qv_2 + 2v_1} \cdot \frac{qv_2 - (2q-1)v_1}{v_2 - (2q-1)v_1}$. The decentralized firm's optimal product evaluation strategy is to incentivize both managers to exert (i) high effort if $c \leq \zeta_4$; and (ii) low effort if $c > \zeta_4$. Moreover, $\zeta_4 < \zeta_1$ and there exist parameter values such that $\zeta_4 > \zeta_2$.*

As we would intuitively expect, the presence of information asymmetry between the managers and the firm makes the process of product evaluation "more expensive" to the firm. As a result, the area for which product evaluation is undertaken shrinks. This is clearly illustrated in Figure 2.4 which plots the optimal evaluation strategy under decentralization vis-à-vis the optimal policy of the integrated firm (dashed line): In the region ABFEC a decentralized firm does not undertake any high-effort product evaluation but an integrated firm does. Mathematically, this corresponds to $\zeta_4 < \max\{\zeta_1, \zeta_3\}$.

Interestingly, however, this result does not imply that the decentralized firm always undertakes less evaluation effort compared to the integrated one. On the contrary, when $\zeta_4 > \zeta_2$ (region CED in Figure 2.4), the decentralized firm undertakes more evaluation effort by exerting high-effort evaluation for both products whereas an integrated firm exerts high-effort evaluation for only one of them. In other words, the decentralized firm is actually over-investing in information acquisition compared to the first-best policy. This over-investment in information is caused by the firm's inability to observe neither the managers' efforts nor the outcomes of their evaluation. In addition, as discussed in Lemma 2.2, the firm cannot offer a truth-inducing contract that incentivizes a high-effort evaluation for one product and a low-effort evaluation for the other one. Consequently, either manager can claim that he exerted high-effort evaluation, and therefore, request resources for his project.

Figure 2.4.: The decentralized firm's optimal product evaluation strategy.



Notes: The firm's optimal contract induces (i) $e^* = (h,h)$ in the light gray region; and (ii) $e^* = (l,l)$ in the white area.

2.5 The Effect of Decentralization on the Firm's Product Portfolio Scope and Welfare Implications

So far, we have discussed the effect of decentralization on the firm's optimal product evaluation strategy. This evaluation strategy, in turn, determines the information that the firm has available when making its resource allocation decisions, and therefore, the firm's product portfolio scope. While the extant literature in NPD has studied extensively the information acquisition process for a single project (e.g., Thomke, 2007, and references therein) and the resource allocation decisions for the product portfolio (e.g., Kavadias and Chao 2007, and references therein), the effect of the former on the latter has been rather overlooked. In this section, we begin by investigating how changes in the firm's evaluation strategy affect its product portfolio scope. We then examine the firm's profits and the social welfare, and identify the conditions where decentralization leads to greater or lesser profit and welfare losses.

2.5.1. Product Portfolio Scope

Before discussing the effect of decentralization on the firm's product portfolio scope, it is instructive to clarify the relationship between the product evaluation strategy and the product portfolio scope for the integrated firm. From Lemma 2.1 and Proposition 2.1, we have the following direct observations: (i) when the firm pursues low-effort evaluation for both products, it always ends up splitting resources evenly across products, and thus, developing both products; (ii) when the firm pursues high-effort evaluation for only one of the products, and the information is relatively reliable, then the firm always develops a single product; (iii) when the firm pursues high-effort evaluation for both of its products, then it is equally likely that the firm develops one or two products.

In other words, there is a non-monotonic relationship between the extent of product evaluation and the number of products that the firm develops: a firm with little information spreads its risks across both products to increase the chance that at least one product is successful, a partially informed firm makes a crude decision by developing only one, while a fully informed firm might choose either allocation strategy depending on its refined information. This non-monotonic effect is illustrated in Figure 2.5 which plots the integrated firm's expected product development scope for all possible cases (dashed line). Proposition 2.5 sheds light on how decentralization affects the firm's product portfolio scope.

Proposition 2.5. *Let n^{fb} and n be the expected number of products developed by the integrated and decentralized firm, respectively. Then, for any given q and c, decentralization weakly increases a firm's expected product portfolio scope, i.e., $n \geq n^{fb}$.*

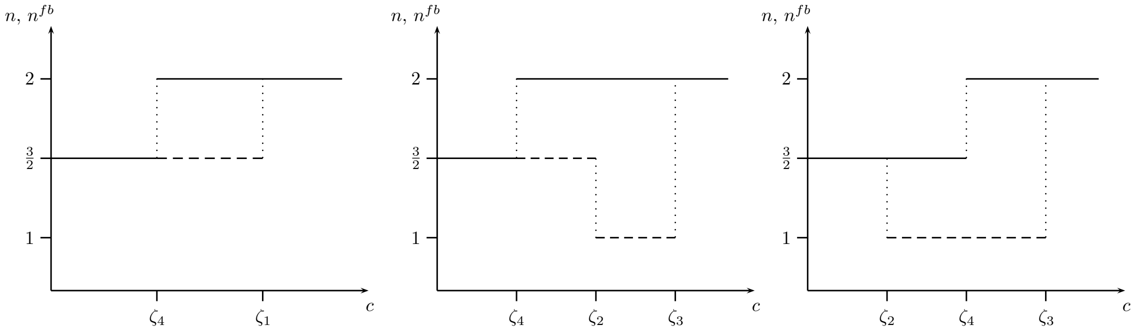
Proposition 2.5 highlights that decentralization leads a firm to broaden its product portfolio scope compared to an integrated firm. Recall from Proposition 4 that in some regions, decentralization results in under-investment in information (region ABFEC in Figure 2.4), while in others it results in over-investment (region CED in Figure 2.4). In either case, decentralization impedes an asymmetric high-effort evaluation strategy, which corresponds to launching a single product on the market. Instead, the decentralized firm has to choose between spreading its bets across products under limited information versus a more refined, but overly costly, product portfolio allocation. Our result regarding the role of decentralization on the firm's product portfolio scope is also consistent with Thomas (2011) who shows that the observed product range of multinational firms exceeds the optimal firm-level response to differences in consumer preferences and the retail environment.[7]

2.5.2. Profit and Welfare Loss

To measure the efficiency of the firm's contract scheme, we employ two different performance indicators: the firm's percentage profit loss, which captures the effect of decentralization on the firm's profits, $\eta_p \equiv 1 - \frac{\Pi(e^\star)}{\Pi^{fb}(e^{fb})}$, and the percentage welfare loss, which reflects the loss in total welfare due to decentralization, $\eta_w \equiv 1 - \frac{\Pi(e^\star)+U_i(e^\star)+U_j(e^\star)}{\Pi^{fb}(e^{fb})}$. These two performance measures quantify the implications of decentralization on two different levels of aggregation. While η_p captures the effect on the firm's level, η_w measures the contract's social efficiency for the entire system (firm and managers).

[7] The recent work of Alonso et al. (2008), and Rantakari (2008) also discusses how decentralization might lead to inefficiencies in an organization's decision making processes. Their work, however, is not concerned with product evaluation and resource allocation decisions, but rather with the tradeoff of coordination (across the divisions) versus adaptation (to the local market conditions).

Figure 2.5.: Expected scope of product development.



Notes: The firm's expected product development scope under decentralization (solid line) and integration (dashed line) for $q < q_c$ (left), $q \geq q_c$ and $\zeta_4 < \zeta_2$ (middle), and $q \geq q_c$ and $\zeta_4 \geq \zeta_2$ (right), respectively.

Proposition 2.6. *If the integrated and the decentralized firm both pursue a low-effort product evaluation strategy for the two products, then $\eta_p = 0$. If the decentralized firm under-invests in product evaluation, then the percentage profit loss increases in q and v_2, and decreases in c. In any other case, the percentage profit loss decreases in q and v_2, and increases in c.*

According to Proposition 2.6, the effect of decentralization varies significantly across the different regions depicted in Figure 2.4. Recall from Figure 2.4 that if the cost of information acquisition is very high ($c > \max\{\zeta_1, \zeta_3\}$), then both the integrated and decentralized firm do not exert any high-effort product evaluation, and therefore, the decentralized firm does not need to incentivize its managers. As such, the decentralized firm is able to accrue all the profits ($\eta_p = 0$). When the decentralized firm under-invests in product evaluation (region ABFEC in Figure 2.4), then η_p increases in q and v_2, and decreases in c. Intuitively, as the decentralized firm under-invests in product evaluation, a higher q implies that more valuable information is lost, and therefore the profit loss becomes steeper. Obviously, this effect is even more severe as v_2 increases, and the value of ex-post winner-picking is higher. Lastly, when the firm induces high-effort product evaluation (region under ACE) for both products, η_p decreases in q and v_2, and increases in c. As discussed in Proposition 2.3, in that region a higher q or v_2 reduce the incentive misalignment between the managers and the firm, while a higher c widens it. The former effect reduces the firm's profit losses, whereas the latter increases it.

Proposition 2.7. *If the decentralized firm pursues the same product evaluation strategy as the integrated firm, then there is no welfare loss under decentralization, $\eta_w = 0$. Otherwise, if the decentralized firm under-(over-)invests in product evaluation, then the percentage welfare loss increases (decreases) in q and v_2, and decreases (increases) in c.*

According to Proposition 2.7, if decentralization does not affect the firm's optimal evaluation strategy, then there is no welfare loss; the total generated value remains intact and it is only the distribution of profits between the firm and the managers that changes. As discussed in Figure 2.4, this happens either when the information fidelity is very high and the evaluation cost very low, or at the other extreme, when the information fidelity is very low and the evaluation cost very high. In the former case, information acquisition is so effective that both firms always evaluate both products, while in the latter, it is so ineffective that both firms always choose to forgo costly product evaluation. In reality, most firms face environments where valuable information is also costly. Importantly, in these regions, decentralization interferes with the firm's optimal evaluation strategy, and leads to a welfare loss.

Similar to the percentage profit loss, the effects of the evaluation fidelity and cost on the percentage welfare loss, η_w, vary significantly across the regions. If the decentralized firm collects less information than is socially optimal, i.e., under-invests in product evaluation, then the welfare loss is most severe when the fidelity of information is high and the evaluation costs are low. In contrast, if the decentralized firm gathers more information than an integrated firm, i.e., the firm over-invests in product evaluation, then the social value of this additional information gain increases as the information fidelity becomes higher and the evaluation costs lower.

2.6 Conclusions

This essay aims at understanding a key concern of many senior R&D executives: *"how do you make good decisions when the information you need to make those decisions comes largely from the project champions who are competing against one another for resources"* (Sharpe and Keelin, 1998, p.45). Prior academic literature has extensively discussed the importance of such a question when managing parallel projects (e.g., Loch et al., 2006), but without offering explicit guidance on how to structure appropriate incentive mechanisms that address these challenges. This is also highlighted in Lerner

(2012, p. 170) who emphasizes that *"one crucial, though often neglected, point is that such tolerance for failure requires a rethinking not just of compensation schemes, but also of how projects are selected and funded. [...] A question that would reward both further research by economic theorists and real-world exploration is how to induce 'truth-telling' when evaluating high-risk innovative projects"*. The main contribution of this essay is to offer a formal framework on the tradeoffs involved between incentivizing information acquisition and truthful revelation among new product development teams. More specifically, our study makes three contributions in the literature.

First, we show that by offering a combination of individual and shared incentives, the firm can incentivize managers to undertake high evaluation efforts and at the same time disclose truthfully their findings. In doing so, we disentangle the role of each incentive type: individual incentives give the manager the potential to request more resources for his project if he receives a good signal of high fidelity. On the other hand, shared incentives induce the manager who receives a bad signal to "step aside" and let his peer receive his resources as the latter might have better chances on the market. We then show that a higher information fidelity or a lower information acquisition cost lead to lower pay-performance sensitivity for both the individual and shared incentives. Intuitively, both parameters make the acquisition and disclosure of information lead to a better alignment between the managers' and the firm's interests, thereby reducing the managers' information rents. At the same time, our analysis highlights that in environments with lower evaluation fidelity the firm should shift the balance towards emphasizing shared rather than individual incentives. This is so because any change in the fidelity of information is always more impactful ex-post (i.e., when a bad signal has already been realized) rather than ex-ante (i.e., when either good or bad information is likely to appear).

Second, our analysis reveals how decentralization impedes the implementation of an optimal product evaluation strategy, specifically in environments where valuable information is costly. In particular, decentralization might lead a firm to either under-invest or over-invest in product evaluation. Importantly, this has implications for the firm's product portfolio scope: a decentralized firm spreads its resources into a portfolio at least as broad, and for most parameters strictly broader, than that of an integrated firm. What is noteworthy here is that both under- and over-investment in product evaluation have the same effect on the firm's product portfolio scope. This happens because in the former case the high uncertainty forces the firm to spread its bets among multiple projects while in the latter case the firm develops more products as a response to more information which nonetheless comes at an overly high cost. Lastly, our work shows that distinguishing between the regions where decentralization leads to under-investment versus over-investment in product evaluation has crucial implications for the firm's profit loss and the total welfare loss. In the over-investment region, the losses decrease in the information fidelity while they increase in the information cost. Intuitively, over-spending in information becomes less detrimental when this information is valuable, but becomes more detrimental when this information is expensive. The exact opposite effects take place in the under-investment region.

In order to maintain tractability and develop a parsimonious model, we have made some assumptions regarding the role of product managers, and correspondingly, the specific functional forms of the incentive structure. Specifically, our essay focuses on the project selection stage of NPD, and as such, on the evaluation rather than the generation of different alternatives (e.g., higher effort in our setting improves the selection process but not the quality of the different alternatives). Recent work has offered important insights on the structure of the opportunity spaces (Kornish and Ulrich, 2011) as well as on the effect of decentralization on the search process itself (Mihm et al., 2010). Moreover, our analysis considers ex-ante symmetric projects. In practice, firms are often faced with projects that vary significantly with respect to their state of execution, uncertainty, and need for resources. While our model captures some first-order effects regarding the interplay between information acquisition and resource allocation, we believe that capturing tradeoffs among projects that evolve over time is a fruitful avenue for future research.

Chapter III

Seasonal Products: Scale and Timing of Inventory Availability

with Moritz Fleischmann[1]

3.1 Introduction

In the last decades, the classical newsvendor model has received widespread attention as the most prominent decision support tool in stochastic inventory theory. The central question that it strives to answer is (Porteus, 2002): For a seasonal product, how much inventory should a firm stock to best satisfy uncertain customer demand over the product's limited selling season? This problem is pertinent for many products in diverse industries, and by applying the newsvendor model scholars provide manifold recommendations on how to successfully manage these products (for a good overview, see Cachon and Kök, 2007). Yet, despite its popularity as decision support tool, the classical newsvendor model also possesses essential limitations that impede a wider applicability to more general market environments. Specifically, as a major drawback, the model does not take into account how the specific properties of a product's selling season interact with a firm's inventory strategy. Importantly, it is an open question how firms should manage products with an uncertain demand timing. Such uncertain customer demand patterns, however, are frequently observed in practice. Cawthorn (1998, p. 20) vividly captures this phenomenon with the following quote about customer behavior in the food industry: "*It is not the threat of snow but the sight of snow that sends mothers running to the market for hot chocolate.*" Most importantly, external influences, such as

[1]The research presented in this chapter is based on a paper entitled "Selling over an Uncertain Season: Scale and Timing of Inventory Availability", coauthored with Moritz Fleischmann.

weather conditions, trends, or the diffusion of diseases, do not only affect the magnitude of customer demand, but also the timing of a product's actual selling season. In fact, this latter effect of shifting demand earlier or later is often considered the primary effect (Chen and Yano, 2010). Thus, in markets with uncertain customer demand patterns, a fundamental challenge for each firm is not only to determine how much inventory to stock, but also to decide when to make the product available for sale. This is the primary issue that we address in this paper.

This question is particularly relevant in industries where selling seasons are highly erratic and mistiming costs are substantial. Consider, for example, the market for lawn and garden items. Firms offering high-value garden items, such as lawn tractors, face a two-fold challenge. On the one hand, these firms operate in a high cost, capital-intensive environment because production is expensive and storage costs are significant. On the other hand, customer demand for these products shows a strong seasonality and a high dependence on temperature and weather patterns. One year a season breaks late due to an extraordinary cold winter, while in the next year a heat wave in early spring causes demand to take off early. In such an uncertain market environment, vendors of lawn tractors have to take two crucial decisions: how many tractors to stock, and equally importantly, when to make the tractors available for sale? Too early, and high opportunity and storage costs substantially erode profits. Too late, and customer demand has already gone.

Other examples for products with similar characteristics are sprinkled throughout the academic literature. With a focus on retailing, Starr-McCluer (2000) and Chen and Yano (2010) provide a nice overview on products that exhibit a seasonal pattern that changes from one year to another. In retailing, shelf space is expensive and offering products at the wrong time can dramatically devour revenues. Allen and Schuster (2004) identify similar tradeoffs during the harvest of crops. While the crops' maturation dates are extremely sensitive to weather and soil conditions, decision-makers have to decide upfront on the harvesting times and the required investment in equipment. Since this simultaneous inventory scaling and timing problem has been detected in many industries, specialized software and consulting firms such as Revionics already offer decision support tools for products with volatile demand patterns (Moore, 2010). Surprisingly, however, academic research provides only very limited guidance on how to effectively manage the involved tradeoffs.

The purpose of this paper is to understand how a firm should design its inventory strategy to successfully manage the complex interplay between the two different sources of uncertainty: uncertainty in demand scale, and uncertainty in demand timing. Specifically, we answer the following question: For a seasonal product, when and how much inventory should a firm stock to best satisfy uncertain customer demand over an uncertain selling season? For a firm operating in such a volatile market environment, the key to successful inventory management is understanding the involved tradeoffs and their mutual interdependency. To explore these tradeoffs, we build a theoretical model that accommodates both forms of demand uncertainty, while allowing the firm to decide on its inventory scale and timing. This framework enables us to clearly elicit how a firm should manage the different sources of uncertainty.

Our study makes three contributions to the existing literature. First, we show that the introduction of stochasticity in the product's selling season exposes the firm to a novel tradeoff that has to be managed with a careful inventory timing. Specifically, besides the classical newsvendor tradeoff, the firm also has to balance the product's market potential with the product's time on the market. We find that this challenge induces the firm to reduce its inventory scale and to shorten the product's availability period, respectively. Our results also shed light on the subtle interaction between the firm's scale and timing decision. Interestingly, we show that the firm may choose to build higher inventories when the product's market potential decreases. The reason behind this counter-intuitive finding is that the firm can reduce inventory costs by shortening the product's selling period. A shorter season, in turn, is cheaper to serve, thereby enticing the firm to increase inventories. We highlight that this non-monotonic relation also influences how the firm reacts to changes in the cost structures. Intriguingly, in contrast to the classical newsvendor literature, the firm may increase its inventories when operational costs increase.

Second, we find that the uncertainty in demand timing has more severe repercussions on the firm's optimal inventory strategy than the uncertainty in demand scale. From the classical newsvendor literature, we know that an adequately chosen inventory scale enables the firm to effectively manage the risk stemming from the uncertainty in the customer demand scale. Surprisingly, however, managing the timing risk is much more complex. We find that when the timing uncertainty is too severe, the firm's flexibility to adjust the product's availability period may not be sufficient to prevent the firm from exiting the market. This result is driven by the firm's inability to reduce the product's inventory costs without affecting the product's market potential. By shortening the product's availability period, the firm reduces the inventory costs, but also sacrifices some of the product's market potential. These countervailing forces, which are not present in classical newsvendor contexts, are the reason why a firm needs to thoroughly design its inventory strategy to successfully manage products with an uncertain selling season.

Third, we provide a parsimonious and analytically tractable mechanism to explicitly integrate inventory holding costs and mistiming costs into a general newsvendor framework. This helps us to discover the links between the different cost components and the firm's inventory strategy. Importantly, we find that the presence of inventory holding costs and earliness costs simultaneously affects the firm's overage costs, underage costs, and mistiming costs. This happens because all of these costs are directly influenced by the firm's inventory scaling and timing decisions. Moreover, this result questions the common approach in the classical newsvendor literature to attribute inventory holding costs only to the firm's overage costs (e.g., Kouvelis and Gutierrez, 1997). Instead, we show that it is important for the firm to have a more differentiated view on the effects of inventory holding costs.

3.2 Literature Review

The goal of this paper is to understand the mutual interdependency between two central questions that critically determine a product's profitability: when to make a product available for sale, and how much inventory to stock? By combining these two decisions into an integrated framework, our work intersects with two rich streams of prior research: (i) the literature on stochastic inventory management; and (ii) the literature on new product introductions.

The extensive literature on stochastic inventory management centers around the question of how much inventory to stock to best satisfy stochastic future customer demand. Given the importance of this question for virtually every product, scholars provide rich answers for many different products in many different market configurations. For an overview of this literature see, e.g., Porteus (2002). Most closely related to our work is the classical newsvendor literature on inventory management for seasonal products. Stripped to its essence, the classical newsvendor model determines the optimal inventory scale for a single product with probabilistic customer demand that is sold over a single deterministic selling season (Cachon and Kök, 2007). To further enhance its practical applicability, the classical newsvendor model has received considerable extensions along one or more dimensions. These extensions focus on investigating joint inventory and pricing decisions (Petruzzi and Dada, 1999; Raz and Porteus, 2006; Salinger and Ampudia, 2011), the impact of different risk attitudes (Eeckhoudt et al., 1995; Chen et al., 2009), the repercussions of limited demand information (Perakis and Roels, 2008; Ben-Tal et al., 2013), the value of advanced demand information and quick response strategies (Iyer and Bergen, 1997; Milner and Kouvelis, 2005; Cachon and Swinney, 2011), and the consequences of different financing options (Gaur and Seshadri, 2005; Kouvelis and Zhao, 2012). All these papers, albeit examining diverse market environments, are silent about the issues arising from a stochastic selling season. However, as highlighted earlier, in practice many firms only have limited information about their products' selling seasons. We contribute to the newsvendor literature by addressing the challenges resulting from this additional timing uncertainty. Moreover, we study how to actively manage this uncertainty by allowing the firm to choose its inventory scale and inventory timing.

To our knowledge, the only other paper that investigates joint inventory scaling and timing decisions in a newsvendor context is Ülkü et al. (2005). By analyzing a firm's optimal capacity investment timing when a delayed investment leads to a reduced market potential, but also to a more accurate demand forecast, they show that the firm may deliberately sacrifice some of its product's market potential to elicit more precise demand information. While we also emphasize the importance of the firm's inventory timing decision, our work differs from Ülkü et al. (2005) in multiple significant aspects. Most notably, in our work the firm's primary motivation to postpone its inventory timing is the stochasticity in the properties of the selling season. We also examine how this uncertainty affects a product's effective cost structures.

So far, the newsvendor literature has largely disregarded the issue of when to make a product available for sale. Instead, this question has been extensively discussed in the new product development area. Our work therefore also touches upon previous research on the optimal timing of new product introductions. This literature provides mixed evidence of whether firms should prefer an early or a late market entry (Krishnan and Ulrich, 2001). Advocates of an early product availability assert that being early enables a firm to maximize the product's market potential, to minimize product development costs, to build a strong reputation, to achieve higher profit margins, and to create a sustainable competitive advantage (Lieberman and Montgomery, 1988; Lilien and Yoon, 1990; Hendricks and Singhal, 1997; Klastorin and Tsai, 2004). We follow these papers by adopting the view that the firm's primary motivation for early market entry is a high market potential and that this potential decreases over time.

Previous work also identifies tradeoffs that may induce a firm to choose a late product availability. McCardle (1985) argues that a firm should wait with its product introduction in order to acquire more precise information about the product's specific market environment. Kalish and Lilien (1986) emphasize the tradeoff between introduction timing and product performance. By postponing the product's availability timing, a firm can invest more time in improving product performance. A better product, in turn, improves customer value and therefore spurs customer demand (Bayus et al., 1997). Savin and Terwiesch (2005) highlight the positive impact of a delayed product availability on a product's unit costs. Although deferring a product's introduction timing offers many potential benefits for a firm, actually realizing these benefits is extremely challenging, especially for products with short selling seasons (Cohen et al., 1996). Specifically, a firm may wait too long and lose the product's entire market potential. We complement previous research by formally analyzing how stochasticity in a product's selling season influences a firm's inventory timing decision. As such, our work differs from previous papers in multiple dimensions. Most importantly, in our setting the firm's main concern is a costly mismatch between the inventory scaling and timing decision, and the stochastic customer demand pattern.

Recently, Ke et al. (2013) were the first to examine the effects of operational costs on a firm's decision of when to launch a new product generation. They identify inventory holding costs as a major reason for postponing a product's introduction. We support this view, but with our model setup, we are able to identify another important factor that influences a firm's optimal timing strategy: mistiming costs that arise due to the threat of a premature product availability.

3.3 The Model

Consider a firm that is faced with the challenge of determining its inventory strategy for a seasonal product. For the firm, the inventory strategy consists of two key decisions: the *timing* and *scale* of product availability, i.e., when to make the product available on its target market, and how much inventory to stock? Typically, the firm has to take these decisions well before the product becomes available to customers as the firm needs time, e.g., to initiate and ramp up the production, to build sufficient stocks, and to advertise the product (see, e.g., Kurawarwala and Matsuo, 1996; Van Mieghem, 2003; Ülkü et al., 2005). As such, when choosing its inventory strategy the firm has only limited information about the future market environment and cannot perfectly predict the product's market potential and the timing of customer demand. Due to this inherent uncertainty, the firm's inventory strategy may suffer from costly mistiming and inadequate scaling decisions. Offering the product before customers actually demand the product evokes earliness costs, while a late inventory availability results in lost customers. Similarly, excess inventories reduce the firm's profitability, whereas insufficient stocks lead to unmet demand. Ultimately, the firm seeks to maximize expected profits by making the product available at the right time and in the right quantity.

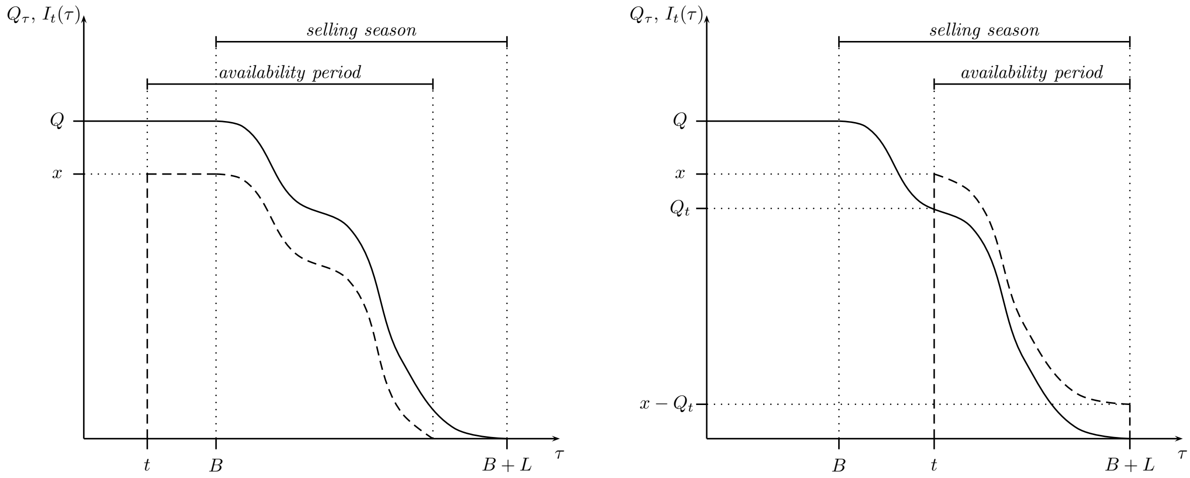
A central and novel aspect of our model is the discrimination between a product's *selling season* and its *availability period.* In line with the classical newsvendor literature, we define the product's selling season as the time span during which customers are willing to buy the product. To be specific, the selling season starts with the first, and ends with the last customer demanding the product. In contrast, we define the product's availability period as the time during which the firm actually tries to sell the product on the market. The availability period starts when the product is first made available on the market, and ends either when the firm stocks out or when the selling season closes. In order to maximize profits, the firm needs to optimally synchronize the product's availability period with the actual selling season by choosing and executing a specific inventory strategy. In practice, however, this is not a trivial task because customer behavior is not perfectly predictable. To capture this synchronization issue in our modeling framework, we follow Kalyanaram and Krishnan (1997) and Ülkü et al. (2005) by assuming that customer demand occurs irrespective of whether or not the product is available for sale. Thus, in contrast to the product's availability period, the selling season is exogenous and cannot be influenced by the firm. Importantly, we depart from prior literature by assuming that the selling season is stochastic and that the firm only learns about the product's actual selling season after the firm has chosen its inventory strategy. Due to this imperfect knowledge about the selling season, the product's availability period need not coincide with the selling season. We now explain our modeling assumptions in greater detail.

The firm's inventory strategy is represented by the pair (x, t), where x is the amount of inventory that the firm stocks, and t is the time when the product is first made available for sale. Throughout, we measure time τ continuously. The product's (stochastic) market environment, $\mathcal{M} = (Q, \mathcal{S})$, is characterized by the product's market potential, Q, and its selling season, $\mathcal{S}$. In practice, Q and $\mathcal{S}$ are typically dependent on one another; e.g., a short (long) selling season may come with a small (high) market potential. We explicitly allow for such dependencies by only assuming that $\mathcal{M}$ follows a known continuous multivariate distribution with strictly positive density. The product's *market potential* is the cumulative customer demand over the product's entire selling season, i.e., Q is the maximum number of products that the firm can sell to its customers. We assume Q to be stochastic with support on $\mathbb{R}^+$. The product's *selling season* determines during which time span customers are willing to buy the product, and how customer demand is distributed over this period. Mathematically, $\mathcal{S}$ is a collection of three stochastic elements, $\mathcal{S} = (B, L, A(\tau|Q, B, L))$. The beginning of the product's selling season is designated by the random variable B with support on $[0, b_u]$, and the season length is given by the random variable L with support on $(0, l_u]$. We assume that customer demand occurs gradually over time and that each customer tries to buy the product only once at a single point in time within the product's selling season. This is in line with Hendricks and Singhal (1997) who highlight that unserved customers may not be willing to wait in case of product unavailability. To represent the customers' dynamic buying behavior, we follow Ülkü et al. (2005) by defining for each realization of (Q, B, L) a function $A(\tau|Q, B, L)$ that designates the fraction of the product's full market potential that will realize between time τ and the end of the selling season.[2] Mathematically, our assumptions on customer behavior imply that $A(\tau|Q, B, L)$ satisfies: (i) $A(\tau|Q, B, L) = 1$ for all $\tau \leq B$; (ii) $A(\tau|Q, B, L) = 0$ for all $\tau \geq B + L$; and (iii) $A(\tau|Q, B, L)$ decreases for all other τ. In other words, demand is concentrated within the product's selling season, and unserved customers are lost. To simplify the mathematical exposition, we also assume that $A(\tau|Q, B, L)$ is once continuously differentiable in τ for any realization of (Q, B, L), and we label the first derivative of any function z with respect to τ by z'. For brevity, we refer to the product's market potential at time τ by $Q_\tau \equiv A(\tau|Q, B, L)Q$. With this definition, the stochastic customer demand rate at time τ is $-Q'_\tau$. Finally, we define $d_\tau(Z) \equiv \mathbb{E}\left[-Q'_\tau 1_{\{Z\}}\right]$, where $1_{\{Z\}}$ is the indicator function of event Z. Figure 3.1 graphically visualizes the relationship between the product's market potential, its

[2] All our results continue to hold for $A(\tau)$ being a random function as long as $A(\tau)$ is drawn from a measurable set of functions.

selling season, and its availability period.

Figure 3.1.: Market environment and inventory strategy.



Notes. The evolution of the product's market potential, Q_τ, (solid line) and the firm's inventory level, $I_t(\tau)$, (dashed line) over time. In the left panel, the firm makes the product available before the selling season starts, and sells out before the season ends. In the right panel, the firm misses the beginning of the selling season and has unsold items at the end of the season.

Before the product is first made available, the firm orders the desired inventories at unit costs, c, and during its availability period, the product is sold at unit price, $p > c$. If the product is made available for sale before the selling season starts, i.e., $t < B$, then the firm incurs earliness costs. We consider two different sources for such earliness costs; opportunity costs, o, and idle time holding costs, w. When being too early, the firm forgoes the opportunity to dedicate its resources into more profitable alternatives, because offering the product at hand blocks financial resources and scarce capacities. Ultimately, this leads to lost revenues. To capture this loss of revenue, we charge the firm opportunity costs per time, o, until the product's selling season starts. In addition, before being able to sell the product, the firm has to stock its inventories until the start of the product's selling season. As such, the firm experiences idle time holding costs, w, per unit inventory and time. During the product's effective time on sale, i.e., for $\tau \in \{\max\{t, B\}, B+L\}$, the firm incurs holding costs, h, per unit inventory and time.[3] Given that the firm offers the product from time t on, the product's inventory

[3]We differentiate between "pre-season" holding costs, w, and "in-season" holding costs, h, to clearly

level at time $\tau \geq t$ is $I_t(\tau) \equiv [x - (Q_t - Q_\tau)]^+$, which is non-increasing in τ, and where $z^+ = \max\{z, 0\}$. Lastly, as the product's selling season ends, the firm recaptures a salvage value, $s < c$, for each unsold item. In summary, the firm seeks to choose the inventory strategy that maximizes expected profits, comprising the product's sales revenues minus procurement, earliness, inventory holding, and salvage costs. Formally, the firm solves the following optimization problem:

$$\max_{x,t} \Pi(x,t) = \mathbb{E}\left[(p-c)x - (o+wx)(B-t)^+ - h\int_{\max\{t,B\}}^{B+L} I_t(\tau)d\tau - (p-s)(x-Q_t)^+\right]. \tag{3.1}$$

At this point, it is worthwhile to clarify how our model relates to the classical newsvendor model. Recall that the primary focus of the classical newsvendor model is to determine the optimal inventory scale, x, of a firm that faces an uncertain customer demand, Q (Cachon and Kök, 2007). While this question is also present in our framework, we depart from the classical newsvendor model in two dimensions. First, we study the repercussions of a stochastic selling season on a firm's optimal inventory strategy. In contrast, classical newsvendor models provide only an aggregated view on the selling season without considering how mistiming costs and specific properties of the selling season affect a firm's decision. Secondly, we extend the scope of a firm's inventory strategy to include not only the inventory scale, but also the inventory timing. This latter decision enables a firm to actively manage the adverse effects of a stochastic selling season, and is therefore a crucial element of a firm's inventory strategy.

For future reference, we note that the classical newsvendor's optimal inventory scale, x_{NV}, satisfies $\mathbb{P}(Q \leq x_{NV}) = \frac{p-c}{p-s}$.

3.4 The Effects of a Probabilistic Season Start and Length

As highlighted before, our model setup structurally departs from the standard literature on stochastic inventory theory by considering that the firm faces an uncertain selling

isolate how the firm's inability to synchronize the product's availability period with the selling season influences the firm's inventory strategy.

season. Most notably, this uncertainty is reflected in the probabilistic beginning of the selling season and the stochastic season length. Figure 3.2 positions our work relative to the classical newsvendor model.

In this section, we disentangle how these different sources of uncertainty individually affect the firm's optimal inventory strategy. We initiate our analysis by establishing important properties of the firm's expected profit, $\Pi(x, t)$, and by discussing the implications of these properties on the firm's optimal inventory strategy (§4.1). In a next step, we investigate two instructive special cases. These scenarios help us to clearly elicit how the introduction of a stochastic selling season, and the opportunity to choose a product's inventory timing influence the firm's optimal strategy. In the first scenario, we restrict attention to the effects of a stochastic season length (§4.2), while in the second scenario, we examine the repercussions of a stochastic season beginning (§4.3). Studying these different sources of uncertainty in isolation greatly facilitates the understanding of the combined effects that appear in the fully stochastic model (3.1), which we examine in Section 5. Additionally, we show that the illustrated special cases also reflect specific market environments that are present in many industries.

Figure 3.2.: The role of uncertainty in different models.

		Season length	
		certain	uncertain
Season start	certain	Classical newsvendor	Probabilistic length (§4.2)
	uncertain	Probabilistic start (§4.3)	Uncertain season (§5)

3.4.1. Structural Properties

For the classical newsvendor model, it is well known that the firm's expected profits are concave in the firm's inventory scale, x (see, e.g., Perakis and Roels, 2008). This fundamental property of the expected profit function is preserved when the firm faces a stochastic selling season. All proofs are presented in Appendix B.

Lemma 3.1. *For given t, $\Pi(x, t)$ is strictly concave in x.*

Lemma 3.1 indicates that for any inventory timing that the firm chooses, a unique profit-maximizing inventory scale exists. In general, however, expected profits are not concave in the firm's timing decision, t. This implies that the firm's optimal inventory strategy, $(x^\star, t^\star) = \text{argmax}_{x,t}\, \Pi(x,t)$, is not necessarily an interior solution to the firm's optimization problem (3.1). In fact, the firm may find it optimal to make the product available at the very first opportunity, or to never sell the product at all. To be precise, the firm knows that the selling season never starts before $\tau = 0$, and never terminates after $\tau = b_u + l_u$. Choosing an inventory timing outside this time interval results in substantial mistiming costs without benefiting customer demand. It is therefore never economically rational for the firm to offer the product before or after these theoretical boundaries of the selling season. However, the firm may optimally choose to make the product available at the very first opportunity, $t = 0$. In this case, the firm entirely avoids the risk of losing customers due to a tardy inventory availability. We call this strategy *instant inventory availability*. If the firm chooses an inventory timing that satisfies $0 < t < b_u + l_u$, then we say that the firm pursues a *risk exploitation* inventory strategy. By definition, such a strategy is always an interior solution to the firm's optimization problem (3.1). The last potentially optimal strategy for the firm is a *market exit*. With this strategy, the firm deliberately forgoes any sales by never making the product available to customers. Obviously, when the firm exits the market, it earns zero profits. Thus, a market exit is chosen only if any earlier inventory timing leads to negative expected profits. We will show that this may happen if the firm's mistiming costs are severe, or if there is considerable uncertainty in the properties of the selling season.

3.4.2. Managing a Stochastic Season Length

Given that the start of the selling season is known in advance, what is the optimal inventory strategy for a product with a probabilistic season length? This question is prevalent for many products in diverse industries. Consider, e.g., the market for seasonal sporting goods, and in particular the market for ski equipment. Typically, the first customers buy their equipment for the new season during late autumn, thereby marking the well anticipated start of the selling season. The length of the season, however, is not so easily predictable as it highly depends on the weather conditions during winter and early spring. A lot of snow in early spring keeps demand high for a long time, whereas demand ceases early if the winter months are exceptionally mild. Obviously, at the time the firm decides on its inventory strategy, these weather conditions are highly unpredictable. Thus, firms in the market for ski equipment face a substantial uncertainty regarding the length of their selling season. Besides the seasonal sporting goods industry, similar issues also arise, e.g., for sun care products, and beach wear.

When the firm knows that the product's selling season starts at time $\tau = b$, then the firm never makes the product available for sale prior to the beginning of the season. This is true because a premature product availability has no upside potential for the firm, but only results in earliness costs. Formally, the firm would not spur customer demand with such a strategy since $Q_\tau = Q$ for all $\tau \leq b$. It follows immediately that the firm's optimal inventory strategy satisfies $t \geq b$, and solves the following optimization problem:

$$\max_{x,t \geq b} \Pi_L(x,t) = \mathbb{E}\left[(p-c)x - h\int_t^{b+L} I_t(\tau)d\tau - (p-s)(x-Q_t)^+\right]. \tag{3.2}$$

The firm maximizes the expected product margin net of inventory holding and salvage costs. Earliness costs are irrelevant for the firm's decision problem, since the product is never introduced before the season starts. Clearly, (3.2) is a special case of the fully stochastic model described in (3.1). Following the discussion in Section 4.1, we notice that in general, $\Pi_L(x,t)$ is not jointly concave in x and t; i.e., the firm's optimal inventory strategy need not be an interior solution to (3.2). Nevertheless, we begin our analysis with a discussion of the firm's optimal *risk exploitation* inventory strategy. Afterwards, we characterize the firm's general optimal inventory strategy.

Lemma 3.2. *Any optimal risk exploitation inventory strategy, $(x^\star, t^\star)$, simultaneously satisfies the following two first-order necessary optimality conditions:*

$$\mathbb{P}(Q_{t^\star} \leq x^\star) + \frac{h}{p-s}\int_{t^\star}^{b+l_u} \mathbb{P}(Q_{t^\star} - Q_\tau \leq x^\star, L > \tau - b)d\tau = \frac{p-c}{p-s} \tag{3.3}$$

$$h\left[x^\star \mathbb{P}(L > t^\star - b) - \int_{t^\star}^{b+l_u} d_{t^\star}(Q_{t^\star} - Q_\tau \leq x^\star, L > \tau - b)d\tau\right] = (p-s)d_{t^\star}(Q_{t^\star} \leq x^\star). \tag{3.4}$$

Lemma 3.2 shows that with its optimal risk exploitation inventory strategy, the firm manages a two-fold tradeoff originating from the two different uncertainties in customer demand scale and timing. To be concrete, to offer the right amount of inventories at the right time, the firm balances the two interdependent tradeoffs between stocking too much and too little, and between making the product available too early and too late. For a given inventory timing, the optimal amount of inventories, $x^\star$, is determined by (3.3). This condition has strong similarities with the optimality condition in the classical newsvendor model. In fact, without the second term on the left-hand side, (3.3) is a common critical fractile solution which trades off the firm's underage costs, $c_u = p - c$, with the overage costs, $c_o = c - s$. However, there are two major structural differences compared to the classical newsvendor solution. Firstly and intuitively, the firm does not take into account the entire market potential, Q, but only the market potential that will realize after the product is made available for sale, $Q_{t^\star}$. Secondly, the inclusion of inventory holding costs reduces the firm's effective underage costs, while simultaneously increasing the effective overage costs. As a result, the firm's optimal inventory scale is adjusted down.

For a given inventory scale, the optimal time to make the product available for sale is also determined by a marginal analysis (3.4). Postponing the product's market availability reduces expected inventory holding costs because the product has to be kept on stock for a shorter time period. However, such a postponement comes at the cost of more expected lost sales since more customers that try to buy the product prior to market availability cannot be served. This leads the firm to choose its optimal inventory timing, $t^\star$, by equating the expected marginal inventory holding cost savings with the expected marginal lost sales costs.

Lemma 3.2 illustrates two key characteristics that are innate to the firm's decision problem. Firstly, there is a high degree of interdependence between the uncertainties in demand scale and timing, and the firm's inventory strategy. As a result, $x^\star$ and $t^\star$ are closely interlinked in manifold ways. The optimal inventory scale, $x^\star$, is chosen to best satisfy the market potential at the time of product availability, $Q_{t^\star}$, which is obviously a function of the inventory timing, $t^\star$. Inventory holding costs influence both the optimal inventory scale and timing because the size of these costs depends on both decisions. Similarly, lost sales costs are also nourished by two different sources: the risk of stocking too little inventory to satisfy the market potential; and the risk of losing customers due to a tardy availability of the product. While the first source is well established and studied in the classical newsvendor literature, the latter source has received considerably less attention.

Secondly, as we would expect, higher inventory holding costs force a firm to lower the product's inventory scale. While this finding is intuitive, (3.3) shows that the dynamics behind this result are more complex than previously postulated in the academic literature. Specifically, a large part of the classical newsvendor literature proposes that inventory holding costs increase a firm's overage costs, while leaving the underage costs unaffected (see, e.g., Kouvelis and Gutierrez, 1997; Van Mieghem and Rudi, 2002). In contrast to this perception, however, our analysis reveals that inventory holding costs not only increase a firm's overage costs, but also reduce the firm's underage costs, thereby keeping the sum of overage and underage costs invariant. This difference has considerable implications for the firm's optimal inventory strategy. To see these repercussions note how inventory holding costs affect the firm's critical fractile under the different approaches. Prior academic literature suggests to augment the firm's overage costs, c_o, with some inventory holding costs, H, to receive the adjusted critical fractile $\frac{c_u}{c_u+c_o+H}$. In contrast, (3.3) shows that the correct structure of the critical fractile adjusted for inventory holding costs is $\frac{c_u-H}{c_u+c_o}$. Three important managerial implications abound from our finding. First, Lemma 3.2 provides an exact characterization of the inventory holding cost term that is required for a correct adjustment of the critical fractile, i.e., $H(x,t) = h\int_t^{b+l_u} \mathbb{P}(Q_t - Q_\tau \leq x, L > \tau - b)d\tau$. Second, since $\frac{c_u-H}{c_u+c_o} < \frac{c_u}{c_u+c_o+H}$, the classical approach underestimates the negative effect of inventory holding costs on a product's profitability. Most notably, our approach always leads to a smaller optimal inventory scale. Third, as can be seen in (3.3), the firm endogenously determines the relevant inventory holding costs by choosing the product's inventory timing. Thus, the additional timing flexibility enables the firm to actively manage the product's optimal target service level and to increase the product's profitability. We are now ready to establish the firm's optimal inventory strategy.

Proposition 3.1. *The firm's optimal inventory strategy is as follows:*

(a) In the absence of inventory holding costs, $h = 0$, the firm makes the product instantly available at the start of the selling season, $t^\star = b$, with the optimal inventory scale satisfying $\mathbb{P}(Q \leq x^\star) = \frac{p-c}{p-s}$.

(b) Suppose the firm incurs inventory holding costs, $h > 0$. Then, there exists a decreasing and continuously differentiable function $\overline{h}(c)$ such that the firm (i) pursues the risk exploitation inventory strategy defined in Lemma 3.2 if $h \leq \overline{h}(c)$; or (ii) exits the market otherwise.

Proposition 3.1 establishes how inventory holding costs and the different sources of uncertainty affect the firm's optimal inventory strategy. As we would intuitively expect, if the firm is not charged any inventory holding costs, then it is optimal to pursue an instant product availability strategy. This is true because postponing the product's availability leads to a reduced market potential without resulting in any cost savings. Thus, deferring the product's inventory timing is never beneficial for the firm.

Remarkably, in the absence of inventory holding costs, the firm's optimal inventory scale resolves the classical newsvendor tradeoff. In such a situation, the uncertainty in the selling season, $\mathcal{S}$, does not generate any additional costs for the firm, but only complicates the derivation of the appropriate market potential distribution. In fact, the firm needs to use the marginal distribution of Q by averaging over all possible realizations of the stochastic selling season, $\mathcal{S}$. In practice, this result implies that firms that do not suffer from inventory holding costs and that have a good understanding of how the properties of their selling season affect the product's market potential can determine their optimal inventory strategy by simply applying the classical newsvendor model.

Yet, as Proposition 3.1(b) indicates, this is no longer true when a firm incurs inventory holding costs because these costs fundamentally change the firm's optimal inventory strategy. With $h > 0$, it is never optimal to make the product instantly available. As a result, the product's selling season and its availability period no longer coincide. Instead, the firm either follows a risk exploitation strategy, or it decides to exit the market. Two levers critically determine which strategy the firm chooses in optimum: the magnitude of the inventory holding costs, and the amount of uncertainty involved. If there is only low uncertainty regarding the season length and holding costs are moderate, then the firm pursues a risk exploitation strategy. In contrast, if the involved uncertainty is severe and holding costs are high, then being on the market is too costly for the firm. In such a situation, the product generates negative expected profits and therefore, the firm has to abandon the product.

Previously, Ülkü et al. (2005) have shown that a firm may sacrifice some of its product's market potential in order to receive more advanced demand information. We provide another explanation why firms may deliberately reduce their market potential by delaying their inventory availability: the existence of inventory holding costs. In practice, most firms incur inventory holding costs for their products. Our results reveal that firms that ignore these costs suffer from a premature product availability and excessive stocks. Obviously, this problem is most severe for products with substantial inventory holding costs and long selling seasons because for these products, an ill-designed inventory strategy can fully erode the firm's profits. For instance, based on the classical newsvendor literature, a naive decision-maker could be misled to follow a simple "now or never" timing strategy, i.e., make the product instantly available or exit the market. However, in the presence of inventory holding costs, Proposition 3.1(b) clearly shows that such a strategy cannot be optimal. Instead, the main question for the firm is: how long to postpone product availability? This result is consistent with recent findings of Ke et al. (2013) who show that operational costs induce a firm to postpone the introduction timing of successive product generations.

3.4.3. Managing a Stochastic Season Start

External factors such as general weather conditions, the spread of diseases, or the occurrence of fashion trends may not only influence the length of a product's selling season, but also the season's beginning. Consider for instance the market for pollen allergy drugs. The selling season for these drugs typically coincides with the blooming period of allergy-causing trees and plants. While over the years blooming periods are relatively stable in their length, their beginning can heavily change from one year to another. Unfortunately, predicting the start of a blooming period is a tough challenge as seasons highly depend on climatic conditions such as precipitation and temperature. Therefore, manufacturers of pollen allergy drugs oftentimes face a selling season with a probabilistic beginning and an almost deterministic length. Such a market environment is not exclusive for allergy drugs, but is also prevalent, e.g., in the agrochemical industry.

In this section, we study a firm's optimal inventory strategy for a product that is sold over a selling season with a probabilistic beginning and a deterministic length. We are particularly interested in how the stochasticity of the season beginning and the occurrence of earliness costs affect the firm's inventory scale and timing. For now, to better isolate these two effects, we disregard any inventory holding costs by setting $h = 0$. The omission of inventory holding costs helps us to clearly elicit the role that opportunity and idle time holding costs play in determining the firm's optimal inventory strategy. (We reintroduce inventory holding costs in Section 5 when we discuss our full model.) In a market environment as described above, the firm maximizes expected product margins minus the expected earliness and salvage costs:

$$\max_{x,t} \Pi_B(x,t) = \mathbb{E}\left[(p-c)x - (o+wx)(B-t)^+ - (p-s)(x-Q_t)^+\right]. \tag{3.5}$$

Similar to the preceding section, we first establish the firm's optimal risk exploitation strategy, and then characterize the firm's general optimal inventory strategy.

Lemma 3.3. *Any optimal risk exploitation inventory strategy, $(x^\star, t^\star)$, simultaneously satisfies the following two first-order necessary optimality conditions:*

$$\mathbb{P}(Q_{t^\star} \leq x^\star) + \frac{w}{p-s}\int_{t^\star}^{b_u} \mathbb{P}(B \geq b)db = \frac{p-c}{p-s} \tag{3.6}$$

$$(o+wx^\star)\mathbb{P}(B \geq t^\star) = (p-s)d_{t^\star}(Q_{t^\star} \leq x^\star). \tag{3.7}$$

The firm's optimal risk exploitation strategy is again aimed at resolving two intertwined tradeoffs: for a given inventory timing, the inventory scale, $x^\star$, is chosen to balance the risk of having insufficient inventories with the costs of having excess stocks (3.6); for a given inventory scale, the inventory timing, $t^\star$, is chosen to balance potential earliness cost savings with the risk of losing customers (3.7). There are strong analogies between Lemma 3.3 and the results discussed in Lemma 3.2. Recall that (3.3) indicates that "in-season" holding costs, h, reduce the firm's optimal inventory scale. Intutitively, (3.6) reveals that "pre-season" holding costs, w, have a similar influence on the firm's inventory scale. Importantly, however, both effects are not identical because their size is in general substantially different. It is also noteworthy that opportunity costs, o, influence the firm's optimal inventory scale, $x^\star$, only indirectly through the firm's choice of the product's inventory timing, $t^\star$. This is true because opportunity costs are independent of the chosen inventory scale, but only depend on the firm's inventory timing decision. Conversely, procurement costs, c, have no direct impact on the firm's optimal inventory timing, as c does not affect the firm's mistiming costs.

Despite the above analogies, Lemma 3.3 also reveals that an uncertain season start has fundamentally different implications for the firm's risk exploitation inventory strategy than an uncertain season length. To be specific, the main difference is that the firm may now introduce the product before customers actually demand the product. This is in contrast to an implicit assumption shared in the newsvendor and new product introduction literature that the firm can always sell a product to customers once it is introduced on the market. In the absence of explicit mistiming costs, this assumption may be rather unproblematic. Yet, once a firm incurs earliness costs, the stochasticity in the beginning of the selling season seriously changes the firm's inventory scale and its inventory timing, because earliness costs alter the firm's per unit underage and overage costs, and equally importantly, the firm's mistiming costs. Without earliness costs, a postponement of the product availability only has a negative impact on firm profits due to a reduced market potential. With the inclusion of earliness costs, however, a countervailing trend is introduced that creates an incentive to postpone the inventory timing. This result becomes even more explicit when we analyze the firm's optimal inventory strategy.

Proposition 3.2. *The firm's optimal inventory strategy is as follows:*

(a) In the absence of earliness costs, $o = w = 0$, the firm makes the product instantly available, $t^\star = 0$, and the optimal inventory scale solves $\mathbb{P}(Q \leq x^\star) = \frac{p-c}{p-s}$.

(b) Suppose the firm incurs earliness costs, $o + w > 0$. Then, there exists a decreasing and continuously differentiable function $\overline{o}(c)$ such that the firm (i) pursues the risk exploitation strategy defined in Lemma 3.3 if $o \leq \overline{o}(c)$; or (ii) exits the market otherwise.

Without earliness costs, a delay in the product's inventory availability has no upside, but only a downside effect because the firm may lose customers and experience lower sales and higher salvage costs. This imbalance forces the firm to make the product instantly available at the very first opportunity, $t^\star = 0$. Intriguingly, this timing strategy illustrates the firm's inability to synchronize the product's availability period with the selling season when the season start is stochastic. Note that this problem is not present when the firm only faces a probabilistic season length. As highlighted in Proposition 3.1(a), if the firm knows the beginning of the selling season, then the firm makes the product available right at the start of the selling season, thereby achieving an ideal synchronization between the product's selling season and its availability period.

Similar to the findings of Proposition 3.1(b), the introduction of mistiming costs attenuates the trend towards an instant product availability. In fact, the presence of earliness costs entices the firm to refrain from an instant product availability, and to delay its inventory timing. The higher the earliness costs, the more the firm strives to reduce these costs by delaying the time when inventory is made available to customers. In this endeavor to save costs, however, the firm more and more sacrifices its customer service as more and more customers are left unserved. This tendency, in turn, has detrimental effects on the firm's sales revenues and therefore may ultimately induce the firm to remove its product from the market.

Proposition 3.2(a) vividly shows that to tackle the uncertainty in the season start, the firm tries to execute a "safe" inventory strategy by avoiding any market potential loss due to an early demand occurrence. Thus, without earliness costs, the firm can completely offset the adverse effects of an uncertain season start on the product's market potential. With increasing earliness costs, however, this "safe" inventory timing becomes prohibitively expensive. As a result, the firm has to postpone its inventory timing which increases the risk of losing valuable market potential. Surprisingly, the literature on new product introductions has so far entirely ignored earliness costs as a determinant of a firm's product introduction strategy. Admittedly, due to significant modeling differences our results are not directly transferable to a new product introduction setting. Nevertheless, we believe that our analysis offers a substantial argument why earliness costs may also be important for new product introductions.

3.5 Selling over an Uncertain Season

In Section 4, we disentangled the direct effects that a stochastic season start and season length, respectively, have on the firm's optimal inventory strategy. We now proceed to study the interaction between these individual effects. In particular, by solving (3.1), we establish and analyze the firm's optimal inventory strategy when the firm faces an entirely stochastic selling season. Similar to the preceding analysis, we will first discuss the firm's optimal risk exploitation strategy. In a second step, we then determine the firm's optimal inventory strategy. Lastly, we elaborate on specific properties of this optimal strategy.

Lemma 3.4. *Any optimal risk exploitation inventory strategy,* $(x^\star, t^\star)$*, simultaneously* *satisfies the following two first-order necessary optimality conditions:*

$$\mathbb{P}(Q_{t^\star} \leq x^\star) + \frac{w}{p-s}\int_{t^\star}^{b_u} \mathbb{P}(B \geq b)db + \frac{h}{p-s}\int_0^{b_u+l_u} \mathbb{P}(Q_{t^\star} - Q_\tau \leq x^\star, \max\{t^\star, B\} \leq \tau \leq B+L)d\tau = \frac{p-c}{p-s} \tag{3.8}$$

$$h\left[x^\star\mathbb{P}(B \leq t^\star \leq B+L) - \int_{t^\star}^{b_u+l_u} d_{t^\star}(Q_{t^\star} - Q_\tau \leq x^\star, \tau \leq B+L, B \leq t^\star)d\tau\right] + (o + wx^\star)\mathbb{P}(B \geq t^\star) = (p-s)d_{t^\star}(Q_{t^\star} \leq x^\star). \tag{3.9}$$

Lemma 3.4 illustrates three important insights into the dependence structures between the different sources of uncertainty and the firm's inventory strategy. Firstly, we observe that the optimality conditions (3.8) and (3.9) collect the marginal effects that are already present in the optimality conditions given in Lemmas 3.2 and 3.3. Thus, the tradeoffs that a firm experiences when selling a product over a stochastic selling season are structurally equivalent to the tradeoffs identified in Section 4. Specifically, the firm balances the costs of having excessive inventories and the costs of offering the product too early with the opportunity costs of losing customers because of product unavailability. Secondly, while earliness and salvage costs are not influenced by the mutual interplay between the uncertainty in the start and the length of the selling season, inventory holding costs are simultaneously affected by both types of uncertainty. This can be clearly seen by comparing Lemmas 3.2 and 3.3 with Lemma 3.4. There is an intuitive explanation for this finding. Earliness costs depend solely on the relation between the firm's inventory timing and the start of the selling season, but not on the season length. Similarly, irrespective of the specific structure of the selling season, salvage costs are determined by the chosen inventory scale and the realized market potential. In contrast, inventory holding costs are determined by the complex interaction between the firm's inventory scale and timing, the selling season's beginning and length, and the market potential.

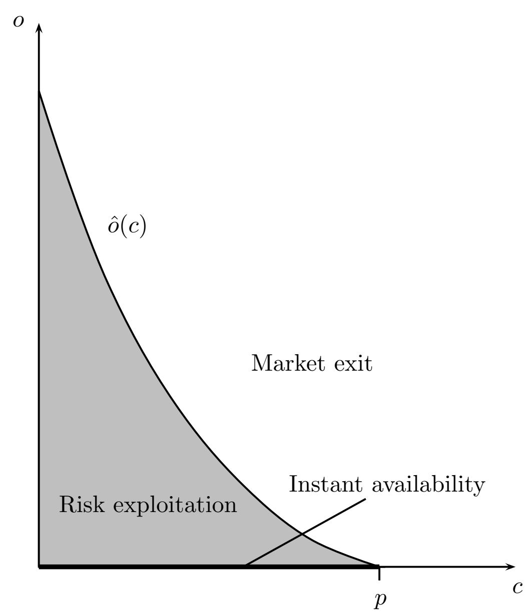
Lastly, the firm's ability to decide on the product's inventory timing is vital to actively manage the multiple sources of uncertainty. Without this flexibility, as in the classical newsvendor setup, the firm could only influence the different cost components by adjusting the product's inventory scale. Such an approach, however, impedes an effective inventory management for products with an uncertain selling season. Most importantly, to maximize profits, the firm has to be proactive in influencing the product's inventory holding, earliness, and salvage costs by choosing and executing an adequate inventory strategy. This finding receives further support from the following proposition.

Proposition 3.3. *The firm's optimal inventory strategy is as follows:*

(a) In the absence of earliness and inventory holding costs, $w = o = h = 0$, the firm makes the product instantly available, $t^\star = 0$, and the optimal inventory scale solves $\mathbb{P}(Q \leq x^\star) = \frac{p-c}{p-s}$.

(b) Suppose $w + o + h > 0$. Then, there exists a decreasing and continuously differentiable function $\hat{o}(c)$ such that the firm (i) pursues the risk exploitation strategy defined in Lemma 3.3 if $o \leq \hat{o}(c)$; or (ii) exits the market otherwise.

Figure 3.3.: The firm's optimal inventory strategy.



Notes. The firm's optimal inventory strategy with respect to the opportunity costs, o, and the procurement costs, c, given that $w = h = 0$. The firm chooses an instant product availability if $o = 0$, a risk exploitation strategy in the gray region, and a market exit elsewise.

Figure 3.3 visualizes the results of Proposition 3.3. Not surprisingly, the firm makes the product instantly available whenever there are no earliness and inventory holding costs. This is no longer true once the firm also incurs costs for making the product available to customers. Then, the firm defers its inventory timing to reduce the charged earliness and inventory holding costs. Such a risk exploitation inventory strategy is optimal as long as opportunity and procurement costs remain moderate. Once opportunity costs surpass a critical level, $\hat{o}(c)$, the firm refrains from offering the product on the market because the product becomes more and more unprofitable.

Proposition 3.3 also reveals an intriguing difference between the firm's reaction towards uncertainty in customer demand scale, and towards uncertainty in customer demand timing. Notably, the latter uncertainty has much more severe repercussions on the firm's inventory strategy. Specifically, even the joint flexibility to adjust the product's inventory scale and timing is not sufficient to always prevent the firm from exiting the market when the product faces a stochastic selling season. This happens because of the firm's inability to reduce the product's unit costs without sacrificing market potential. As a consequence, the firm may not be able to compensate all costs that arise from the uncertain selling season, leaving the product with a negative effective unit margin. This finding highlights the need for a carefully chosen inventory strategy. We next present two important results that follow from Proposition 3.3.

Corollary 3.1. *If the product's market potential, Q, and the properties of the selling season, $\mathcal{S}$, are stochastically independent, then the firm's optimal inventory scale is smaller than that of a classical newsvendor, $x^\star \leq x_{NV}$, with equality if and only if $w = o = h = 0$.*

Corollary 3.1 summarizes the effects of a stochastic selling season on the firm's optimal inventory scale. If the product's market potential is not affected by the specific structure of the selling season, then both, the firm and a classical newsvendor face the same inventory scaling problem: how much inventory to stock to best satisfy the uncertain market potential, Q? Although this initial question is identical for both firms, their answer is different. A classical newsvendor always stocks more than a firm that also experiences stochasticity in the selling season because this additional uncertainty makes it more expensive for the firm to have excess stocks. As a result, the firm becomes more conservative in its inventory scaling decision.

Intriguingly, this argument no longer holds if Q and $\mathcal{S}$ are stochastically dependent. Consider, e.g., a market where a late (early) season start is associated with a high (low) market potential. In such a situation, a firm could bet on a late season start. The firm would postpone product availability, save on earliness costs, and try to exploit the large market potential. Ultimately, this additional timing flexibility may induce the firm to stock more than a classical newsvendor who is not able to actively manage the product's market potential by shifting the inventory timing.

Corollary 3.2. *The firm's expected profit, $\Pi(x,t)$, increases in p and s, and decreases in c, o, w, and h, if the firm's inventory strategy is either held fixed or adjusted optimally as the parameters change.*

The firm's expected profits change monotonically in all revenue and cost parameters. As we would intuitively expect, the firm always benefits from a higher sales price, p, and a higher salvage value, s. In contrast, the firm suffers from eroding profits when procurement costs, c, opportunity costs, o, and holding costs, w and h, increase.

While the firm's expected profits are monotonic, we now show that the optimal inventory strategy does not exhibit such a monotonic behavior. We establish this important result through a series of Lemmas. In a first step, we analyze whether the firm's optimal inventory scale, $x^\star$, changes monotonically with the firm's inventory timing, t. One might expect that $x^\star$ decreases in t because a later inventory timing implies a stochastically smaller market potential for the product, which in turn should entice the firm to stock less inventories. However, Lemma 3.5 indicates that this intuitive reasoning is not necessarily true.

Lemma 3.5. *(a) If the firm incurs neither earliness nor inventory holding costs, then the firm's optimal inventory scale, $x^\star(t)$, decreases in the inventory timing, t.*

(b) There exist situations when the firm's optimal inventory scale, $x^\star(t)$, increases in t.

The interplay between the firm's optimal inventory scale and timing is determined by two countervailing effects. On the one hand, with a late inventory timing, the firm sacrifices sales because the expected number of customers that try to buy the product prior to the product's availability period increases in t. Thus, the product's market potential decreases and the firm is induced to reduce the product's inventory scale. On the other hand, a delayed inventory timing reduces the expected earliness and inventory holding costs that the firm has to pay. Less earliness and holding costs, in turn, increase (decrease) the firm's effective underage (overage) costs. Ultimately, this gives the firm a reason to choose a higher inventory scale.

Whether the firm's inventory scale decreases in the inventory timing decision, or not, crucially depends on the relation between these two effects. Obviously, if the firm does not incur any earliness or inventory holding costs at all, then a delayed inventory timing does not result in any cost savings. In such a situation, the firm's inventory scale always decreases in t to account for the product's reduced market potential. Yet, if earliness costs are high and delaying the inventory timing has only a small effect on the product's market potential, then the firm may actually increase the product's inventory scale as t increases. In this case, the expected cost savings outweigh the negative influence of a smaller customer base.

This finding is remarkable. Lemma 3.5(b) implies that a firm may actually build larger inventories although it serves stochastically less customers. As such, this result is fundamentally different from any common logic in the classical newsvendor model where a stochastically smaller market potential always leads to lower inventories (see, e.g., Li, 1992). The reason for this difference is the explicit consideration of the product's selling season together with the associated mistiming costs. These mistiming costs introduce a novel tradeoff that is not present in the classical newsvendor literature: the tradeoff between the length of the product's availability period and the size of the product's market potential. Although a short availability period only offers a small market potential, it is cheap to serve. In contrast, a long availability period promises a large market potential, but serving a long period may be overly costly.

Lemma 3.6. *(a) For fixed t, $x^\star$ increases in p and s; decreases in c, h, and w; and is invariant in o.*

(b) For fixed x, $t^\star$ increases in w, o, h, and s; decreases in p; and is invariant in c.

The direct influence of the different revenue and cost parameters on the firm's optimal inventory scale and timing, respectively, is summarized in Lemma 3.6. As in the classical newsvendor model, the firm's inventory scale increases in the sales price, p, and salvage value, s, and decreases in the procurement costs, c. This is true because p and s have a positive impact on the product's unit margin, whereas c has a negative impact. Similarly, the optimal inventory scale also decreases in w and h since idle time and inventory holding costs exert a negative influence on the product's profit margin. Interestingly, however, opportunity costs do not have any effect on the firm's inventory scale for given t, because o does not influence a product's unit profit margin.

Clearly, the firm postpones its inventory timing if earliness and holding costs increase. Less intuitive, however, is the effect of p, c, and s on the firm's optimal inventory timing. As can be verified in (3.9), the product's sales price and salvage value determine the firm's effective tardiness costs. For the firm, tardiness evokes additional lost sales and thus, more items need to be salvaged at the end of the season. This downside of a delayed inventory timing is most severe when the sales price, p, is high and the the salvage value, s, is low. Consequently, the optimal inventory timing decreases in p and increases in s. Finally, the firm's timing decision is not affected by the product's procurement costs because c has no impact on the firm's mistiming costs.

Lemma 3.6 shows that, in isolation, the different revenue and cost parameters have a monotonic influence on the firm's optimal inventory scale and timing, respectively. As the next Proposition indicates this monotonicity of the optimal inventory strategy is not preserved for all parameters when including all indirect effects. Specifically, opportunity costs and procurement costs have an ambiguous effect on the firm's optimal inventory strategy.

Proposition 3.4. *(a) While the firm's optimal inventory timing, $t^\star$, increases in the opportunity costs, o, the optimal inventory scale, $x^\star$, may increase or decrease in o.*

(b) While the firm's optimal inventory scale, $x^\star$, decreases in the procurement costs, c, the optimal inventory timing, $t^\star$, may increase or decrease in c.

Proposition 3.4 offers two surprising results that highlight the substitution effects between the firm's inventory scale and timing. Firstly, the firm may respond to a higher operational cost burden by increasing the product's inventory scale while at the same time shortening the product's availability period. Clearly, with higher opportunity costs, the firm always postpones the product's inventory availability in order to dampen the burden of increasing earliness costs. At the same time, the firm reduces the costs of having left-over inventories at the end of the selling season, thereby creating an incentive to increase the product's inventory scale. Thus, when mistiming costs increase, the firm sacrifices some of the product's market potential, but tries to serve a larger portion of the remaining customer demand.

Secondly, when confronted with higher procurement costs, the firm may find it optimal to extend the product's availability period, while limiting the product's inventory scale. Intuitively, since higher procurement costs erode the product's unit margin, the firm always reduces the available inventories. Having less inventories, however, makes it cheaper for the firm to offer the product on the market. This explains why the firm may optimally choose to make the product available earlier. Intriguingly, as a result, the firm serves a higher market potential with less inventories.

3.6 Conclusions

A key concern of many firms is to determine an appropriate inventory strategy for a seasonal product that possesses a demand pattern “with an uncertain start date, an uncertain end date, and whose size cannot be known in advance with certainty” (Allen and Schuster, 2004, p. 227). Prior academic literature has provided manifold examples of products that suffer from such uncertainties in demand scale and timing (e.g., Chen and Yano, 2010, and references therein), but without offering explicit guidance on how to optimally manage inventories under these adverse market conditions. Our main contribution is to provide a formal framework on the tradeoffs arising from the different sources of demand uncertainty, and to give recommendations on how to successfully manage products in such volatile market environments.

Our results have important implications for managers in charge of products with uncertain customer demand patterns. Managers need to be aware of the tradeoff between the length of a product’s availability period and the product’s market potential. While at first glance, it may seem a promising strategy to serve as high a market potential as possible, our results reveal that an uncertain selling season paired with mistiming costs impedes such a naive strategy. Moreover, managers should exploit the substitution effects between a product’s inventory scale and its inventory timing. This involves making counter-intuitive decisions: when mistiming costs are relatively high, managers should choose relatively short availability periods, but offer relatively high inventories.

Our analysis also highlights that managers do well not to underestimate the negative impact of an uncertain timing of customer demand. Simply shortening a product’s availability period may not always be a prudent response. Albeit such a strategy enables the reduction of the inventory and mistiming costs, it also sacrifices valuable market potential. When this latter effect dominates, products are suffering from devouring revenues. To combat this detrimental tendency, managers have to carefully rebalance their inventory scaling and timing decisions. At the very extreme, when the timing uncertainty is too severe, managers may also be left with a product accruing no profits.

Ultimately, we stress the importance for managers to have a clear understanding of how their operational costs affect a product’s optimal inventory strategy. As our results suggest, disregarding some of these effects leads to inadequate decisions. Inventory holding costs are a notable example for this phenomenon. They simultaneously exert a subtle influence on a product's mistiming costs as well as on the firm's effective lost sales costs. When ignoring the interaction between these two effects, a manager is likely to overestimate both, the product's optimal inventory level and the optimal time on the market.

Our analytical framework offers a strong foundation on which future studies can build. By restricting our attention to a single firm, we have made a first step towards the understanding of how a stochastic selling season affects a firm's inventory decisions. Yet, in practice, many firms sell their products not only in an uncertain market environment, but also under intense competition. Investigating how firms adapt their inventory strategy under competition is an exciting alley for further research. The occurrence of rival firms would force a firm to simultaneously engage in quantity and time competition. Whether such competition induces firms to strive for an early market entry, or to prefer a late market release, is an open question.

Chapter IV

Substitution Effects in a Supply Chain with Upstream Competition

with Moritz Fleischmann[1]

4.1 Introduction

In recent years, a diverse body of research has focused on how firms should optimally react to customer substitution. For firms that directly serve customers, investigations range from strategic assortment planning (Kök and Fisher, 2007; Honhon et al., 2010) over promotion strategies (Walters, 1991) to optimal stocking decisions (Netessine and Rudi, 2003; Jiang et al., 2011). In a supply chain setting, only the most downstream stage directly experiences the impact of customer substitution; however, indirect substitution effects also diffuse across the entire supply chain. This essay therefore investigates how different stages of a supply chain are affected by customer substitution. In particular, we examine the optimal production and stocking decisions of different supply chain members under upstream competition and vertical information asymmetries.

We are interested in markets where competition and substitution arise simultaneously within the supply chain. While competition occurs due to the non-cooperative behavior of independent firms, substitution emerges from the competitive structures within the set of available products. Note that competition and substitution are neither inclusive nor exclusive concepts: Competition without substitution arises if multiple independent firms offer an identical product (in a supply chain setting, e.g., Cachon, 2001; Adida and DeMiguel, 2011), while substitution without competition occurs if a monop-

[1]The research presented in this chapter is based on a paper entitled "Substitution Effects in a Supply Chain with Upstream Competition", coauthored with Moritz Fleischmann.

olistic firm offers non-identical, yet similar products that serve a common customer base (e.g., Nagarajan and Rajagopalan, 2008).

Initially, our work is motivated by the agrochemical market. Agrochemical manufacturers sell their products through locally monopolistic wholesalers to their customers, mostly farmers or farmer unions. Substitution in this market arises from customers' focus on active ingredients, resulting in low brand loyalty. In consequence, stock-outs at the wholesaler lead to high substitution rates among products. This effect is even further enhanced by the inherent finiteness of the selling season for agrochemicals and the non-durability of some chemical components. Information asymmetries in this market stem from the wholesaler's bargaining power and the substantial production lead-times at the manufacturers which can amount to two years (Shah, 2004). While production needs to be initiated well in advance of the desired selling season, the wholesaler cannot be forced to commit to order quantities at this early stage. Final orders are typically released close to the selling season when (weather-dependent) demand can be predicted sufficiently well. In essence, production and ordering decisions are based on potentially different information sets, and thus, vertical information asymmetries arise.

To analyze the manufacturer's (wholesaler's) optimal production quantities (stocking levels), we consider a supply chain in which potentially multiple manufacturers sell partially substitutable products for a single season through a monopolistic wholesaler. We focus on a single period setting because (i) it yields a very good approximation of the agrochemical market where the selling season is finite and some chemical components cannot be stored until the next season; and (ii) it is a necessary first step in the analysis of substitution effects within supply chains which is in line with the existing literature and thus makes our results comparable. To capture the influence of upstream competition, we compare two distinct supply chain scenarios: a horizontally integrated (hereafter 'non-competitive') supply chain with a single manufacturer producing all available products; and a horizontally competitive (hereafter 'competitive') supply chain with multiple manufacturers, each producing only one product. While inspired by the agrochemical market, our framework generally suits industries in which (1) products are partial substitutes, (2) products and market structures exhibit typical newsvendor characteristics, and (3) customers are served by a monopolistic wholesaler.

Our work contributes to the literature on (i) vertical information asymmetries in supply chains; and, most importantly, (ii) optimal stocking levels under customer substitution. Information sharing within supply chains has been a prevalent research area in the last decades (Li, 2002; Özer and Wei, 2006). Apart from the issue of truthful information sharing, literature also investigates how asymmetric information affect operational problems. In the presence of short capacity at the manufacturer, Cachon and Lariviere (1999) show that wholesalers exploit their informational advantage by manipulating the manufacturer's allocation mechanism. Under asymmetric information, Corbett (2001) depicts that the introduction of consignment stocks at the wholesaler leads to reduced cycle stocks at the expense of increased safety stocks. If wholesalers are allowed to share inventories, Yan and Zhao (2011) conclude that wholesalers share demand information with each other, but not with the manufacturer. We extend this research stream by characterizing how the interaction between information asymmetries and customer substitution impacts supply chain decision making.

There has been an extensive literature on the repercussions of customer substitution on the wholesaler's optimal stocking levels. As common building block, the single-stage newsvendor inventory (competition) model with stock-out-based substitution as pioneered by McGillivray and Silver (1978), Parlar (1988), Lippman and McCardle (1997), Bassok et al. (1999), Smith and Agrawal (2000), and Netessine and Rudi (2003) has evolved. In a seminal paper, Netessine and Rudi (2003) extend the preceding work by characterizing the structure of the optimal stocking levels for an arbitrary number of products under centralization and competition. Based on these results, recent work has investigated various competitive environments under customer substitution. Mishra and Raghunathan (2004), Kraiselburd et al. (2004), and Kim (2008) explore the consequences of introducing Vendor Managed Inventory for the wholesaler's stocking levels and advertisement efforts. Nagarajan and Rajagopalan (2008) embed the substitution framework into a multi-period setting, and Jiang et al. (2011) provide a robust optimization approach that determines stocking levels by minimizing absolute regret. Recently, Vulcano et al. (2012) have developed an efficient procedure to empirically estimate required substitution parameters.

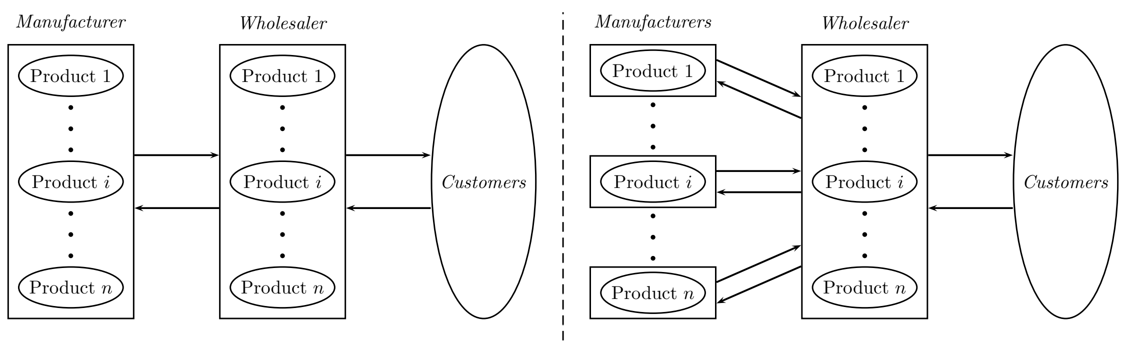
As common in the newsvendor framework, existing models assume that the wholesaler is unconstrained in his stocking decision, i.e., any arbitrary amount of products can be stocked. Being true in a single-stage setting, this assumption is problematic in a supply chain setting. Here, a manufacturer's production or capacity decision constitutes a natural upper bound on the wholesaler's decision space (compare this to the literature on capacity choice, e.g., Cachon and Lariviere, 1999; Montez, 2007). By explicitly integrating these dependencies into our model, we make a two-fold contribution to the existing literature: first, we investigate a constrained wholesaler's optimal stocking decision; second, to the best of our knowledge, we are the first to examine how customer substitution affects the production decision of upstream stages. To be specific, the main contributions of this essay are as follows: (1) We derive the optimal stocking levels of a constrained wholesaler and characterize the non-monotonic effects that a change in a manufacturer's production quantity exerts on these stocking levels. (2) We formally analyze the influence of changing substitution rates on the wholesaler's stocking levels. In contrast to an intuitive conjecture of Netessine and Rudi (2003), we show that stocking levels for certain products may increase even if customer substitution away from these products increases. (3) We characterize the optimal production quantities of an incompletely informed manufacturer with and without upstream competition by applying a Bayesian (Nash-) Stackelberg game. (4) We explicitly compare monopolistic and competitive optimal production quantities and find that competition may lead to reduced production. (5) We show that for some products, end-of-season inventories at the manufacturer may decrease under competition, even when initial production quantities increase.

The remainder of this essay is organized as follows. The structure of the supply chain under consideration and the distribution of information are described in §4.2. Furthermore, we elaborate on the properties of the resulting supply chain game. In §4.3, we present our model of a constrained wholesaler and derive the optimal stocking levels. We proceed by analyzing the effects of changing substitution rates on these optimal stocking levels. The manufacturer's production quantities are the focus of §4.4. We first characterize the equilibrium production quantities of a manufacturer under competition, before determining a monopolistic manufacturer's optimal production quantities. We then compare monopolistic and competitive production quantities, and examine the manufacturer's end-of-season inventories under both scenarios. Section 4.5 provides a discussion of our results and concluding remarks.

4.2 Supply Chain Structure and Information Distribution

We consider a two-stage supply chain with possibly multiple manufacturers (she) and a single wholesaler (he) selling $n \geq 2$ partially substitutable products for one period. While competition among manufacturers at the upstream stage may arise, we restrict attention to a monopolistic downstream wholesaler. In the non-competitive situation, a single manufacturer provides all n products (bilateral monopoly), whereas in the competitive scenario, n independent manufacturers each produce a different product (unilateral monopoly with upstream competition). Figure 4.1 illustrates both supply chain structures. In the agrochemical market, a monopolistic manufacturer occurs whenever a family of patents that allows for the provision of different, yet substitutable products is exclusively held by a single firm. In contrast, upstream competition is introduced if different manufacturers hold different patents for similar, but not identical products, or if patents run out.

Figure 4.1.: Bilateral monopoly (left) and unilateral monopoly with upstream competition (right).



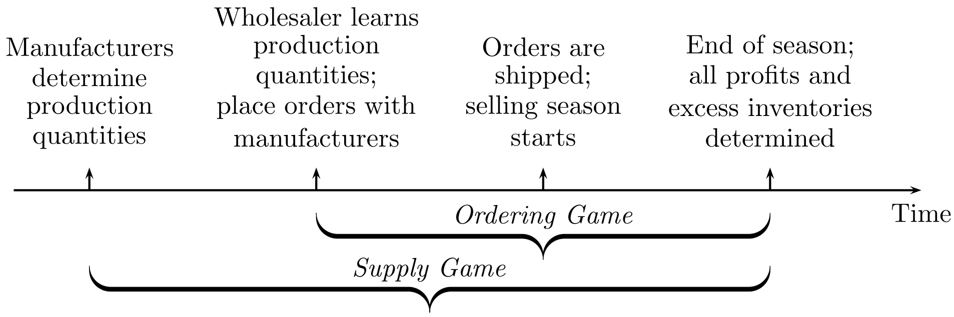
We assume that information is asymmetrically distributed between manufacturers and the wholesaler. As mentioned earlier, this vertical information asymmetry between supply chain stages arises naturally in the agrochemical market due to the wholesaler's bargaining power and manufacturers' production lead-times. Besides such market-driven causes for differing information sets, scholars have also identified many other reasons, including technological issues (Lee and Whang, 2000) and the fear of information leakage

(Anand and Goyal, 2009). To be precise, in line with the literature on vertical information asymmetries, e.g., Li (2002), Özer and Wei (2006) and Yan and Zhao (2011), we assume that manufacturers are incompletely informed about the wholesaler's optimal stocking levels. In contrast, upstream information are common knowledge across manufacturers, i.e., no horizontal information asymmetry arises, and production quantities are commonly verifiable. These assumptions are reasonable in the agrochemical market since manufacturers produce substitutable, hence comparable products and thus, they are able to credibly estimate their competitors' cost structures. Furthermore, for a "fair" comparison of production quantities, we need to ensure that decisions are based on identical information sets under both supply chain structures. Following the argument of Harsanyi (1968) and Myerson (2004), we assume that manufacturers hold a common prior belief about the wholesaler's optimal stocking levels. Hence, manufacturers' beliefs are consistent. This prior belief represents the manufacturers' perception about the collection of information that are not common knowledge. In summary, supply chain structure and information distribution imply a Bayesian (Nash-) Stackelberg Game as first introduced by Gal-Or (1987). The relevant case of multiple-leader Stackelberg games has first been studied by Sherali (1984) and recently by DeMiguel and Xu (2009), but only for complete, non-Bayesian information structures.

The sequence of events is as follows: In the first stage, manufacturers maximize expected profits and determine their optimal production quantities, based on their beliefs about the wholesaler's subsequent stocking levels. In the second stage, before the start of the selling season, the wholesaler learns these production quantities and, given his private information, derives his optimal stocking levels by maximizing expected profits. Afterwards, orders are submitted and shipped before the selling season starts. Throughout the selling season the wholesaler experiences customer demand and realizes profits. We refer to the subgame with given production quantities as the Ordering Game, while the entire game is denoted as the Supply Game. As such, production quantities are exogenously given in the Ordering Game, while they are decision variables in the Supply Game. Figure 4.2 summarizes the chronology.

We assume that stochastic customer demand appears exclusively at the wholesaler and no manufacturer can pursue a direct selling strategy. Prices are exogenously given by the market and neither player can negotiate on the price to pay. Furthermore, we restrict attention to pure-strategy equilibria.

Figure 4.2.: Sequence of events.



4.3 The Ordering Game

Focusing on the Stackelberg follower in this section, we derive the wholesaler's optimal stocking levels given the manufacturers' production quantities and characterize its sensitivity with respect to (i) changes in a manufacturer's production quantity, and (ii) substitution effects.

4.3.1. Optimal Stocking Levels

For each product $i \in \{1, \ldots, n\}$, the wholesaler pays a unit wholesale price w_i to the manufacturer and sells the product at a unit retail price r_i, satisfying $r_i > w_i > 0$. Additionally, the wholesaler incurs a unit holding or disposal cost of $h_i \geq 0$ for each unsold item. Total demand occurrence follows the standard model of stock-out-based substitution processes as defined by Netessine and Rudi (2003), Kök et al. (2009), and Jiang et al. (2011). Customers arrive at the wholesaler with an initial product preference. Thus, the wholesaler faces random initial demand for product i given by D_i, which is assumed to have a continuous demand distribution with positive support. Second choice (substitution) demand stems from customers whose initially preferred product is out of stock. If a stock-out of product i occurs, an exogenously given fraction α_{ij} of unserved customers is willing to substitute from product i to j; naturally $\sum_{j \neq i} \alpha_{ij} \leq 1$ for all i. Each initially unserved customer makes at most one substitution attempt, which, if again unserved, results in a lost sale. Total demand for product i after substitution is denoted by $D_i^s = D_i + \sum_{j \neq i} \alpha_{ji} \max\{0, D_j - x_j\}$, where x_j is the wholesaler's stocking level for product j. For future reference, denote by x_{-j} the $(n-1)$-dimensional vector of stocking levels for all products $i \neq j$.

Let x be the vector of stocking levels and $\Pi_W(x)$ be the wholesaler's expected profit when choosing x. Since the vector of production quantities y is common knowledge and verifiable, the wholesaler faces an optimization problem under complete information. Thus, he determines his optimal stocking levels by solving the following maximization problem P_y:

$$\begin{aligned}\max_{0\le x\le y} \Pi_W(x) &= \mathbb{E}\left[\sum_i r_i \min\{x_i, D_i^s\} - w_i x_i - h_i \max\{x_i - D_i^s, 0\}\right]\\ &= \mathbb{E}\left[\sum_i u_i x_i - (u_i + o_i)\max\{x_i - D_i^s, 0\}\right], \end{aligned} \tag{4.1}$$

where $u_i = r_i - w_i$ and $o_i = h_i + w_i$ are the wholesaler's underage and overage costs, respectively. The wholesaler's objective is to maximize his expected profit under the quantity restrictions imposed by the manufacturers' production y. If there are no such restrictions, we let $y = \infty$ and refer to this case as the unconstrained problem P_∞. We start our analysis of the optimal stocking levels with a brief discussion on the properties of $\Pi_W(x)$. All proofs are given in Appendix C.

Lemma 4.1. *For arbitrary i and given x_{-i}, $\Pi_W(x)$ is not concave in x_i, in general.*

Lemma 4.1 formalizes the numerical results in Netessine and Rudi (2003) that $\Pi_W(x)$ is not always concave in each individual stocking level x_i. This also implies that $\Pi_W(x)$ is not necessarily jointly concave in x, either. Thus, there may exist multiple local optima. For the unconstrained problem P_∞, we know from Proposition 1 in Netessine and Rudi (2003) that the optimal stocking levels $\hat{x}$ must simultaneously satisfy the following first-order necessary optimality conditions for all $i \in \{1, \ldots, n\}$:

$$\mathbb{P}(D_i < \hat{x}_i) - \mathbb{P}(D_i < \hat{x}_i < D_i^s) + \sum_{j\neq i} \alpha_{ij} \frac{u_j + o_j}{u_i + o_i} \mathbb{P}(D_j^s < \hat{x}_j, D_i > \hat{x}_i) = \frac{u_i}{u_i + o_i}. \tag{4.2}$$

In the remainder, denote by $\hat{x}_i(x_{-i})$ the solution to product i's optimality condition (4.2) for given fixed values of x_{-i}. Analogously, let $\hat{x}_{-i}(x_i)$ be the solution vector of the remaining $(n-1)$ optimality conditions in (4.2) for products $j \neq i$ if x_i is fixed. We further refer to product j's entry in $\hat{x}_{-i}(x_i)$ as $\hat{x}_j(x_i)$. By Lemma 4.1, it is not ensured that $\hat{x}_i(x_{-i})$ is unique. Therefore, for a given problem instance P_y, we define $\hat{x}_i(x_{-i})$

to be the largest solution that is feasible in P_y and for simplicity, we let $\hat{x}_i(x_{-i}) \equiv \infty$ if there exists no feasible solution. The introduction of this tie-breaking rule ensures uniqueness of $\hat{x}_i(x_{-i})$ and helps us to avoid ambiguities when comparing two scenarios with multiple optima.

The interpretation of (4.2) is appealing. It is a standard newsvendor fractile solution, adjusted by substitution effects. The second term on the left hand side increases the optimal stocking level to account for additional second choice demand, whereas the third term reduces the optimal stocking level by considering that a stock-out need not result in a lost sale. The optimal solution of the constrained problem P_y follows a similar pattern. Whenever feasible, the wholesaler tries to stock the quantity that solves (4.2), given the other products' optimal stocking levels. If this is not possible, he procures the entire available production quantity y_i. Proposition 4.1 formalizes this intuition.

Proposition 4.1. *Denote the vector of the wholesaler's optimal stocking levels for the constrained problem P_y by $x^\star(y)$. Further, refer to $x^\star(y)$ as a directionally largest optimal solution if there exists no other optimal solution $x'^\star(y)$ with $x^\star_{-i}(y) = x'^\star_{-i}(y)$ and $x^\star_i(y) < x'^\star_i(y)$ for any i. Then, any directionally largest optimal solution simultaneously satisfies*

$$x^\star_i(y) = \min\{\hat{x}_i(x^\star_{-i}(y)), y_i\}, \tag{4.3}$$

for all $i = 1, \ldots, n$.

From hereon, we explicitly restrict our analysis to directionally largest optimal solutions. Obviously, each optimization problem P_y has at least one directionally largest optimal solution, and our numerical experiments indicate that non-directionally largest optimal solutions occur very rarely. Moreover, our subsequent key results highlight some counter-intuitive effects. We emphasize that if these counter-intuitive findings apply to directionally largest optimal solutions, then they also apply to the full set of optimal solutions, but not necessarily vice versa. Thus, the restriction to directionally largest optimal solutions does not drive our main results, but helps us to avoid ambiguities.

Note that $x^\star(\infty) = \hat{x}$. Therefore, the optimal stocking levels given in (4.3) are consistent with the solution to the unconstrained problem P_∞ given in Netessine and Rudi (2003). Furthermore, in any Bayesian (Nash-) Stackelberg equilibrium, the wholesaler plays his best-response against the manufacturers' initial decision y, which is given by $x^\star(y)$.

We now investigate the sensitivity of the wholesaler's optimal stocking levels with respect to changes in a manufacturer's production quantity. In particular, we are interested in the question if the wholesaler's optimal reaction to changes in y is monotonic. From a manufacturer's perspective, when altering y_i, monotonicity of the wholesaler's best-response function at least guarantees predictability of the direction of change of $x^\star(y)$, even in the asymmetric information case. In contrast, under information asymmetries, a non-monotonic best-response function is much harder to predict. We start our analysis by exogenously forcing one stocking level to increase in the unconstrained problem P_∞.

Lemma 4.2. *Let $\varepsilon > 0$ and denote by e_i the unit vector for product i.*

(i) For given x_{-i} and $x'_{-i} = x_{-i} + \varepsilon e_j$ with $j \neq i$, $\hat{x}_i(x_{-i}) \geq \hat{x}_i(x'_{-i})$.

(ii) For given x_j and $x'_j = x_j + \varepsilon$, there are instances of P_∞ for which $\hat{x}_i(x_j) < \hat{x}_i(x'_j)$ for some $i \neq j$.

Using the results of Lemma 4.2, we can now endogenize the increasing stocking level by explicitly considering changes in a manufacturer's production quantity y_j. This is done in the first part of Proposition 4.2. Building on this result, the second and third part transfer the findings of Lemma 4.2 to the solution of the constrained problem P_y.

Proposition 4.2. *Let $y' = y + \varepsilon e_j$, $\varepsilon > 0$, for arbitrary j. Then:*

(i) $x^\star_j(y') \geq x^\star_j(y)$.

(ii) For arbitrary i and j, fix $x^\star_k$ for all $k \neq i, j$ and solve (4.3) for i and j. Then, there always exist optimal solutions for which $x^\star_i(y') \leq x^\star_i(y)$.

(iii) Solve (4.3) for $k = 1, \ldots, n$. There are instances of P_y for which $x^\star_i(y') > x^\star_i(y)$ for some $i \neq j$.

In essence, Proposition 4.2 highlights that the wholesaler's best-response is not necessarily monotonic in a manufacturer's production decision. The reason for this lies in the multidimensionality of substitution which comprises direct and indirect effects. If the available production quantity for one product j is increased, (i) and (ii) indicate that the wholesaler increases his stocks for product j and, all else equal, reduces any other stock $i \neq j$. This is the direct effect which is in line with our common understanding of economic substitutes. However, each increase or decrease in any one product's stocking level has immediate effects on all other products' optimal stocking levels. Hence, if the wholesaler optimizes his stocking levels across all products, a cascade of indirect effects arises due to the mutual interdependency of all products. We find that in some situations these indirect effects dominate the direct effects so that, in optimum, the wholesaler may increase stocking levels for more than one product (iii). Indirect effects are dominant if, e.g., the market's substitution structure is heterogeneous in the sense that there is little direct substitution between products j and i, but frequent substitution between products j and k, and k and i.

4.3.2. Substitution Effects

We now investigate the sensitivity of the wholesaler's optimal stocking levels and expected profit with respect to changing substitution rates. A change in the customers' reaction to product stock-outs implies changing substitution rates. Naturally, this also affects the total demand for the wholesaler's products. To be specific, increasing substitution rates imply a stochastically larger total demand at the wholesaler, or mathematically, D_i^s is stochastically increasing in α_{ji} for all $j \neq i$. Intuition suggests that this increased demand is always beneficial for the wholesaler since the probability of incurring lost sales decreases. Moreover, Netessine and Rudi (2003) conjecture intuitively that optimal stocking levels for a product increase (decrease) if substitution rates to (from) this product increase. We now test this intuition.

We start our analysis with the sensitivity of the wholesaler's expected profit. As already argued, demand is stochastically increasing in any substitution rate. Furthermore, it is well known that, on expectation, a wholesaler benefits from increased demand if trade is profitable (Li, 1992). Accordingly, the wholesaler's expected profit increases in any substitution rate. The following proposition formally states this argument.

Proposition 4.3. *Suppose $\sum_{i \neq j} \alpha_{ji} < 1$. The wholesaler's expected profit $\Pi_W(x)$ is increasing in any substitution rate α_{ji} if stocking levels x are adjusted optimally to changes in substitution rates.*

Proposition 4.3 is true for the constrained and unconstrained problems P_y and P_∞, respectively. Note that, if $\sum_{i \neq j} \alpha_{ji} = 1$, then α_{ji} can only increase if at least one other substitution rate α_{jk}, $k \neq i$, simultaneously decreases. In this case, Π_W may actually decrease in α_{ji}.

While the sensitivity of the wholesaler's expected profit has a monotonic behavior, we now show that, in contrast to common intuition, his optimal stocking levels might be non-monotonic in the substitution rates. As a starting point we analyze how $\hat{x}$ changes in α_{ji}.

Lemma 4.3. *(i) For arbitrary i, $\partial \hat{x}_i(x_{-i})/\partial \alpha_{ji} \geq 0$ for all $j \neq i$.*
(ii) There are instances of P_∞ for which $\partial \hat{x}_j(x_{-j})/\partial \alpha_{ji} > 0$ for some i and j.

As we would intuitively expect, the wholesaler stocks more of product i if substitution rates to product i increase. This is happening because the total demand for product i, D_i^s, is stochastically increasing in α_{ji}. Contrary to intuition, however, the optimal stocking level for product j may also increase in α_{ji}. This surprising effect is explained by the increasing stock-out risk for product i. Increasing α_{ji} stochastically increases D_i^s, thereby increasing the risk of running out of stock for product i. For given stocking levels, this decreases the expected quantity of product i that is available for covering an additional unit of excess demand for product j. Thus, the effective marginal underage cost for product j increases, which in return justifies a higher stocking level.

Proposition 4.4. *There are instances of P_y for which $dx_j^\star/d\alpha_{ji} > 0$ for some i and j.*

Proposition 4.4 highlights that after the inclusion of all direct and indirect substitution dynamics, the total effect of α_{ji} on $x_j^\star$ can still be positive. Importantly, there are two independent drivers for this counter-intuitive result. Firstly, and not surprisingly, this result can be a direct consequence of Lemma 4.3(ii). Secondly, it may also stem from the substitution cascades identified in Proposition 4.2. In this latter case, Proposition 4.4 can hold even when $\hat{x}_j(x_{-j})$ decreases in α_{ji}. The wholesaler increases his stocks for product j, although there is a higher substitution away from this product, if indirect substitution dynamics dominate the direct effects. To conclude, Lemma 4.3 together with Proposition 4.4 indicate that the wholesaler's optimal stocking levels are in general non-monotonic in the substitution rates.

4.4 The Supply Game

In this section, we analyze the manufacturer's optimal production quantities under incomplete information about the wholesaler's stocking decision. We first focus on the competitive scenario with multiple Stackelberg leaders and then investigate the situation with a single Stackelberg leader. Subsequently, we compare the optimal production quantities for both scenarios and illustrate our findings with a numerical example.

The Ordering Game which takes production quantities y as given is the second stage of the Supply Game. In the first stage, manufacturers choose y to maximize their expected profits given their beliefs about the wholesaler's subsequent behavior. The manufacturers' unit production costs and selling prices for product i are c_i and w_i, respectively, with $w_i > c_i > 0$, $i \in \{1, \dots, n\}$. We assume that manufacturers credibly and simultaneously announce their production quantities y_i. Further, $y_i \in [0, K]$, with K sufficiently large so that it never constrains any manufacturer. Since the wholesaler has private information on his optimal stocking levels, manufacturers can only hold a belief about the wholesaler's equilibrium stocking levels. We explicitly model this uncertainty about the wholesaler's orders for product i as a random variable with support on $X_i(y)$ that depends on the chosen production quantities y. To be specific, let $\chi_i \in X_i(y)$ with cumulative distribution $\Phi_i(\chi_i, y)$ and density $\phi_i(\chi_i, y) > 0$. We assume $\Phi_i(\chi_i, y)$ to be twice continuously differentiable in all arguments y and define $\mu_i(y) \equiv \int_{X_i(y)} \chi_i d\Phi_i(\chi_i, y)$. We restrict attention to rational beliefs.

Definition 4.1. *We say that a manufacturer's belief about the wholesaler's stocking levels is rational if it satisfies the following conditions for all products i:*

1. $X_i(y) = [0, y_i]$;
2. $\partial^2\Phi_i(\chi_i, y)/\partial y_i \partial y_j \geq 0$, $j \neq i$;
3. $\partial\Phi_i(\chi_i, y)/\partial y_i \leq 0$ *and* $\partial^2\Phi_i(\chi_i, y)/\partial y_i^2 \geq 0$.

Definition 4.1 ensures three structural properties of a manufacturer's belief. First, manufacturers assign a positive probability mass only to non-negative stocking levels which are naturally bounded from above by the chosen production quantity y_i. Second, ceteris paribus, manufacturers consider all products to be economic substitutes. Third, production quantities exert a stimulating effect on the wholesaler's stocking decision, i.e., stocking levels stochastically increase with the available production quantities, but at a decreasing rate (for a thorough discussion on stimulating effects of inventories, see Balakrishnan et al., 2008).

We emphasize that Definition 4.1 imposes very mild restrictions on a manufacturer's belief. The wholesaler, by construction, never orders more than y. Therefore, the first property is in line with the results of Proposition 4.1. The second property ensures that manufacturers correctly believe that they compete in a substitution market. Finally, the third property follows immediately from Proposition 4.2(i) which states that $x_i^\star(y)$ increases in y_i. Irrespective of the kind of information asymmetries, any rational manufacturer can always predict these properties, only the magnitude of these effects may be unknown to her. Note that we neither require beliefs to be correct on expectation, nor do we make any assumption on how the belief for product i changes with y_j, since Propositions 4.2(ii) and (iii) indicate that $x_i^\star(y)$ can increase or decrease in y_j.

The manufacturer's decision problem structurally differs in two ways from the one of the wholesaler. First, the wholesaler's reaction to limited production quantities is fundamentally different from the customers' reaction to stock-outs. While customers only try to substitute once with a given probability, the wholesaler's reaction to short production capacities is based on a non-monotonic optimization strategy across all products. Second, the manufacturer can influence the wholesaler's stocking level for product i by changing y_i, whereas the wholesaler cannot influence customer demand for product i by varying x_i.

4.4.1. Competing Manufacturers

We now establish the equilibrium of the first stage of the Supply Game when there are n competing manufacturers, each selling a different, yet partially substitutable product through a monopolistic wholesaler. Before the wholesaler communicates his stocking levels, manufacturers simultaneously choose their production quantities. Accordingly, manufacturers act as Bayesian Stackelberg leaders with respect to the wholesaler, but as Nash competitors with respect to the other manufacturers. Thus, each manufacturer maximizes her expected profit, given the other manufacturers' production quantities and given her rational beliefs about the wholesaler's subsequent reaction. Her decision problem for given y_{-i} is

$$\max_{y_i \geq 0} \Pi_{M_i}(y_i|y_{-i}) = w_i \mu_i(y) - c_i y_i, \tag{4.4}$$

where $\Pi_{M_i}(y_i|y_{-i})$ is the ith manufacturer's expected profit. For brevity, let $\Pi_{M_i} \equiv \Pi_{M_i}(y_i|y_{-i})$ and denote by $y_i^c = \arg\max_{y_i \geq 0} \Pi_{M_i}$ the ith manufacturer's best-response to her competitors' production quantities y_{-i}.

We start our equilibrium analysis by noting that rational beliefs are sufficient to guarantee concavity of each manufacturer's expected profit.

Lemma 4.4. *Assume rational beliefs. Given y_{-i}, Π_{M_i} is a concave function of the production quantity y_i for all i.*

Due to the concavity of Π_{M_i}, we can derive each manufacturer's best-response y_i^c by examining the first-order conditions which are necessary and sufficient for optimality.

Proposition 4.5. *Assume rational beliefs. The following system of first-order necessary optimality conditions characterizes any manufacturer Nash equilibrium:*

$$\left.\frac{\partial \mu_i(y)}{\partial y_i}\right|_{y=y^c} = \frac{c_i}{w_i}, \tag{4.5}$$

$i = 1, \ldots, n.$

A simple trade-off argument explains the optimality conditions (4.5). On expectation, increasing the production quantity y_i raises the wholesaler's subsequent stocking level for product i (see Proposition 4.2). This generates a marginal increase in revenue given by $w_i \partial\mu_i(y)/\partial y_i$, while simultaneously inducing marginal costs of c_i. Equating marginal revenue and marginal costs provides the desired result. Note that y_i^c constitutes an upper bound on the wholesaler's decision space. Hence, in any case, the wholesaler's stocking level is smaller than y_i^c. Naturally, (4.5) not only determines each manufacturer's best-response in the manufacturer Nash game, i.e., in the competition among leaders, but also persists in the entire Bayesian Nash-Stackelberg game. Here, any Bayesian Nash-Stackelberg equilibrium is given by the wholesaler's optimal stocking levels $x^\star(y^c)$ and the manufacturers' production quantities y^c which form a Nash equilibrium in the manufacturer Nash game. In a next step, we establish existence and uniqueness of the manufacturer Nash equilibrium.

Proposition 4.6. *Assume rational beliefs. For the competitive scenario, a pure-strategy manufacturer Nash equilibrium exists and is found by solving (4.5). If Π_{M_i} is strictly concave in y_i and*

$$2 + \sum_{j \neq i} \frac{\partial y_i^c}{\partial y_j} - \sum_{j \neq i} \frac{\partial^2 \mu_j(y)/\partial y_i \partial y_j}{\partial^2 \mu_i(y)/\partial y_i^2} > 0, \tag{4.6}$$

$i = 1, \ldots, n$, for all y, then the manufacturer Nash equilibrium is unique.

Proposition 4.6 states two sufficient conditions for uniqueness of the manufacturer Nash equilibrium. Each manufacturer's expected profit Π_{M_i} is strictly concave in y_i

if and only if her belief satisfies $\partial^2\Phi_i(\chi_i, y)/\partial y_i^2 > 0$. Further note that a necessary condition for (4.6) to hold is given by $\sum_{j\neq i} |\partial y_i^c/\partial y_j| < 2$. Intuitively, the sensitivity of each manufacturer's best-response with respect to the other manufacturers' production decisions has to be bounded. A special case where (4.6) is automatically satisfied occurs if the effects of y_i and y_{-i} on $\mu_i(y)$ are additive separable, i.e., $\mu_i(y) = g_i(y_i) + h_i(y_{-i})$ for arbitrary differentiable functions g_i and h_i. If g_i is furthermore strictly concave, then the manufacturer Nash equilibrium is unique.

While Proposition 4.6 ensures uniqueness of the manufacturer Nash equilibrium, the stated conditions are not sufficient to generally guarantee a unique Bayesian Nash-Stackelberg equilibrium in the Supply Game. As discussed in §3, the wholesaler's optimal stocking levels given the manufacturers' production quantities are not necessarily unique. Consequently, the wholesaler might have multiple best-responses. Accordingly, for a unique equilibrium of the Supply Game, the wholesaler's optimal stocking levels must also be unique. Corollary 4.1 states a simple condition that guarantees uniqueness.

Corollary 4.1. *Let the conditions of Proposition 4.6 hold. Suppose $\Pi_W(x)$ is jointly concave in x. Then, the Supply Game has a unique Bayesian Nash-Stackelberg equilibrium in the competitive scenario.*

4.4.2. Monopolistic Manufacturer

As a benchmark, we now derive the Bayesian Stackelberg equilibrium of the Supply Game without manufacturer competition. To be specific, a monopolistic manufacturer simultaneously produces all n substitutable products and sells them through a monopolistic wholesaler. Therefore, the manufacturer serves as Bayesian Stackelberg leader with respect to the wholesaler. Thus, she maximizes her expected profit Π_M across all products given her belief about the wholesaler's subsequent stocking levels. Her decision problem is

$$\max_{y\geq 0} \Pi_M(y) = \sum_i \left(w_i\mu_i(y) - c_i y_i\right). \tag{4.7}$$

For given rational beliefs, denote by $y^{nc} = \arg\max_{y\geq 0} \Pi_M(y)$ a vector of optimal production quantities. In contrast to the competitive scenario, the manufacturer's expected profit Π_M is not generally concave in y. Thus, first-order optimality conditions provide only necessary, but not sufficient conditions for the manufacturer's optimal production quantities.

Proposition 4.7. *Assume rational beliefs. In any Bayesian Stackelberg equilibrium of the non-competitive scenario, the manufacturer's production quantities satisfy the system of first-order necessary optimality conditions*

$$\left.\frac{\partial \mu_i(y)}{\partial y_i} + \sum_{j \neq i} \frac{w_j}{w_i} \frac{\partial \mu_j(y)}{\partial y_i}\right|_{y=y^{nc}} = \frac{c_i}{w_i}, \tag{4.8}$$

$i = 1, \ldots, n$.

Analogously to the optimality conditions of the competitive scenario, the monopolistic manufacturer's optimal decision also follows a trade-off argument. Again, the manufacturer equates marginal costs and marginal revenues. This time, however, the shift in revenue accounts not only for the increased revenue for product i, but also for the altered revenue for all other products $j \neq i$. Intuitively, the monopolistic manufacturer considers the influence of her production quantities on the revenue for all products, whereas each competitive manufacturer only cares about her own product. Neither the manufacturer's optimal production quantities y^{nc} nor the wholesaler's optimal stocking levels $x^\star(y^{nc})$ are necessarily unique. In consequence, the Bayesian Stackelberg equilibrium of the Supply Game is not guaranteed to be unique. A sufficient condition for uniqueness is given in Corollary 4.2.

Corollary 4.2. *Suppose $\Pi_W(x)$ and $\Pi_M(y)$ are jointly concave in x and y, respectively. Then, the Supply Game has a unique Bayesian Stackelberg equilibrium in the non-competitive scenario.*

4.4.3. The Consequences of Manufacturer Competition

Competing manufacturers adopt production quantities, y^c, that differ substantially from a monopolistic manufacturer's production quantities, y^{nc}, even though they hold identical beliefs about the wholesaler's subsequent stocking levels. In this context, the natural question arises whether competition causes manufacturers to increase production quantities, i.e., $y^c > y^{nc}$? Furthermore, vertical information asymmetries induce supply chain inefficiencies that manifest in end-of-season inventories at the manufacturer. However, are these effects smaller or larger under upstream competition? We now explore these questions.

Intuition suggests that the wholesaler prefers competing manufacturers to a monopolistic manufacturer because we expect production quantities to increase under competition. Hence, the wholesaler's decision space would be less restricted under manufacturer competition and so, he could provide a more profitable service to his customers. Proposition 4.8 shows that this intuition is not always true.

Proposition 4.8. *For given rational beliefs, the relationship between y^c and y^{nc} is as follows:*

(i) If

$$\sum_{j \neq i} w_j \frac{\partial \mu_j(y)}{\partial y_i} \leq 0 \tag{4.9}$$

for all products i, then $y_i^c \geq y_i^{nc}$ for at least one product i.

(ii) There are rational beliefs such that $y_i^c < y_i^{nc}$ for some product i.

It can never happen that all production quantities decrease under competition, if (4.9) holds. This condition ensures that each product has in total a negative effect on the other products, which is the very nature of substitute products. A sufficient condition for (4.9) are rational beliefs that additionally satisfy $\partial \Phi_i(\chi_i, y)/\partial y_j \geq 0$ for all $j \neq i$, or intuitively, each product j should exert a negative influence on every other product i. Yet, note that Proposition 4.2(iii) indicates that this need not be true for all products. There exist situations where two products have a positive effect on each other, which would be reflected by $\partial \Phi_i(\chi_i, y)/\partial y_j < 0$ for some i and j, and does not contradict our definition of rational beliefs. Condition (4.9) also captures these contingencies because we only require the weighted sum over all individual effects, i.e., the aggregated effect, to be negative, not each single effect. Thus, (4.9) imposes a very mild condition, and any product that violates it, is eventually an economic complement for the other products.

An availability trade-off explains why a monopolistic manufacturer sometimes stocks more than a competitive manufacturer (ii). A monopolistic manufacturer can coordinate the availability of all products, i.e., she can optimally increase stocks of a product i, while simultaneously decreasing the availability of products $j \neq i$. Under competition, a manufacturer cannot accomplish this availability trade-off since she cannot force her competitors to reduce production quantities. This contingency occurs for a product i

if, e.g., manufacturers believe that y_i exerts only a limited influence on the wholesaler's stocking decision for the other products $x^\star_{-i}$, or if product i offers a very high profit margin to the manufacturer. Markets with such heterogeneous product margins and substitution structures typically include no-name and brand products (Ailawadi and Keller, 2004), or functionally heterogeneous products. If the effects of y_i and y_{-i} on $\mu_i(y)$ are additive separable for all i, or if (4.9) holds and all products are homogeneous and symmetric, then production increases under competition for all products, $y^c \geq y^{nc}$.

Note that the results of Proposition 4.8 are similar to the findings of Netessine and Rudi (2003) for competition among wholesalers. However, these two results are based on different problem characteristics because the wholesaler's and manufacturer's problem differ structurally in numerous ways. In particular, substitution dynamics and demand characteristics are completely different. Therefore, Proposition 4.8 establishes the transferability of the previous results to the manufacturer stage.

Naturally, as manufacturers' production quantities change under competition, the wholesaler also adjusts his stocking levels. This implies that end-of-season inventories at the manufacturer, i.e., excess inventories after trading, change if competition is introduced. These residual inventories are a direct consequence of the vertical information asymmetry within the supply chain. If manufacturers could perfectly predict the wholesaler's best-response stocking levels, they would never produce more than this quantity, and they would never incur end-of-season inventories. We now examine how the manufacturers' end-of-season inventories change under competition. We denote the end-of-season inventory level of product i at the manufacturer by $I_i(y) = y_i - x^\star_i(y)$.

Proposition 4.9. *Let $y' \geq y$. Then, the following relations between $I(y')$ and $I(y)$ hold:*

(i) $I_i(y') \geq I_i(y)$ for at least one product i.

(ii) There are instances of the Supply Game where $I_i(y') < I_i(y)$ for some product i.

Proposition 4.9 sheds light on the influence of competition on end-of-season inventories. As an illustration, consider the extreme case of Proposition 4.8 that all production quantities increase under competition, $y^c \geq y^{nc}$. Interestingly, despite the monotonic influence on production quantities, competition does not necessarily increase each product's end-of-season inventories. In fact, for some products, end-of-season inventories may decrease. In such a case, the wholesaler increases his stocking level for product i more than the manufacturer increases y_i. Again, this result is explained by both, the mutual interdependency of all products and the occurrence of indirect substitution cascades as described in Proposition 4.2. In summary, even when competition exerts a monotonic effect on the manufacturer's production quantities, supply chain inefficiencies due to asymmetric information need not change monotonically.

4.4.4. Numerical Illustration

We now provide a small numerical example to illustrate our theoretical findings. Consider a market with three substitutable products. For the sake of analytical tractability, suppose that each manufacturer believes that the wholesaler's stocking levels follow a truncated exponential distribution with support on $[0, y_i]$ and rate parameter $\lambda_i(y)$, i.e., $\Phi_i(\chi_i, y) = [1-exp(-\lambda_i(y)\chi_i)]/[1-exp(-\lambda_i(y)y_i)]$. Note that our framework also works for any other common distribution such as truncated Normal, Gamma, or Weibull distributions, but at the cost of analytical tractability.

Following Definition 4.1, beliefs about the wholesaler's stocking level for product i should be stochastically increasing in y_i. Thus, each rate parameter $\lambda_i(y)$ is a function of the manufacturers' production quantities which decreases in y_i. To be specific, we employ the following simple structural form: $\lambda_i(y) = y_i^{-1} + \sum_{j \neq i} k_{ji} y_j + 1$. By setting $k_{ji} \geq 0$, we ensure that products are economic substitutes. We work with the inverse of y_i and not with $-y_i$ to ensure non-negativity of $\lambda_i(y)$. Intuitively, each scale parameter k_{ji} captures the magnitude of the effect that y_j exerts on the wholesaler's stocking decision for product i.

The truncated exponential distribution together with the specification of $\lambda_i(y)$ ensures that each manufacturer holds rational beliefs as described in Definition 1. It is readily shown that $\mu_i(y) = [1/\lambda_i(y)] - [y_i exp(-\lambda_i(y)y_i)/(1 - exp(-\lambda_i(y)y_i))]$. Thus, the influence of y_i and y_{-i} on $\mu_i(y)$ is not additive separable. For all investigated scenarios, we assume $c_i = 2$ for all i. All other parameter values w_i and k_{ji} are given in Table 4.1. Parameters include high and low margin cases, and high and low substitution rates. Note that for all displayed parameter values, a unique Bayesian (Nash-) Stackelberg equilibrium exists. For each scenario, we display the optimal production decisions for both supply chain configurations.

Obviously, in a market with symmetric price and substitution structure, production quantities increase if manufacturer competition is introduced (A). In our example, this result remains valid if there is no substitution *to* one product in the assortment (B). If

Table 4.1.: Optimal production decisions.

	Parameters									Optimal decision					
Scenario	w_1	w_2	w_3	k_{21}	k_{31}	k_{12}	k_{32}	k_{13}	k_{23}	y_1^c	y_2^c	y_3^c	y_1^{nc}	y_2^{nc}	y_3^{nc}
A	8	8	8	0.5	0.5	0.5	0.5	0.5	0.5	0.70	0.70	0.70	0.61	0.61	0.61
B	8	8	8	0	0	0.5	0.5	0.5	0.5	1.20	0.63	0.63	1.00	0.60	0.60
C	8	8	8	0.5	0.5	0	0.5	0	0.5	0.65	0.84	0.84	0.71	0.69	0.69
D	8	8	8	0	0	0.5	0	0.5	0	1.20	0.75	0.75	0.81	0.85	0.85
E	10	8	8	0.5	0.5	0.5	0.5	0.5	0.5	1.00	0.66	0.66	1.07	0.45	0.45
F	11.9	8	8	0.5	0.5	0.5	0.5	0.5	0.5	1.24	0.62	0.62	1.89	0.06	0.06
G	11.9	10	7	0.5	0.5	0.5	0.5	0.5	0.5	1.20	0.91	0.44	1.44	0.59	0.05

instead one product does not influence the other products, i.e., there is no substitution *away* from the product, then production quantities decrease for this product under competition (C,D). In such a scenario, a monopolistic manufacturer optimally increases the availability of the product at the cost of decreasing the other products' availability. In a competitive environment, a manufacturer cannot coordinate product availability across multiple products because her competitors are reluctant to lose market shares. In the agrochemical market, these heterogeneous substitution structures arise due to the coexistence of single- and multi-purpose products. While single-purpose products are specialized to fight a single plant disease such as mildew, multi-purpose products are effective against a wider class of diseases. Naturally, substitution from the specialized to the more general product is likely to occur, because the specialized product lies within the application range of the general product. In contrast, the specialized product need not be useful for a customer initially desiring the more general product.

In our example, production quantities for high margin products decrease under competition, while production increases for low and medium margin products (E,F,G). We observe this behavior because a monopolistic manufacturer shifts as much demand as possible to the high margin products, thereby reducing the other products' availability to a minimum. In contrast, a similar demand shift cannot be accomplished under competition. Note that under a monopolistic manufacturer, low margin products almost disappear from the market, while competition ensures product diversity (F,G). Concurrent with intuition, overall production increases with the introduction of manufacturer competition.

4.5 Discussion

In this essay, we analyzed the optimal production and stocking decisions of a manufacturer and a wholesaler in a two-stage supply chain with upstream competition and vertical information asymmetries. We characterize the wholesaler's equilibrium stocking levels and show that these quantities are non-monotonic in both, available production quantities and customer substitution rates. For the upstream stage of the supply chain, we derive the equilibrium production quantities of a monopolistic and a competitive manufacturer, respectively. We find that production quantities for some products decrease if upstream competition is introduced. Furthermore, we highlight the counter-intuitive situation that some end-of-season inventories at the manufacturer decrease although initial production quantities increase.

We can identify two key drivers for these non-monotonic and partially counter-intuitive results: (i) customer substitution; and (ii) the products' heterogeneity. If there exists no substitution among products ($\alpha_{ij} = 0$ for all i, j), then our n-product problem can be decomposed into n single-product problems. As such, there is no interaction between products and therefore, direct and indirect substitution dynamics disappear. Similarly, if products are completely homogeneous, then products affect one another only in monotonic and intuitive ways. Thus, our counter-intuitive results only occur in markets which exhibit a minimum level of substitution and product heterogeneity. The agrochemical market, e.g., is shaped by these heterogeneities. Brand manufacturers and (former) patent holders compete with generic products, which oftentimes differ in price and profit margins. Furthermore, the market's substitution structure is skewed due to the coexistence of single- and multi-purpose products.

4.5.1. Robustness

We now discuss the robustness of our results with respect to changes in the information and supply chain structure. Additionally, we delineate opportunities for future research.

Concerning the *information structure*, we assume that (i) manufacturers' production quantities y are verifiable, and (ii) $\Phi_i(\chi_i, y)$ is differentiable in y. Verifiability of y ensures that the wholesaler determines his stocking levels under complete information about the manufacturer's strategy. Consequently, we can ignore communication issues between manufacturer and wholesaler. This is not true if y is unverifiable and thus privately observed by the manufacturer. In this case, the manufacturer's equilibrium behavior consists of her production and communication strategy, which introduces an additional inference problem for the wholesaler. Under strategic communication, the manufacturer need not pursue a truth-telling strategy or she may not communicate any information at all, which inherently changes the timing of the game to simultaneous moves. Whether the structure of our results remains valid under such a scenario, or not, is an interesting question for future research.

The differentiability of a manufacturer's belief, $\Phi_i(\chi_i, y)$, about the wholesaler's subsequent stocking level is a common assumption in the literature (Cachon and Lariviere, 1999; Özer and Wei, 2006), but clearly, it is not ensured that, in equilibrium, $x_i^\star(y)$ is actually differentiable. Nevertheless, it is guaranteed that $x_i^\star(y)$ is continuous in y. In a similar framework, Cachon and Lariviere (1999) show numerically that the differentiability assumption provides an excellent approximation. We therefore expect our results to be robust with respect to the differentiability of beliefs.

Concerning the *supply chain structure*, we assume that competition occurs only among manufacturers. This assumption is inspired by our observations in the agrochemical market, but obviously, a general extension of our framework is to allow for downstream competition as well. Such an extension introduces two additional issues that need to be incorporated into the model. First, manufacturers need to decide on allocation mechanisms for their production quantities in case that total orders exceed the available production quantities. Second, these allocation schemes induce the wholesalers to place strategic orders. The influence of such allocation problems on supply chains in substitution markets should be a focal point of future work.

Additionally, under downstream competition, the assumption that $\Phi_i(\chi_i, y)$ is differentiable in y becomes much more problematic. At some point, competition among heterogeneous wholesalers can induce competitors to leave the market. Generally, such a market exit induces discontinuities in the stocking levels of the remaining competitors. Therefore, the differentiability assumption provides a less reliable approximation. Nevertheless, we expect that such an approximation will still yield structurally valid results, even under downstream competition.

To deepen our understanding of the repercussions that substitution exerts on the individual supply chain members, more fundamental extensions should also be examined. In particular, we believe that future models should incorporate pricing decisions, but this might come at the expense of analytical tractability. Another aspect that deserves future research is the introduction of multiple time periods. In such a setting, initial product demand changes dynamically over time because a substituting customer may change his product preferences due to product unavailability.

Appendix A

Proofs of Chapter II

Proof of Lemma 2.1. The firm's optimal resource allocation for each realization of e and m maximizes the expected market value of both products, $\mathbb{E}_\theta[\nu_i + \nu_j|m,e]$, where the expectation is taken over the products' market potential. The proof now proceeds by comparing the expected market value, $\mathbb{E}_\theta[\nu_i + \nu_j|m,e] = Pr(\theta_i = G|m_i, e_i)\nu_i(\theta_i = G) + Pr(\theta_j = G|m_j, e_j)\nu_j(\theta_i = G)$, of different resource allocation schemes for all e and m, given that managers truthfully reveal their signals, $m = s$.

Suppose that both managers evaluate their products with only low effort, $e = (l,l)$. Then, the firm's posterior belief about the products' market potential is identical to its prior belief for all possible recommendations m, i.e., $Pr(\theta_i = G|m_i, e_i = l) = 1/2$. If the firm now invests all its resources in a single product, then the product's expected market value is $v_2/2$. If, in contrast, the firm splits resources evenly, then each product's expected market value is $v_1/2$, yielding a total expected market value of v_1. Since by assumption $v_2 < 2v_1$, the firm's optimal resource allocation for $e = (l,l)$ and any m is to split resources evenly.

Now, consider the case where both managers exert a high-effort product evaluation, $e = (h,h)$. In this setting, the firm revises its prior beliefs according to the received recommendations. In particular, if the firm receives a good recommendation for product i, then its posterior belief about product i having a good market potential is q, while a bad signal implies a posterior belief of $1-q$. Assume that the firm receives identical recommendations for both products, $m_i = m_j$, which implies that posterior beliefs for both products are also identical. Hence, the firm maximizes the expected market value of both products by simply optimizing $\nu_i(\theta_i = G) + \nu_j(\theta_j = G)$, which is largest if the firm splits resources evenly. Now, assume to the contrary that recommendations are different, e.g., $m = (g,b)$. Allocating all resources to product i gives an expected market value of qv_2, while after an even split of resources both products have a total expected market value of $qv_1 + (1-q)v_1 = v_1$. It follows that the firm optimally allocates all resources to product i if $q > v_1/v_2$, and splits resources evenly otherwise.

Lastly, we analyze the asymmetric evaluation effort strategy, $e = (h, l)$. As the recommendation for product j is uninformative, the firm allocates resources only based on the recommendation for product i. If the firm receives a good recommendation for product i, then allocating all resources to this product has an expected market value of qv_2. Splitting resources evenly, however, results in a total expected market value of $qv_1 + v_1/2$. Thus, it is optimal for the firm to split resources evenly only if $q < q_a$, and allocate all resources to product i otherwise. Now, suppose the recommendation for product i is bad. Then, it is never optimal to allocate both resources to product i. An even split of resources yields an expected market value of $(1-q)v_1 + v_1/2$, whereas the expected market value is $v_2/2$ if all resources are allocated to product j. Hence, the firm optimally splits resources evenly only if $q < q_b$ and allocates all resources to product j otherwise. $\square$

Proof of Proposition 2.1. We prove this proposition in three steps: First, we derive the integrated firm's expected profit for any possible product evaluation strategy, which is a necessary requirement for our subsequent discussion. Second, we establish that the integrated firm never chooses an asymmetric evaluation strategy if $q < q_a$, which helps us to simplify the exposition. Lastly, we discuss the threshold functions ζ_1, ζ_2, and ζ_3 to conclude the proof.

Profit derivation: As a preliminary, note that the integrated firm's optimal resource allocation is identical to the decentralized firm's allocation strategy, and thus given by Lemma 2.1. This is true because if managers truthfully reveal their private signals, $m = s$, then the decentralized firm can perfectly infer the received signals. Accordingly, the integrated and decentralized firm are endowed with the same information upon making their resource allocation decisions, and therefore, these decisions must be equivalent.

If the firm exerts only low evaluation efforts for both products, then it eventually splits its resources evenly across the two products. Therefore, product i's ex-ante expected market value is

$$\mathbb{E}_\theta[\nu_i|e = (l, l)] = Pr(\theta_i = G|s_i = g)Pr(s_i = g)v_1 + Pr(\theta_i = G|s_i = b)Pr(s_i = b)v_1 = \frac{v_1}{2}.$$

Due to the symmetry of products and since no evaluation costs are incurred, the firm's ex-ante expected profit becomes

$$\Pi^{fb}(e = (l,l)) = v_1. \tag{A.1}$$

In contrast, if the firm decides to exert high-effort evaluation for both products, then it incurs evaluation costs for both of them. However, the firm now uses the additional information to revise its initial beliefs about the true market potential of the two products. If $q \leq v_1/v_2$, then the firm always splits resources evenly, and following (A.1), expected profits are $v_1 - 2c$, which can never be optimal. In contrast, if $q > v_1/v_2$, the firm may either split resources evenly if products are equally promising, or it may fund only one of the products. The ex-ante expected market value of product i is then

$$\mathbb{E}_\theta[\nu_i | e = (h,h)] = \frac{1}{4}qv_1 + \frac{1}{4}(1-q)v_1 + \frac{1}{4}qv_2 = \frac{1}{4}(qv_2 + v_1),$$

and consequently,

$$\Pi^{fb}(e = (h,h)) = \frac{1}{2}(qv_2 + v_1) - 2c. \tag{A.2}$$

Lastly, the firm also has the option to pursue an asymmetric product evaluation strategy by exerting high effort for only one product. Again, the derivation of the firm's ex-ante expected profit is similar to the above cases, and we need to consider that the optimal resource allocation changes with q (see Lemma 2.1). Thus, the firm's ex-ante expected profit is a piecewise function of q:

$$\Pi^{fb}(e = (h,l)) = \begin{cases} v_1 - c & \text{if } q < q_b \\ \frac{1}{4}(v_2 + (2q+1)v_1) - c & \text{if } q_b \leq q < q_a \\ \frac{1}{4}(2q+1)v_2 - c & \text{if } q \geq q_a. \end{cases} \tag{A.3}$$

Asymmetric evaluation: We now show that, in optimum, the firm never chooses an asymmetric product evaluation strategy if $q < q_a$. First, for $q < q_b$, $\Pi^{fb}(e = (h,l)) = v_1 - c < v_1 = \Pi^{fb}(e = (l,l))$ because $c > 0$ by assumption. Thus, if $q < q_b$, the firm always prefers low-effort product evaluation over an asymmetric product evaluation strategy. Second, high-effort product evaluation for only one product is also a dominated strategy if $q_b \leq q < q_a$, i.e., $\Pi^{fb}(e = (h,l)) > \max\{\Pi^{fb}(e = (l,l)), \Pi^{fb}(e = (h,h))\}$ is a contradiction. In fact, $\Pi^{fb}(e = (h,l)) > \Pi^{fb}(e = (h,h))$ if and only if $c > (2q-1)(v_2 - v_1)/4 \equiv \underline{c}$; and $\Pi^{fb}(e = (h,l)) > \Pi^{fb}(e = (l,l))$ if and only if $c < [(2q-3)v_1 + v_2]/4 \equiv \overline{c}$. However, $\overline{c} < \underline{c}$, which yields the desired contradiction.

Optimal product evaluation: The threshold functions ζ_1, ζ_2, and ζ_3 are derived by pairwise comparing (A.1) with (A.2), (A.2) with (A.3), and (A.1) with (A.3), respectively. Accordingly, the firm exerts high-effort product evaluation for both products if $c \leq \min\{\zeta_1, \zeta_2\}$, high effort for only one product if $\zeta_2 < c \leq \zeta_3$, and low effort for both products if $c > \max\{\zeta_1, \zeta_3\}$. Additionally, we note that $q_c \geq q_a$ if and only if $q_c \leq 1$.

(i) If $q < q_c$, then $\zeta_3 < \zeta_1 < \zeta_2$. It follows that the firm chooses $e^*_{fb} = (h,h)$ for $c \leq \zeta_1$, and $e^*_{fb} = (l,l)$ otherwise.

(ii) If $q \geq q_c$, then $\zeta_2 < \zeta_1 < \zeta_3$. Now, the firm chooses $e^*_{fb} = (h,h)$ for $c \leq \zeta_2$, $e^*_{fb} = (h,l)$ for $\zeta_2 < c \leq \zeta_3$, and $e^*_{fb} = (l,l)$ otherwise. □

Proof of Lemma 2.2. The proof proceeds in two steps. First, we revisit the decentralized firm's optimal resource allocation. Second, we show that a compensation scheme that induces asymmetric effort levels is never incentive compatible in effort.

Resource allocation: If both managers are truth-telling, but pursue different evaluation effort levels under decentralization, then the firm is not able to observe the managers' product evaluation strategy. In fact, the firm does not know whether $e = (h,l)$ or $e = (l,h)$. This ambiguity has to be taken into account when allocating resources to products (Lemma 2.1 is not straightforward applicable because now, e is not known).

Suppose both managers send the same recommendation, $m_i = m_j$. If recommendations are good, then both products have a total expected market value of $qv_1 + v_1/2$, if the firm splits resources evenly, while the expected market value of a product that receives all resources is $(qv_2 + v_2/2)/2$. Similarly, if both recommendations are bad, then an even split of resources yields an expected market value of $(1-q)v_1 + v_1/2$, while the expected market value of a product that received all resources is $((1-q)v_2 + v_2/2)/2$. Thus, it is optimal to split resources evenly across products if recommendations are identical, because $v_2 < 2v_1$ by assumption.

Now, assume managers give different recommendations, e.g., $m = (g,b)$. Dedicating all resources to the well recommended product i gives an expected market value of $(qv_2 + v_2/2)/2$, whereas splitting resources evenly generates an expected market value of v_1. Therefore, the firm invests all resources in product i if $q \geq (4v_1 - v_2)/2v_2$ and splits resources evenly otherwise.

Incentive compatibility: By using the firm's optimal resource allocation, we can now conclude this proof by showing that any truth-inducing contract with $e_i \neq e_j$ is never incentive compatible in effort. This implies that one manager always wants to deviate from his current effort level, such that $e_i \neq e_j$ cannot be part of any equilibrium.

If $q < (4v_1 - v_2)/2v_2$, then the firm always allocates resources equally to both products. Hence, exerting high-effort product evaluation is costly for a manager, but does not affect the firm's allocation decision. Therefore, each manager's expected utility is always largest under low-effort product evaluation.

If $q \geq (4v_1 - v_2)/2v_2$, then the firm allocates all resources to a single product if recommendations are unequal, and splits resources evenly elsewise. Without loss of generality, assume that manager i and j exert high and low effort, respectively, and suppose that a truth-inducing contract exists in this setting. Then, this contract must be incentive compatible in effort, i.e.,

$$U_i(e_i = h | e_j = l, m = s) \geq U_i(e_i = l | e_j = l, m = s)$$
$$U_j(e_j = h | e_i = h, m = s) < U_j(e_j = l | e_i = h, m = s).$$

Manager i's effort incentive compatibility condition is satisfied if $2k_s q v_2 - 8c \geq k_s v_2$, while manager j's constraint is true if $2k_s q v_2 - 8c < k_s v_2$. Obviously, both constraints contradict each other, and thus, there exists no contract that induces asymmetric effort levels in equilibrium. □

Proof of Proposition 2.2. This proof consists of three steps. In a first step, for clarity, we derive the decentralized firm's optimization problem (2.1) - (LL). Step two determines the optimal wage contract that induces high-effort product evaluation and truth-telling by both managers. Finally, the third step provides the sensitivity analysis which completes the proof.

Optimization problem: The expected profit of the decentralized firm (2.1) is similar to the integrated firm's expected profit (A.2). However, under decentralization the firm does not directly incur the effort costs c, but it has to incentivize its managers to exert high effort by paying a bonus scheme $k = (k_s, k_p)$. Thus, the firm maximizes its expected profits, which comprise of the products' expected market value net the managers' compensation, i.e.,

$$\begin{aligned}\Pi(k) &= (1 - k_s - k_p)\mathbb{E}_\theta[\nu_i + \nu_j|k] \\ &= (1 - k_s - k_p)\frac{1}{2}(qv_2 + v_1).\end{aligned}$$

We now turn to the truth-telling constraints (IC-g) and (IC-b). Manager i truthfully reveals a good signal if and only if

$$U_i(m_i = g|s_i = g, e_i = e_j = h, m_j = s_j) \geq U_i(m_i = b|s_i = g, e_i = e_j = h, m_j = s_j),$$

where the manager assumes that the firm will optimally allocate resources according to the managers' recommendations. Similarly, truthful revelation of a bad evaluation outcome is guaranteed if and only if

$$U_i(m_i = b|s_i = b, e_i = e_j = h, m_j = s_j) \geq U_i(m_i = g|s_i = b, e_i = e_j = h, m_j = s_j).$$

The required utilities are derived as follows:

$$\begin{aligned}U_i(m_i = g|s_i = g, e_i = e_j = h, m_j = s_j) &= \mathbb{P}(s_j = g)\left(k_s\mathbb{E}_{\theta_i}[\nu_i|k, m, e] + k_p\mathbb{E}_{\theta_j}[\nu_j|k, m, e]\right) \\ &\quad + \mathbb{P}(s_j = b)k_s\mathbb{E}_{\theta_i}[\nu_i|k, m, e] \\ &= \frac{1}{2}\left(k_sqv_1 + k_pqv_1\right) + \frac{1}{2}\left(k_sqv_2\right).\end{aligned}$$

By a structurally identical argument, we can develop the three remaining utility functions:

$$\begin{aligned}U_i(m_i = b|s_i = g, e_i = e_j = h, m_j = s_j) &= \frac{1}{2}\left(k_pqv_2\right) + \frac{1}{2}\left(k_sqv_1 + k_p(1-q)v_1\right), \\ U_i(m_i = g|s_i = b, e_i = e_j = h, m_j = s_j) &= \frac{1}{2}\left(k_s(1-q)v_1 + k_pqv_1\right) + \frac{1}{2}\left(k_s(1-q)v_2\right), \\ U_i(m_i = b|s_i = b, e_i = e_j = h, m_j = s_j) &= \frac{1}{2}\left(k_pqv_2\right) + \frac{1}{2}\left(k_s(1-q)v_1 + k_p(1-q)v_1\right).\end{aligned}$$

Canceling out identical terms gives the desired truth-telling conditions (IC-g) and (IC-b). In a next step, we analyze the firm's effort incentive condition (IC-e). Manager i

exerts high-effort product evaluation if and only if

$$U_i(e_i = h|e_j = h, m = s) \geq U_i(e_i = l|e_j = h, m = s),$$

where the manager assumes that the firm will optimally allocate resources according to the managers' recommendations, and that recommendations are truthful. These utilities are given by

$$\begin{aligned}
U_i(e_i = h|e_j = h, m = s) &= \mathbb{P}(s_i = g, s_j = g)\left(k_s\mathbb{E}_{\theta_i}[\nu_i|k, m, e] + k_p\mathbb{E}_{\theta_j}[\nu_j|k, m, e]\right)\\
&\quad + \mathbb{P}(s_i = g, s_j = b)k_s\mathbb{E}_{\theta_i}[\nu_i|k, m, e]\\
&\quad + \mathbb{P}(s_i = b, s_j = g)k_p\mathbb{E}_{\theta_j}[\nu_j|k, m, e]\\
&\quad + \mathbb{P}(s_i = b, s_j = b)\left(k_s\mathbb{E}_{\theta_i}[\nu_i|k, m, e] + k_p\mathbb{E}_{\theta_j}[\nu_j|k, m, e]\right) - c\\
&= \frac{1}{4}\left(k_s q v_1 + k_p q v_1\right) + \frac{1}{4}k_s q v_2 + \frac{1}{4}k_p q v_2\\
&\quad + \frac{1}{4}\left(k_s(1-q)v_1 + k_p(1-q)v_1\right) - c,\\
U_i(e_i = l|e_j = h, m = s) &= \frac{1}{4}\left(k_s\frac{1}{2}v_1 + k_p q v_1\right) + \frac{1}{4}k_s\frac{1}{2}v_2 + \frac{1}{4}k_p q v_2\\
&\quad + \frac{1}{4}\left(k_s\frac{1}{2}v_1 + k_p(1-q)v_1\right).
\end{aligned}$$

Collecting terms yields the firm's effort incentive constraint (IC-e). Lastly, the firm needs to ensure that $k_s, k_p \geq 0$, since managers are protected by limited liability. If bonuses were negative, then there would exist situations that result in negative wages, which is strictly forbidden by assumption.

Optimal wages: Maximizing the firm's expected profit (2.1) is equivalent to minimizing $k_s + k_p$. Now, for the contract to be incentive compatible in effort, (IC-e) requires that $k_s \geq \frac{8c}{(2q-1)v_2}$. Additionally, the contract is truth-inducing if and only if k_s and k_p simultaneously satisfy (IC-g) and (IC-b). Rewriting these constraints gives

$$\frac{(1-q)v_2}{q(v_2 - v_1) + (1-q)v_1} \cdot k_s \leq k_p \leq \frac{q v_2}{q(v_2 - v_1) + (1-q)v_1} \cdot k_s. \tag{A.4}$$

Thus, to minimize $k_s + k_p$, we choose k_s as small as possible and then determine k_p by transforming the left inequality in (A.4) into an equality. Therefore, the firm's optimal contract is

$$k_s^\star = \frac{8c}{(2q-1)v_2}, \quad k_p^\star = \frac{8(1-q)c}{(2q-1)(q(v_2-v_1)+(1-q)v_1)},$$

which also satisfies the limited liability constraint (LL).

Sensitivity: By (A.4), $k_p^\star = \frac{(1-q)v_2}{q(v_2-v_1)+(1-q)v_1} \cdot k_s^\star$. Now, to show that $k_s^\star > k_p^\star$, it is sufficient to verify that $\frac{(1-q)v_2}{q(v_2-v_1)+(1-q)v_1} < 1$. Rearranging this inequality and solving for q assures that the condition holds for any $q > 1/2$. Thus, $k_s^\star > k_p^\star$.

To show that $k_p^\star/k_s^\star$ is concave decreasing in q, convex decreasing in v_2, and constant in c, we explicitly investigate the first- and second-order partial derivatives of

$$\frac{k_p^\star}{k_s^\star} = \frac{(1-q)v_2}{q(v_2-v_1)+(1-q)v_1}$$

with respect to q, v_2, and c, respectively. It is easy to see that $k_p^\star/k_s^\star$ is independent of c. In addition, straightforward differentiation yields

$$\frac{\partial}{\partial q}\frac{k_p^\star}{k_s^\star} = -\frac{v_2(v_2-v_1)}{(q(v_2-v_1)+(1-q)v_1)^2} < 0, \quad \frac{\partial^2}{\partial q^2}\frac{k_p^\star}{k_s^\star} = -\frac{2v_2(2v_1-v_2)(v_2-v_1)}{(q(v_2-v_1)+(1-q)v_1)^3} < 0,$$

and

$$\frac{\partial}{\partial v_2}\frac{k_p^\star}{k_s^\star} = -\frac{(1-q)(2q-1)v_1}{(q(v_2-v_1)+(1-q)v_1)^2} < 0, \quad \frac{\partial^2}{\partial v_2^2}\frac{k_p^\star}{k_s^\star} = \frac{2q(2q-1)(1-q)v_1}{(q(v_2-v_1)+(1-q)v_1)^3} > 0,$$

which proves the claim. □

Proof of Proposition 2.3. The manager: The contract scheme $k^\star$ incentivizes each manager to exert high-effort product evaluation. Thus, each manager's expected utility is given by $U_i(k^\star) = \mathbb{E}[w_i(k^\star)] - c$. Since, ex-ante, both products have the same expected market value, $\mathbb{E}_\theta(\nu_i|k^\star) = (qv_2+v_1)/4$, manager i's expected wage is

$$\mathbb{E}[w_i(k^\star)] = (k_s^\star + k_p^\star)\mathbb{E}_\theta(\nu_i|k^\star) = c\phi_1\phi_2,$$

where $\phi_1 = \frac{2qv_2+2v_1}{(2q-1)v_2} > 1$ and $\phi_2 = \frac{v_2-(2q-1)v_1}{qv_2-(2q-1)v_1} \geq 1$. Therefore,

$$\frac{\partial}{\partial c}U_i(k^\star) = \phi_1\phi_2 - 1 > 0,$$

which implies that $U_i(k^\star)$ is linear increasing in c.

Note that $U_i(k^\star)$ is decreasing in q and v_2, respectively, if and only if the manager's expected wage is decreasing in q and v_2. Now, by standard differentiation rules,

$$\frac{\partial}{\partial q}\mathbb{E}[w_i(k^\star)] = c\left(\frac{\partial \phi_1}{\partial q}\phi_2 + \phi_1\frac{\partial \phi_2}{\partial q}\right) \quad \text{and} \quad \frac{\partial}{\partial v_2}\mathbb{E}[w_i(k^\star)] = c\left(\frac{\partial \phi_1}{\partial v_2}\phi_2 + \phi_1\frac{\partial \phi_2}{\partial v_2}\right).$$

Thus, a sufficient condition for decreasing expected wages is that both, ϕ_1 and ϕ_2 decrease in q and v_2, respectively. Evaluating first-order derivatives concludes this proof:

$$\begin{aligned} \frac{\partial}{\partial q}\phi_1 &= -\frac{2v_2+4v_1}{(2q-1)^2 v_2} < 0, & \frac{\partial}{\partial q}\phi_2 &= -\frac{v_2(v_2-v_1)}{(qv_2-(2q-1)v_1)^2} < 0, \\ \frac{\partial}{\partial v_2}\phi_1 &= -\frac{2v_1}{(2q-1)v_2^2} < 0, & \frac{\partial}{\partial v_2}\phi_2 &= -\frac{(1-q)(2q-1)v_1}{(qv_2-(2q-1)v_1)^2} < 0. \end{aligned}$$

The firm: The firm's expected profit is given by (2.1) and can be rewritten as

$$\Pi(k^\star) = 2\cdot(1-k_s^\star-k_p^\star)\mathbb{E}_\theta(\nu_i|k^\star).$$

A simple algebraic argument shows that both, $k_s^\star$ and $k_p^\star$ are decreasing in q and v_2, and increasing in c, whereas $\mathbb{E}_\theta(\nu_i|k^\star)$ is increasing in q and v_2, and constant in c. Thus, it follows immediately that $\Pi(k^\star)$ is increasing in q and v_2, and decreasing in c. □

Proof of Proposition 2.4. Substituting $k_s^\star$ and $k_p^\star$ into (2.1) and comparing expected profits with $\Pi(k=(0,0)) = v_1$ immediately gives ζ_4. Using previous notation, we can rewrite $\zeta_4 = \zeta_1(\phi_1\phi_2)^{-1}$, and we know that $\phi_1\phi_2 > 1$. Thus, $\zeta_4 < \zeta_1$. Next, by example, we prove the claim that there exist parameter values such that $\zeta_4 > \zeta_2$. Assume $q=1$ and $v_2 = 1.8v_1$. Then, $\zeta_4 = \frac{9}{140}v_1 > \frac{1}{20}v_1 = \zeta_2$, which establishes the result.

Moreover, ζ_4 is convex increasing in q. To see why note that first- and second-order partial derivatives of ζ_1, ϕ_1^{-1}, and ϕ_2^{-1}, respectively, are given by:

$$\frac{\partial \zeta_1}{\partial q} = \frac{v_2}{4} > 0, \quad \frac{\partial \phi_1^{-1}}{\partial q} = \frac{v_2(2v_1+v_2)}{2(qv_2+v_1)^2} > 0, \quad \frac{\partial \phi_2^{-1}}{\partial q} = \frac{v_2(v_2-v_1)}{(v_2-(2q-1)v_1)^2} > 0,$$

and

$$\frac{\partial^2 \zeta_1}{\partial q^2} = 0, \quad \frac{\partial^2 \phi_1^{-1}}{\partial q^2} = -\frac{v_2^2(2v_1+v_2)}{(qv_2+v_1)^3} < 0, \quad \frac{\partial^2 \phi_2^{-1}}{\partial q^2} = \frac{4v_1v_2(v_2-v_1)}{(v_2-(2q-1)v_1)^3} > 0.$$

Since all first-order partial derivatives are strictly positive, we conclude that ζ_4 is strictly increasing in q. Convexity is now established through evaluation of the second-order partial derivative of ζ_4:

$$\frac{\partial^2 \zeta_4}{\partial q^2} = 2\frac{\partial \zeta_1}{\partial q}\left[\frac{\partial \phi_1^{-1}}{\partial q}\phi_2^{-1} + \phi_1^{-1}\frac{\partial \phi_2^{-1}}{\partial q}\right] + \zeta_1 \phi_1^{-1}\frac{\partial^2 \phi_2^{-1}}{\partial q^2} + \zeta_1\left[2\frac{\partial \phi_1^{-1}}{\partial q}\frac{\partial \phi_2^{-1}}{\partial q} + \frac{\partial^2 \phi_1^{-1}}{\partial q^2}\phi_2^{-1}\right].$$

The first two terms are strictly positive, so it remains to verify that the third term is also positive. Setting the third term equal to zero shows that it is positive if

$$q > \frac{v_1 - \sqrt{v_1(v_2 - v_1)}}{2v_1 - v_2}.$$

Furthermore, $\zeta_4 \geq 0$ if and only if $q \geq \frac{v_1}{v_2}$, and we find that

$$\frac{v_1}{v_2} > \frac{v_1 - \sqrt{v_1(v_2 - v_1)}}{2v_1 - v_2}.$$

Thus, ζ_4 is convex increasing in q. □

Proof of Proposition 2.5. To prove the claim, we first note that the firm's expected product development scope depends on the chosen product evaluation strategy as follows: (i) If $e = (l, l)$, then $n = n^{fb} = 2$; (ii) if $e = (h, l)$, then $n = 1$; and (iii) if $e = (h, h)$, then $n = n^{fb} = 1.5$. Combining this observation with Propositions 2.1 and 2.4 concludes the proof. For $q < q_c$,

$$n - n^{fb} = \begin{cases} 0 & \text{if } c < \zeta_4 \\ 0.5 & \text{if } \zeta_4 \leq c \leq \zeta_1 \\ 0 & \text{if } \zeta_1 < c, \end{cases}$$

and for $q \geq q_c$,

$$n - n^{fb} = \begin{cases} 0 & \text{if } c < \min\{\zeta_2, \zeta_4\} \\ 0.5 & \text{if } \min\{\zeta_2, \zeta_4\} \leq c < \max\{\zeta_2, \zeta_4\} \\ 1 & \text{if } \max\{\zeta_2, \zeta_4\} \leq c \leq \zeta_3 \\ 0 & \text{if } \zeta_3 < c. \end{cases}$$

□

Proof of Proposition 2.6. We prove this proposition by investigating the firm's percentage profit loss, η_p, for all five regions indicated in Figure 2.4.

(i) $e^{fb} = e^\star = (h,h)$: If both products are evaluated with high effort under integration as well as decentralization, then

$$\eta_p = 1 - \frac{\Pi(e^\star)}{\Pi(e^\star) + U_i(e^\star) + U_j(e^\star)} \cdot \frac{\Pi(e^\star) + U_i(e^\star) + U_j(e^\star)}{\Pi^{fb}(e^{fb})} > 0. \tag{A.5}$$

It can be readily verified that the second fraction in (A.5) is equal to one, and by applying Proposition 2.3, the first fraction increases in q and v_2, and decreases in c. It follows immediately that η_p decreases in q and v_2, and increases in c.

(ii) $e^{fb} = e^\star = (l,l)$: Since neither evaluation costs nor wages are paid in this scenario, the firm's percentage profit loss is zero, i.e., $\eta_p = 1 - \frac{v_1}{v_1} = 0$.

(iii) $e^{fb} = (h,h)$, $e^\star = (l,l)$: In this case,

$$\eta_p = 1 - \frac{v_1}{\frac{1}{2}(qv_2 + v_1) - 2c} > 0,$$

which obviously increases in q and v_2, and decreases in c.

(iv) $e^{fb} = (h,l)$, $e^\star = (l,l)$: In this case,

$$\eta_p = 1 - \frac{v_1}{\frac{1}{4}(2q+1)v_2 - c} > 0,$$

which obviously increases in q and v_2, and decreases in c.

(v) $e^{fb} = (h,l)$, $e^\star = (h,h)$: If the decentralized firm over-invests in product evaluation, then we can express the firm's percentage profit loss as

$$\eta_p = 1 - \frac{\Pi(e^\star)}{\Pi(e^\star) + U_i(e^\star) + U_j(e^\star)} \cdot \frac{\Pi(e^\star) + U_i(e^\star) + U_j(e^\star)}{\Pi^{fb}(e^{fb})} > 0.$$

As already argued in case (i), the first fraction increases in q and v_2, and decreases in c. Now, by noting that over-investment can only occur if $c > \zeta_2$, we can readily verify that the same results also hold for the second fraction. Thus, η_p decreases in q and v_2, and increases in c.

To conclude the proof, it is sufficient to note that the decentralized firm under-invests in product evaluation in cases (iii) and (iv), while an over-investment occurs solely in case (v). □

Proof of Proposition 2.7. Recall from the previous proof that if the integrated and decentralized firm choose the same product evaluation strategy, i.e., $e^{fb} = e^\star$, then $\Pi(e^\star) + U_i(e^\star) + U_j(e^\star) = \Pi^{fb}(e^{fb})$. Now, applying Propositions 2.1 and 2.4 immediately shows that the percentage welfare loss, η_w, is zero if and only if the decentralized and integrated firm choose the same product evaluation strategy.

If the decentralized firm over-invests in product evaluation, $e^\star = (h, h)$, compared to the integrated firm, $e^{fb} = (h, l)$, then, by the argument in case (v) of the Proof of Proposition 2.6, the percentage welfare loss,

$$\eta_w = 1 - \frac{\Pi(e^\star) + U_i(e^\star) + U_j(e^\star)}{\Pi^{fb}(e^{fb})} > 0,$$

decreases in q and v_2, and increases in c.

If the decentralized firm under-invests in product evaluation, $e^\star = (l, l)$, compared to the integrated firm, $e^{fb} = (h, h)$ or $e^{fb} = (h, l)$, then the percentage welfare loss,

$$\eta_w = 1 - \frac{v_1}{\frac{1}{2}(qv_2 + v_1) - 2c} > 0 \quad \text{or} \quad \eta_w = 1 - \frac{v_1}{\frac{1}{4}(2q + 1)v_2 - c} > 0,$$

increases in q and v_2, and decreases in c. □

Appendix B

Proofs of Chapter III

Proof of Lemma 3.1. It can readily be verified that the first, second, and last term in (3.1) are concave in x for given t. Therefore, to establish the Lemma, it remains to show that the third term is also concave in x. Since this term is integrable and has a bounded derivative, we can interchange the expectation and derivative operators, and the result follows from twice applying Leibniz's formula; i.e.,

$$\begin{aligned}
\frac{\partial \Pi(x,t)}{\partial x} &= \mathbb{E}\left[(p-c) - w(B-t)^{+} - h\int_{\max\{t,B\}}^{B+L} 1_{\{Q_t - Q_\tau \le x\}} d\tau - (p-s)1_{\{Q_t \le x\}}\right] \\
&= (p-c) - w\int_t^{b_u} \mathbb{P}(B \ge b)db - (p-s)\mathbb{P}(Q_t \le x) \\
&\quad - h\int_0^{b_u+l_u} \mathbb{P}(Q_t - Q_\tau \le x, \max\{t,B\} \le \tau \le B+L)d\tau;
\end{aligned}$$

$$\begin{aligned}
\frac{\partial^2 \Pi(x,t)}{\partial x^2} &= -(p-s)f_{Q_t}(x) \\
&\quad - h\int_0^{b_u+l_u} f_{Q_t - Q_\tau \mid \max\{t,B\} \le \tau \le B+L}(x) \cdot \mathbb{P}(\max\{t,B\} \le \tau \le B+L)d\tau \\
&< 0,
\end{aligned}$$

where f_Z is the density function of the random variable Z. The strict inequality follows from $p > s$, and the assumption that density functions are strictly positive. $\square$

Proof of Lemma 3.2. For $t \ge b$, the first-order partial derivatives of $\Pi_L(x,t)$ with respect to x and t are given by:

$$\begin{aligned}\frac{\partial \Pi_L(x,t)}{\partial x} &= \mathbb{E}\left[(p-c) - h\int_t^{b+L} 1_{\{Q_t - Q_\tau \le x\}} d\tau - (p-s)1_{\{Q_t \le x\}}\right] \\ &= (p-c) - h\int_t^{b+l_u} \mathbb{P}(Q_t - Q_\tau \le x, L > \tau - b) d\tau - (p-s)\mathbb{P}(Q_t \le x);\end{aligned} \tag{B.1}$$

$$\begin{aligned}\frac{\partial \Pi_L(x,t)}{\partial t} &= \mathbb{E}\left[-h\left(\int_t^{b+L} -Q_t' 1_{\{Q_t - Q_\tau \le x\}} d\tau - x1_{\{L > t-b\}}\right) - (p-s)\left(-Q_t' 1_{\{Q_t \le x\}}\right)\right] \\ &= h\left[x\mathbb{P}(L > t-b) - \int_t^{b+l_u} d_t(Q_t - Q_\tau \le x, L > \tau - b) d\tau\right] - (p-s)d_t(Q_t \le x).\end{aligned} \tag{B.2}$$

Equating both derivatives to zero and rearranging terms concludes the proof. □

Proof of Proposition 3.1. (a) Suppose $h = 0$. In this case, by (B.2), we have $\frac{\partial \Pi_L(x,t)}{\partial t} = -(p-s)d_t(Q_t \le x) \le 0$ for all x and t. Since expected profits decrease in the firm's inventory timing, the firm introduces the product immediately at the start of the selling season, $t^\star = b$. By definition of Q_τ, $t^\star = b$ implies that $Q_{t^\star} = Q$. Inserting the optimal inventory timing $t^\star$ in (B.1) and equating to zero determines the firm's optimal inventory scale, $x^\star$, through $\mathbb{P}(Q \le x^\star) = \frac{p-c}{p-s}$. In addition, since $p > c$, it is easy to verify that $\Pi_L(x^\star, t^\star) > 0$. Thus, market exit is always a suboptimal strategy.

(b) Suppose $h > 0$. In a first step, we show that instant product availability is never the firm's optimal inventory strategy. Assume to the contrary that $t^\star = b$ is optimal for some $x > 0$. Then, necessarily, $\left.\frac{\partial \Pi_L(x,t)}{\partial t}\right|_{t=b} \le 0$. However, since $A(\tau)$ is continuously differentiable, we know that $A'(b) = 0$. Thus, by the definition of $d_t(\cdot)$, we have $d_b(\cdot) = 0$ and it follows that $\left.\frac{\partial \Pi_L(x,t)}{\partial t}\right|_{t=b} = hx > 0$ for all $x > 0$, which yields the desired contradiction. Finally, we establish that for $x = 0$, instant product availability is never better than a market exit. This is obvious because with $x = 0$ the firm cannot generate positive profits which makes market exit the (weakly) preferred strategy.

Now, since instant product availability is never the firm's optimal inventory strategy, the firm either chooses a risk exploitation inventory strategy or market exit. Comparing the firm's expected profits under both inventory strategies determines the optimal strategy. Note that market exit leads to zero profits. Thus, the firm prefers the risk exploitation strategy defined in Lemma 3.2 if and only if $\Pi_L(x^\star, t^\star) \ge 0$. To establish the existence of the threshold function $\overline{h}(c)$, we make use of the Implicit Function Theorem. Specifically, the Implicit Function Theorem asserts the following for a continuously differentiable function Π_L with coordinates (c, h), and a point (c', h') with $\Pi_L(c', h') = 0$: If $\frac{\partial \Pi_L(c',h')}{\partial h}$ is invertible, then there exists an open set U containing c', an open set V containing h', and a unique continuously differentiable function $\overline{h} : U \to V$, such that $\{(c, \overline{h}(c)) | c \in U\} = \{(c, h) \in U \times V | \Pi_L(c, h) = 0\}$. Since Π_L is continuously differentiable, and $\frac{\partial \Pi_L(x^\star(c,h), t^\star(c,h), c, h)}{\partial h} < 0$, we can conclude that there exists a unique continuously differentiable function $\overline{h}(c)$ such that the optimal inventory strategy is risk exploitation if $h \leq \overline{h}(c)$, and market exit otherwise. Moreover, $\overline{h}(c)$ decreases in c:

$$\frac{\partial \overline{h}(c)}{\partial c} = -\frac{\frac{\partial \Pi_L(x^\star, t^\star)}{\partial c}}{\frac{\partial \Pi_L(x^\star, t^\star)}{\partial h}} = -\frac{x^\star}{\int_{t^\star}^{b+L} I_{t^\star}(\tau) d\tau} < 0.$$

□

Proof of Lemma 3.3. First-order partial derivatives of $\Pi_B(x, t)$ with respect to x and t are as follows:

$$\begin{aligned}\frac{\partial \Pi_B(x,t)}{\partial x} &= \mathbb{E}\left[(p-c) - w(B-t)^+ - (p-s)1_{\{Q_t \leq x\}}\right] \\ &= (p-c) - w\int_t^{b_u} \mathbb{P}(B \geq b) db - (p-s)\mathbb{P}(Q_t \leq x); \end{aligned} \tag{B.3}$$

$$\begin{aligned}\frac{\partial \Pi_B(x,t)}{\partial t} &= \mathbb{E}\left[(o + wx)1_{\{B \geq t\}} - (p-s)\left(-Q_t' 1_{\{Q_t \leq x\}}\right)\right] \\ &= (o + wx)\mathbb{P}(B \geq t) - (p-s) d_t(Q_t \leq x). \end{aligned} \tag{B.4}$$

Equating to zero and rearranging terms concludes the proof. □

Proof of Proposition 3.2. (a) Suppose $o = w = 0$. By (B.4), we have $\frac{\partial \Pi_B(x,t)}{\partial t} = -(p - s) d_t(Q_t \leq x) \leq 0$ for all x and t. Now, we can conclude the proof with a structurally identical argument to the proof of Proposition 3.1(a), which we omit for conciseness.

(b) Suppose $o + w > 0$. In a first step, we show that instant product availability is never the firm's optimal inventory strategy. Assume to the contrary that $t^\star = 0$ is optimal for some $x > 0$. Then, necessarily, $\left.\frac{\partial \Pi_B(x,t)}{\partial t}\right|_{t=0} \leq 0$. However, from the definition of $A(\tau)$ it follows readily that $A'(0) = 0$ almost surely, implying that $d_0(\cdot) = 0$ almost surely. Thus, $\left.\frac{\partial \Pi_B(x,t)}{\partial t}\right|_{t=0} = o + wx > 0$ for all $x > 0$, which yields the desired contradiction. Finally, we establish that for $x = 0$, instant product availability is never better than a market exit. This is obvious because with $x = 0$ the firm generates negative profits which makes market exit the preferred strategy.

Now, since instant product availability is never the firm's optimal inventory strategy, the firm either chooses a risk exploitation inventory strategy or market exit. Comparing the firm's expected profits under both inventory strategies determines the optimal strategy. Again, market exit leads to zero profits. Thus, the firm prefers the risk exploitation strategy defined in Lemma 3.3 if and only if $\Pi_B(x^\star, t^\star) \geq 0$. Similar to Proposition 3.1(b), because $\Pi_B(x,t)$ is continuously differentiable and $\frac{\partial \Pi_B(x^\star(c,o),t^\star(c,o),c,o)}{\partial o} < 0$, the Implicit Function Theorem ensures that there exists a unique continuously differentiable function $\overline{o}(c)$ such that the optimal inventory strategy is risk exploitation if $o \leq \overline{o}(c)$, and market exit otherwise. Moreover, $\overline{o}(c)$ decreases in c:

$$\frac{\partial \overline{o}(c)}{\partial c} = -\frac{\frac{\partial \Pi_B(x^\star,t^\star)}{\partial c}}{\frac{\partial \Pi_B(x^\star,t^\star)}{\partial o}} = -\frac{x^\star}{\mathbb{E}\left[(B-t^\star)^+\right]} < 0.$$

$\square$

Proof of Lemma 3.4. The proof is equivalent to the proofs of Lemmas 3.2 and 3.3; i.e., we need to take first-order partial derivatives of $\Pi(x,t)$ with respect to x and t, and equate them to zero. In fact, the derivatives of the revenue, earliness cost, and salvage cost terms can be derived as before. However, differentiating the holding cost term with respect to t is now much more involved. We will therefore demonstrate how to obtain this important derivative. First, we rewrite the holding cost term (while suppressing h) by using the law of iterated expectations:

$$\begin{aligned}
\mathbb{E}\left[\int_{\max\{t,B\}}^{B+L} I_t(\tau)d\tau\right] &= \mathbb{E}\left[\int_{B}^{B+L} I_t(\tau)d\tau \cdot 1_{\{B>t\}} + \int_{t}^{B+L} I_t(\tau)d\tau \cdot 1_{\{B\leq t\}}\right] \\
&= \int_t^{b_u} \mathbb{E}\left[\int_0^{b_u+l_u} I_t(\tau)1_{\{b\leq\tau\leq b+L\}}d\tau | B=b\right] f_B(b)db \\
&+ \int_0^{t} \mathbb{E}\left[\int_t^{b_u+l_u} I_t(\tau)1_{\{\tau\leq b+L\}}d\tau | B=b\right] f_B(b)db.
\end{aligned}$$

Next, we derive the first-order partial derivative with respect to t by applying Leibniz's formula, by interchanging the expectation and derivative operators, and by noting that

$\frac{\partial I_t(\tau)}{\partial t} = 0$ for $t < B$:

$$\frac{\partial}{\partial t}\mathbb{E}\left[\int_{\max\{t,B\}}^{B+L} I_t(\tau)d\tau\right] = \mathbb{E}\left[\int_t^{b_u+l_u} -Q_t' 1_{\{Q_t - Q_\tau \le x, \tau \le B+L, B \le t\}} d\tau - x 1_{\{B \le t \le B+L\}}\right]$$
$$= \int_t^{b_u+l_u} d_t\left(Q_t - Q_\tau \le x, \tau \le B+L, B \le t\right) d\tau - x\mathbb{P}\left(B \le t \le B+L\right).$$

Based on this analysis, we can now state the first-order partial derivatives of $\Pi(x,t)$ with respect to x and t:

$$\begin{aligned}\frac{\partial \Pi(x,t)}{\partial x} &= \mathbb{E}\left[(p-c) - w(B-t)^+ - h\int_{\max\{t,B\}}^{B+L} 1_{\{Q_t - Q_\tau \le x\}} d\tau - (p-s)1_{\{Q_t \le x\}}\right] \\ &= (p-c) - w\int_t^{b_u} \mathbb{P}(B \ge b)db \\ &\quad - h\int_0^{b_u+l_u} \mathbb{P}\left(Q_t - Q_\tau \le x, \max\{t,B\} \le \tau \le B+L\right)d\tau - (p-s)\mathbb{P}(Q_t \le x);\end{aligned} \tag{B.5}$$

$$\begin{aligned}\frac{\partial \Pi(x,t)}{\partial t} &= -(o+wx)\mathbb{E}\left[-1_{\{B \ge t\}}\right] - (p-s)\mathbb{E}\left[\left(-Q_t' 1_{\{Q_t \le x\}}\right)\right] \\ &\quad - h\frac{\partial}{\partial t}\mathbb{E}\left[\int_{\max\{t,B\}}^{B+L} I_t(\tau)d\tau\right] \\ &= (o+wx)\mathbb{P}(B \ge t) - (p-s)d_t(Q_t \le x) \\ &\quad + h\left[x\mathbb{P}\left(B \le t \le B+L\right) - \int_t^{b_u+l_u} d_t\left(Q_t - Q_\tau \le x, \tau \le B+L, B \le t\right)d\tau\right].\end{aligned} \tag{B.6}$$

□

Proof of Proposition 3.3. The proof follows exactly the same steps as in Propositions 3.1 and 3.2.

(a) Suppose $o = w = h = 0$. By (B.6), we have $\frac{\partial \Pi(x,t)}{\partial t} = -(p-s)d_t(Q_t \le x) \le 0$ for all x and t. From hereon, the proof follows exactly the same steps as in Proposition 3.1(a).

(b) Suppose that $o + w + h > 0$. In a first step, we show that instant product availability is never the firm's optimal inventory strategy. Assume to the contrary that

$t^\star = 0$ is optimal for some $x > 0$. Then, necessarily, $\left.\frac{\partial \Pi(x,t)}{\partial t}\right|_{t=0} \leq 0$. However, from the definition of $A(\tau)$ it follows readily that $A'(0) = 0$ almost surely, implying that $d_0(\cdot) = 0$ almost surely. Thus, $\left.\frac{\partial \Pi_B(x,t)}{\partial t}\right|_{t=0} = o + wx > 0$ for all $x > 0$, which yields the desired contradiction. Finally, we establish that for $x = 0$, instant product availability is never better than a market exit. This is obvious because with $x = 0$ the firm generates negative profits which makes market exit the preferred strategy.

Now, since instant product availability is never the firm's optimal inventory strategy, the firm either chooses a risk exploitation inventory strategy or market exit. Comparing the firm's expected profits under both inventory strategies determines the optimal strategy. Again, market exit leads to zero profits. Thus, the firm prefers the risk exploitation strategy defined in Lemma 3.4 if and only if $\Pi(x^\star, t^\star) \geq 0$. Similar to Proposition 3.1(b), because $\Pi(x,t)$ is continuously differentiable and $\frac{\partial \Pi(x^\star(c,o), t^\star(c,o), c, o)}{\partial o} < 0$, the Implicit Function Theorem ensures that there exists a unique continuously differentiable function $\overline{o}(c)$ such that the optimal inventory strategy is risk exploitation if $o \leq \overline{o}(c)$, and market exit otherwise. Moreover, $\overline{o}(c)$ decreases in c:

$$\frac{\partial \overline{o}(c)}{\partial c} = -\frac{\frac{\partial \Pi(x^\star, t^\star)}{\partial c}}{\frac{\partial \Pi(x^\star, t^\star)}{\partial o}} = -\frac{x^\star}{\mathbb{E}\left[(B - t^\star)^+\right]} < 0.$$

□

Proof of Corollary 3.1. The proof proceeds by comparing the results of Proposition 3.3 with a classical newsvendor's optimal inventory scale. Due to the independence of Q and $\mathcal{S}$, a classical newsvendor's optimal inventory scale, x_{NV}, satisfies $\mathbb{P}(Q \leq x_{NV}) = \frac{p-c}{p-s}$.

By Proposition 3.3(a), if the firm chooses an instant product availability, $t^\star = 0$, then the optimal inventory scale is given by $\mathbb{P}(Q \leq x^\star) = \frac{p-c}{p-s}$. This optimality condition is identical to the classical newsvendor's condition, and therefore $x^\star = x_{NV}$.

By Proposition 3.3(b), if the firm chooses a risk exploitation inventory strategy, then the optimal inventory scale is determined by (3.8). Since the second and third term on the left-hand side of (3.8) are strictly positive, it follows immediately that $\mathbb{P}(Q_{t^\star} \leq x^\star) < \frac{p-c}{p-s}$, or equivalently, $\mathbb{P}(Q_{t^\star} \leq x^\star) < \mathbb{P}(Q \leq x_{NV})$. Since, by construction, $Q_{t^\star}$ is stochastically smaller than Q, we know that in optimum, $\mathbb{P}(Q \leq x^\star) \leq \mathbb{P}(Q_{t^\star} \leq x^\star) < \mathbb{P}(Q \leq x_{NV})$. These inequalities, however, can only hold if $x^\star < x_{NV}$.

Finally, if the firm exits the market, then $x^\star = 0 < x_{NV}$, which concludes the proof. □

Proof of Corollary 3.2. We are interested in the full differential of the expected profit, $\Pi(x,t)$, with respect to any revenue and cost parameter $\alpha \in \{p, s, c, o, w, h\}$; i.e.,

$$\frac{d\Pi(x,t)}{d\alpha} = \frac{\partial\Pi(x,t)}{\partial\alpha} + \frac{\partial\Pi(x,t)}{\partial x}\frac{\partial x}{\partial\alpha} + \frac{\partial\Pi(x,t)}{\partial t}\frac{\partial t}{\partial\alpha}.$$

If we hold the inventory strategy (x,t) fixed, then $\frac{\partial x}{\partial\alpha} = \frac{\partial t}{\partial\alpha} = 0$. Similarly, if the inventory strategy is adjusted optimally, then (i) $\frac{\partial\Pi(x,t)}{\partial x} = \frac{\partial t}{\partial\alpha} = 0$ under instant product availability; (ii) $\frac{\partial\Pi(x,t)}{\partial x} = \frac{\partial\Pi(x,t)}{\partial t} = 0$ under risk exploitation; and (iii) $\frac{\partial x}{\partial\alpha} = \frac{\partial t}{\partial\alpha} = 0$ under market exit. Therefore, $\frac{d\Pi(x,t)}{d\alpha} = \frac{\partial\Pi(x,t)}{\partial\alpha}$. Finally, it is straightforward to show that $\frac{\partial\Pi(x,t)}{\partial\alpha}$ is positive for $\alpha \in \{p, s\}$, and negative for $\alpha \in \{c, o, w, h\}$. □

Proof of Lemma 3.5. (a) Suppose $w = o = h = 0$. Then, Lemmas 3.1 and 3.4 imply that for any t, the firm's optimal inventory scale solves $\mathbb{P}(Q_t \leq x^\star) = \frac{p-c}{p-s}$. Noting that Q_t stochastically decreases in t establishes the desired result.

(b) We prove this result by constructing a situation where $x^\star(t)$ increases in t. The first-order partial derivative of $x^\star(t)$ with respect to t is $\frac{\partial x^\star(t)}{\partial t} = -\frac{\partial^2\Pi(x^\star,t)}{\partial x\partial t} / \frac{\partial^2\Pi(x^\star,t)}{\partial x^2}$. By Lemma 3.1 and the optimality of $x^\star(t)$, we know that $\frac{\partial^2\Pi(x^\star,t)}{\partial x^2} < 0$. Thus, to establish our result, we need to find a situation where $\frac{\partial^2\Pi(x^\star,\hat{t})}{\partial x\partial t} > 0$ for some $\hat{t}$. Assume $h = 0$, $w > 0$, $\hat{t} < b_u$, and $A'(\hat{t}) = 0$ for any realization of (Q, B, L). Intuitively, this corresponds to a situation where no customer demands the product at time $\hat{t}$, i.e., $d_{\hat{t}}(\cdot) = 0$. In this case, $\frac{\partial^2\Pi(x^\star,\hat{t})}{\partial x\partial t} = w\mathbb{P}(B \geq \hat{t}) > 0$, which concludes the proof. □

Proof of Lemma 3.6. (a) For fixed t, we are interested in the differential of the optimal inventory scale, $x^\star$, with respect to any revenue and cost parameter $\alpha \in \{p, s, c, o, w, h\}$; i.e., $\frac{\partial x^\star}{\partial\alpha} = -\frac{\partial^2\Pi(x^\star,t)}{\partial x\partial\alpha} / \frac{\partial^2\Pi(x^\star,t)}{\partial x^2}$. Again, by Lemma 3.1 and the optimality of $x^\star$, $\frac{\partial^2\Pi(x^\star,t)}{\partial x^2} < 0$. By differentiating (B.5) with respect to α, it is easy to verify that the resulting cross-partial is positive for $\alpha \in \{p, s\}$, negative for $\alpha \in \{c, w, h\}$, and zero for $\alpha = o$.

(b) Structurally equivalent to part (a). □

Proof of Proposition 3.4. Suppose the firm's optimal inventory strategy is risk exploitation. Then, according to the Implicit Function Theorem, we can derive the relevant derivatives as follows:

$$\begin{pmatrix} dx^\star/d\alpha \\ dt^\star/d\alpha \end{pmatrix} = -H^{-1} \cdot \begin{pmatrix} \partial^2\Pi(x^\star,t^\star)/\partial x\partial\alpha \\ \partial^2\Pi(x^\star,t^\star)/\partial t\partial\alpha \end{pmatrix}, \tag{B.7}$$

where H^{-1} is the inverse of the Hessian of $\Pi(x,t)$ evaluated at $(x^\star, t^\star)$; i.e.,

$$H^{-1} = \frac{1}{det(H)} \begin{pmatrix} \partial^2\Pi(x^\star,t^\star)/\partial t^2 & -\partial^2\Pi(x^\star,t^\star)/\partial x\partial t \\ -\partial^2\Pi(x^\star,t^\star)/\partial x\partial t & \partial^2\Pi(x^\star,t^\star)/\partial x^2 \end{pmatrix}.$$

Since $(x^\star, t^\star)$ maximizes $\Pi(x,t)$, the Hessian, H, evaluated at this point must be negative definite, and therefore, $det(H) > 0$. Additionally, by optimality, $\partial^2\Pi(x^\star,t^\star)/\partial x^2 \leq 0$ and $\partial^2\Pi(x^\star,t^\star)/\partial t^2 \leq 0$. By Lemma 3.6, we also know that $\partial^2\Pi(x^\star,t^\star)/\partial x\partial\alpha$ is negative (zero) for $\alpha = c$ ($\alpha = o$), and $\partial^2\Pi(x^\star,t^\star)/\partial t\partial\alpha$ is zero (positive) for $\alpha = c$ ($\alpha = o$). Incorporating this information in (B.7) shows that $\partial x^\star/\partial c \leq 0$, and $\partial t^\star/\partial c \geq (<)0$ if $\partial^2\Pi(x^\star,t^\star)/\partial x\partial t \leq (>)0$. Similarly, $\partial t^\star/\partial o \geq 0$, and $\partial x^\star/\partial o \leq (>)0$ if $\partial^2\Pi(x^\star,t^\star)/\partial x\partial t \leq (>)0$. In Lemma 3.5, we have already established that there exist situations where $\partial^2\Pi(x^\star,t^\star)/\partial x\partial t$ is either positive or negative. Thus, in general, $x^\star$ is not monotonic in o, and $t^\star$ is not monotonic in c.

Finally, it remains to verify that $x^\star$ ($t^\star$) also decreases in c (increases in o) if the firm's optimal inventory strategy is either instant product availability or market exit. However, this follows immediately from Proposition 3.3. Hence, $\partial x^\star/\partial c \leq 0$ and $\partial t^\star/\partial o \geq 0$. $\square$

Appendix C

Proofs of Chapter IV

Proof of Lemma 4.1. For given x_{-i}, the first-order and second-order derivatives of $\Pi_W(x)$ with respect to x_i are

$$\begin{aligned}\frac{\partial \Pi_W(x)}{\partial x_i} =& u_i - (u_i + o_i)\mathbb{P}(D_i^s < x_i) - \sum_{j \neq i}(u_j + o_j)\alpha_{ij}\mathbb{P}(D_j^s < x_j, D_i > x_i) \\ =& u_i - (u_i + o_i)\mathbb{P}(D_i^s < x_i) - \sum_{j \neq i}(u_j + o_j)\alpha_{ij}\mathbb{P}(D_j^s < x_j | D_i > x_i)\mathbb{P}(D_i > x_i) \\ \frac{\partial^2 \Pi_W(x)}{\partial x_i^2} =& -(u_i + o_i) f_{D_i^s}(x_i) \\ &+ \sum_{j \neq i}(u_j + o_j)\alpha_{ij}\left[f_{D_i}(x_i)\mathbb{P}(D_j^s < x_j | D_i > x_i) - \alpha_{ij} f_{D_j^s | D_i > x_i}(x_j)\mathbb{P}(D_i > x_i)\right],\end{aligned}$$

$i = 1, \ldots, n$, with f_Y being the density function of random variable Y. By rearranging terms, $\Pi_W(x)$ is concave in x_i if and only if

$$\begin{aligned}(u_i + o_i) f_{D_i^s}(x_i) + \sum_{j \neq i}(u_j + o_j)\alpha_{ij}^2 f_{D_j^s | D_i > x_i}(x_j)\mathbb{P}(D_i > x_i) \\ \geq \sum_{j \neq i}(u_j + o_j)\alpha_{ij} f_{D_i}(x_i)\mathbb{P}(D_j^s < x_j | D_i > x_i)\end{aligned} \tag{C.1}$$

for all x. To prove the lemma, we construct a scenario for which (C.1) is violated for some x.

Let $\eta > 0$, and for given x_i, let $X_\eta(x_i)$ be the set of stocking levels x_{-i} such that $\mathbb{P}(D_j^s < x_j | D_i > x_i) \geq 1/(n-1)$ and $f_{D_j^s | D_i > x_i}(x_j) < \eta$. Note that for any x_i, $X_\eta(x_i)$ is non-empty because $\mathbb{P}(D_j^s < x_j | D_i > x_i) \to 1$ and $f_{D_j^s | D_i > x_i}(x_j) \to 0$ for $x_j \to \infty$. For all $j \neq i$, let (i) $\alpha_{ji} = 0$, i.e., $D_i^s =_{st} D_i$; (ii) $\alpha_{ij} = 1/(n-1)$; and (iii) $(u_j + o_j) = (1 + \nu)(u_i + o_i)(n-1)$, $\nu > 0$. Further assume that $D_i \sim Normal(\mu_i, \sigma_i)$ with $\sigma_i < \nu / \left[(1 + \nu)\eta\sqrt{2\pi}\right]$.

Given these assumptions,

$$\begin{aligned}&(u_i + o_i)\left[f_{D_i}(x_i) + (1+\nu)\eta\right] \\ &> (u_i + o_i) f_{D_i^s}(x_i) + \sum_{j \neq i} (u_j + o_j)\alpha_{ij}^2 f_{D_j^s|D_i > x_i}(x_j)\mathbb{P}(D_i > x_i)\end{aligned} \tag{C.2}$$

and

$$\sum_{j \neq i} (u_j + o_j)\alpha_{ij} f_{D_i}(x_i)\mathbb{P}(D_j^s < x_j | D_i > x_i) \geq (u_i + o_i)(1+\nu) f_{D_i}(x_i). \tag{C.3}$$

By (C.1)-(C.3), it follows that $\Pi_W(x)$ is not concave in x_i, if for some x_i,

$$(1+\nu) f_{D_i}(x_i) > \left[f_{D_i}(x_i) + (1+\nu)\eta\right], \tag{C.4}$$

or equivalently,

$$f_{D_i}(x_i) > \frac{1+\nu}{\nu}\eta. \tag{C.5}$$

Since D_i is normally distributed, we can choose x_i such that $f_{D_i}(x_i) = 1/(\sigma_i\sqrt{2\pi})$ and hence, (C.5) holds for any $\sigma_i < \nu / \left[(1+\nu)\eta\sqrt{2\pi}\right]$. □

Proof of Proposition 4.1. Consider the maximization problem P_y. Since $\Pi_W(x)$ and all constraints are continuously differentiable in x, and all constraints are linear in x, there exists a unique vector λ such that $(x^\star, \lambda)$ satisfies the Karush-Kuhn-Tucker (KKT) conditions:

$$\frac{\partial \Pi_W(x^\star)}{\partial x_i} - \lambda_i = 0 \tag{C.6}$$

$$\lambda_i(x_i^\star - y_i) = 0 \tag{C.7}$$

$$x_i^\star - y_i \leq 0 \tag{C.8}$$

$$x^\star, \lambda \geq 0, \tag{C.9}$$

$i = 1, \ldots, n$. Now, suppose $x^\star$ is a directionally largest optimal solution.

Case 1: $x_i^\star < y_i$. For (C.7) to hold, we need $\lambda_i = 0$, which implies by (C.6) and (4.2) that $x_i^\star = \hat{x}_i(x_{-i}^\star)$.

Case 2: $x_i^\star = y_i$. We need to show that $y_i \leq \hat{x}_i(x_{-i}^\star)$. Suppose to the contrary that there exist situations where $x_i^\star = y_i > \hat{x}_i(x_{-i}^\star)$. By (4.2), $\hat{x}_i(x_{-i}^\star)$ is the wholesaler's optimal stocking level if he is unrestricted in his stocking decision for product i. Now, if this stocking level is also feasible for the bounded problem P_y, then it must also be optimal in P_y. Thus, $x_i^\star = \hat{x}_i(x_{-i}^\star) < y_i = x_i^\star$ which is a contradiction.

Combining Cases 1 and 2 for all i yields $x_i^\star(y) = \min\{\hat{x}_i(x_{-i}^\star(y)), y_i\}$. □

Proof of Lemma 4.2. Given x_{-i}, the wholesaler's optimization problem is now single-dimensional in x_i. Thus, to analyze how $\hat{x}_i(x_{-i})$ changes in x_j, $j \neq i$, we apply the Implicit Function Theorem to gain the required differential

$$\frac{\partial \hat{x}_i(x_{-i})}{\partial x_j} = -\frac{\partial^2 \Pi_W(\hat{x}_i, x_{-i})/\partial x_i \partial x_j}{\partial^2 \Pi_W(\hat{x}_i, x_{-i})/\partial x_i^2}.$$

Due to the optimality of $\hat{x}_i(x_{-i})$, we know that $\partial^2 \Pi_W(\hat{x}_i, x_{-i})/\partial x_i^2 \leq 0$. Furthermore, analysis of the cross-partial yields

$$\begin{aligned}\frac{\partial^2 \Pi_W(\hat{x}_i, x_{-i})}{\partial x_i \partial x_j} =& -(u_i + o_i)\frac{\partial}{\partial x_j}\mathbb{P}(D_i^s < \hat{x}_i) \\ &- \sum_{k \neq i}(u_k + o_k)\alpha_{ik}\frac{\partial}{\partial x_j}\mathbb{P}(D_k^s < x_k | D_i > \hat{x}_i)\mathbb{P}(D_i > x_i).\end{aligned}$$

By construction, D_k^s, $k \neq j$, is stochastically decreasing in x_j and so, $\partial \mathbb{P}(D_i^s < \hat{x}_i)/\partial x_j \geq 0$ and $\partial \mathbb{P}(D_k^s < x_k | D_i > \hat{x}_i)/\partial x_j \geq 0$ for all $k \neq i, j$. Additionally, D_j^s does not dependent on x_j and therefore $\partial \mathbb{P}(D_j^s < x_j | D_i > \hat{x}_i)/\partial x_j \geq 0$. Combining these arguments gives $\partial^2 \Pi_W(\hat{x}_i, x_{-i})/\partial x_i \partial x_j \leq 0$ and finally

$$\frac{\partial \hat{x}_i(x_{-i})}{\partial x_j} \leq 0.$$

Thus, it follows that $\hat{x}_i(x_{-i}) \geq \hat{x}_i(x'_{-i})$.

(ii) Consider a three-product scenario with products denoted by i, j, and k, respectively, and suppose that the density functions of D_i, D_j, and D_k are strictly positive on $\mathbb{R}^+$. This implies that the inequality in Part (i) is strict because $\partial^2 \Pi_W(\hat{x}_i, x_{-i})/\partial x_i \partial x_j < 0$. Assume $\alpha_{jk} > 0$, $\alpha_{ki} > 0$, and any other substitution rate to be zero. Note that $\hat{x}_i(x_j)$ depends on x_j only indirectly through $\hat{x}_k(x_j)$. We now prove the lemma by a sequential argument.

First, we analyze the direct effects between the three products. By Part (i), $x'_j > x_j$

implies $\hat{x}_k(x_j') < \hat{x}_k(x_j)$, and thus $\hat{x}_i(x_j') > \hat{x}_i(x_j)$. Second, to complete the proof, we need to show that an increased stocking level for product i also leads to a decreased stocking level for k, but this is again just an application of Part (i).

Accordingly, since direct and indirect substitution effects point in the same direction, we can conclude that $\hat{x}_i(x_j) < \hat{x}_i(x_j')$. □

Proof of Proposition 4.2. (i) Suppose $x_j^\star(y') < x_j^\star(y)$. This can never happen because $x_j^\star(y')$ is feasible in P_y, but by assumption, it is dominated in P_y by $x_j^\star(y)$. This must also be true in $P_{y'}$ because any feasible solution of P_y is feasible in $P_{y'}$. Thus, $x_j^\star(y')$ cannot be optimal in $P_{y'}$. This is a contradiction and therefore $x_j^\star(y') \geq x_j^\star(y)$.

(ii) By Part (i) and Lemma 4.2(i), it is always true that $\hat{x}_i(x_j^\star(y), x_{-j}^\star) \geq \hat{x}_i(x_j^\star(y'), x_{-j}^\star)$. It follows immediately that $x_i^\star(y) = \min\{\hat{x}_i(x_j^\star(y), x_{-j}^\star), y_i\} \geq \min\{\hat{x}_i(x_j^\star(y'), x_{-j}^\star), y_i\} = x_i^\star(y')$.

(iii) Assume y_i large enough so that it never constrains the wholesaler. This assumption ensures the applicability of Lemma 4.2 because we are guaranteed to find an interior solution to the wholesaler's optimization problem. Hence, by Part (i) and Lemma 4.2(ii), there exist situations where $\hat{x}_i(x_{-i}^\star(y)) < \hat{x}_i(x_{-i}^\star(y'))$ for some $i \neq j$. Thus,

$$x_i^\star(y) = \min\{\hat{x}_i(x_{-i}^\star(y)), y_i\} = \hat{x}_i(x_{-i}^\star(y)) < \hat{x}_i(x_{-i}^\star(y')) = \min\{\hat{x}_i(x_{-i}^\star(y')), y_i\} = x_i^\star(y')$$

for some $i \neq j$. □

Proof of Proposition 4.3. The total differential of $\Pi_W(x)$ with respect to substitution rates is

$$\frac{d\Pi_W(x^\star(\alpha_{ji}), \alpha_{ji})}{d\alpha_{ji}} = \frac{\partial \Pi_W}{\partial \alpha_{ji}} + \sum_k \frac{\partial \Pi_W}{\partial x_k^\star} \frac{\partial x_k^\star}{\partial \alpha_{ji}}.$$

In a first step, we show that $\partial \Pi_W / \partial \alpha_{ji} \geq 0$ for all i and j, $i \neq j$, i.e.,

$$\frac{\partial \Pi_W}{\partial \alpha_{ji}} = (u_i + o_i)\mathbb{E}\left[(D_j - x_j)1_{\{D_i^s < x_i, D_j > x_j\}}\right] \geq 0. \tag{C.10}$$

This is true, since the term under the expectation in (C.10) is non-negative.

In a second step, we investigate the indirect effects of α_{ji} on Π_W. If x is optimally adjusted, then, for all k, $\partial \Pi_W / \partial x_k = 0$ if $x_k^\star < y_k$ and $\partial x_k^\star / \partial \alpha_{ji} = 0$ if $x_k^\star = y_k$. Thus,

$d\Pi_W/d\alpha_{ji} = \partial\Pi_W/\partial\alpha_{ji} \geq 0$ for all i and j, if x is adjusted optimally. □

Proof of Lemma 4.3. (i) Choose an arbitrary product i. Application of the Implicit Function Theorem yields

$$\frac{\partial \hat{x}_i(x_{-i})}{\partial \alpha_{ji}} = -\frac{\partial^2\Pi_W(\hat{x}_i(\alpha),\alpha)/\partial x_i \partial\alpha_{ji}}{\partial^2\Pi_W(\hat{x}_i(\alpha),\alpha)/\partial x_i^2}. \tag{C.11}$$

Due to the optimality of $\hat{x}_i(x_{-i})$, we know that $\partial^2\Pi_W(\hat{x}_i(\alpha),\alpha)/\partial x_i^2 \leq 0$. In addition, the cross-partial $\partial^2\Pi_W/\partial x_i\partial\alpha_{ji}$ is explicitly given by

$$\frac{\partial^2\Pi_W}{\partial x_i \partial\alpha_{ji}} = -(u_i + o_i)\frac{\partial}{\partial\alpha_{ji}}\mathbb{P}(D_i^s < \hat{x}_i), \tag{C.12}$$

for all $j \neq i$. By construction, $D_i^s = D_i + \sum_{k\neq i}\alpha_{ki}(D_k - x_k)^+$. Thus, D_i^s is stochastically increasing in α_{ji}. It follows that $\partial\mathbb{P}(D_i^s < x_i)/\partial\alpha_{ji} \leq 0$, and hence, $\partial^2\Pi_W/\partial x_i\partial\alpha_{ji} \geq 0$. Now, by (C.11), (C.12), and the optimality of $\hat{x}_i(x_{-i})$, $\partial\hat{x}_i(x_{-i})/\partial\alpha_{ji} \geq 0$ for all $j \neq i$.

(ii) Similar to part (i), the proof proceeds by evaluating

$$\frac{\partial \hat{x}_j(x_{-j})}{\partial \alpha_{ji}} = -\frac{\partial^2\Pi_W(\hat{x}_j(\alpha),\alpha)/\partial x_j \partial\alpha_{ji}}{\partial^2\Pi_W(\hat{x}_j(\alpha),\alpha)/\partial x_j^2}. \tag{C.13}$$

In contrast to the proof of part (i), however, the cross-partial can now be positive or negative, since

$$\frac{\partial^2\Pi_W}{\partial x_j \partial\alpha_{ji}} = -(u_i + o_i)\left[\mathbb{P}(D_i^s < x_i, D_j > \hat{x}_j) + \alpha_{ji}\frac{\partial}{\partial\alpha_{ji}}\mathbb{P}(D_i^s < x_i, D_j > \hat{x}_j)\right], \tag{C.14}$$

where $\partial\mathbb{P}(D_i^s < x_i, D_j > \hat{x}_j)/\partial\alpha_{ji} \leq 0$.

We therefore prove the lemma by providing an example. Consider a two-product portfolio with heterogeneous initial demands $D_i \sim Uniform(0,1)$ and $D_j \sim Beta(2,1)$, i.e., $F_j(x_j) = x_j^2$. Assume all other parameters to be symmetric across products. To be concrete: $u_i = u_j = 2$, $o_i = o_j = 8$, and $\alpha_{ij} = \alpha_{ji} = 0.8$. In this setting, we obtain $\partial^2\Pi_W/\partial x_j^2 = -10\left[(x_i + x_j)^2 + x_j^2/4\right] \leq 0$, and $\partial^2\Pi_W/\partial x_j\partial\alpha_{ji} = 125x_i^3/24 \geq 0$. Consequently, $\partial\hat{x}_j(x_{-j})/\partial\alpha_{ji} = 25x_i^3/48\left[(x_i + \hat{x}_j)^2 + \hat{x}_j^2/4\right] > 0$ for $x_i > 0$. □

Proof of Proposition 4.4. The total differential of the optimal stocking level for product

j with respect to substitution rates is

$$\frac{dx_j^\star(x_{-j}^\star(\alpha_{ji}),\alpha_{ji})}{d\alpha_{ji}} = \frac{\partial x_j^\star}{\partial \alpha_{ji}} + \sum_{k\neq j} \frac{\partial x_j^\star}{\partial x_k^\star}\frac{\partial x_k^\star}{\partial \alpha_{ji}}.$$

To prove the claim, we make use of the following two properties: For all k, (a) if $x_k^\star = y_k$, then $\partial x_k^\star/\partial \alpha_{ji} = 0$; and (b) if $x_k^\star < y_k$, then $\partial x_k^\star/\partial \alpha_{ji} = \partial \hat{x}_k/\partial \alpha_{ji}$. From Lemma 4.3(ii), for some i and j, $i \neq j$, there are instances of P_y where $\partial \hat{x}_j/\partial \alpha_{ji} > 0$. Combining this result with property (b), we find that there are instances of P_y with $\partial x_j^\star/\partial \alpha_{ji} > 0$. Now assume that $x_k^\star = \hat{x}_k = y_k$ for all $k \neq j$, yielding $dx_j^\star/d\alpha_{ji} = \partial x_j^\star/\partial \alpha_{ji} > 0$ and the proposition follows. □

Proof of Lemma 4.4. To prove the desired result, we make use of the inverse distribution function $\Phi_i^{-1}(\rho_i, y)$, $\rho_i \in [0,1]$. In particular, $\Phi_i(\chi_i, y) = \rho_i$ and $\Phi_i^{-1}(\rho_i, y) = \chi_i$. Note that the assumptions on rational beliefs imply $\partial^2 \Phi_i^{-1}(\rho_i, y)/\partial y_i^2 \leq 0$. Further, $\Phi_i(0, y) = 0$ and $\Phi_i(y_i, y) = 1$.

Assuming rational beliefs and given y_{-i}, each manufacturer's expected profit can be written as

$$\Pi_{M_i}(y_i|y_{-i}) = w_i \int_0^{y_i} \chi_i d\Phi_i(\chi_i, y) - c_i y_i = w_i \int_0^{y_i} (1 - \Phi_i(\chi_i, y))d\chi_i - c_i y_i. \tag{C.15}$$

Using the inverse distribution function, we can rewrite (C.15) as

$$\Pi_{M_i}(y_i|y_{-i}) = w_i \int_0^1 (1-\rho_i) d\Phi_i^{-1}(\rho_i, y) - c_i y_i = w_i \int_0^1 \Phi_i^{-1}(\rho_i, y) d\rho_i - c_i y_i.$$

Therefore,

$$\frac{\partial^2 \Pi_{M_i}(y_i|y_{-i})}{\partial y_i^2} = w_i \int_0^1 \frac{\partial^2 \Phi_i^{-1}(\rho_i, y)}{\partial y_i^2} d\rho_i \leq 0.$$

□

Proof of Proposition 4.5. Assuming rational beliefs, each manufacturer's expected profit given her competitors' production quantities is

$$\Pi_{M_i}(y_i|y_{-i}) = w_i \mu_i(y) - c_i y_i.$$

Taking the first-order derivative and satisfying the optimality condition yields

$$\frac{\partial \Pi_{M_i}(y_i|y_{-i})}{\partial y_i} = w_i \frac{\partial \mu_i(y)}{\partial y_i} - c_i = 0,$$

and the result follows immediately. □

Proof of Proposition 4.6. A pure-strategy manufacturer Nash equilibrium exists if (i) each manufacturer's strategy space is a non-empty, compact and convex set, and (ii) each manufacturer's profit function Π_{M_i} is continuous in y and quasi-concave in y_i (Debreu, 1952). Lemma 4.4 together with our assumptions ensures that these conditions are satisfied. Thus, there exists at least one pure-strategy manufacturer Nash equilibrium.

To derive our uniqueness conditions, we rely on the fundamental results of Rosen (1965). In particular, Theorem 2 in Rosen (1965) asserts that the manufacturer Nash equilibrium defined by (4.5) is unique if (i) Π_{M_i} is twice continuously differentiable in y for all i, and (ii) $\sigma(y, \delta) = \sum_{i=1}^{n} \delta_i \Pi_{M_i}(y_i|y_{-i})$ is diagonally strictly concave for some fixed $\delta > 0$. While condition (i) is guaranteed by our assumptions, we need some more definitions to verify condition (ii).

Let $g(y, \delta)$ be the pseudogradient of $\sigma(y, \delta)$ for fixed δ, i.e.,

$$g(y, \delta) = \begin{pmatrix} \delta_1 \partial \Pi_{M_1} / \partial y_1 \\ \vdots \\ \delta_n \partial \Pi_{M_n} / \partial y_n \end{pmatrix},$$

and denote by $G(y, \delta)$ the Jacobian of $g(y, \delta)$ with respect to y, i.e.,

$$G(y, \delta) = \nabla_y g(y, \delta) = \left(\delta_i \partial^2 \Pi_{M_i} / \partial y_i \partial y_j \right)_{ij}.$$

Now, Theorem 6 in Rosen (1965) states that $\sigma(y, \delta)$ is diagonally strictly concave if $G(y, \delta)$ is negative definite for all $y \in \times_i [0, y_i] \subseteq [0, K]^n$ and some fixed $\delta > 0$. Thus, the manufacturer Nash equilibrium is unique if, for some $\delta > 0$, $G(y, \delta)$ is negative definite for all y.

Negative definiteness of $G(y, \delta)$: Denote by $G^T(y, \delta)$ the transposed of $G(y, \delta)$. A basic result in fundamental algebra states that $G(y, \delta)$ is negative definite if its symmetric part $G_{sym}(y, \delta) = \left[G(y, \delta) + G^T(y, \delta) \right] / 2$ is negative definite. This is true if all eigenvalues of $G_{sym}(y, \delta)$ are negative. Note that, due to Definition 4.1, all elements of $G_{sym}(y, \delta)$ are non-positive. Hence, by the Gershgorin Circle Theorem (see Varga, 2004), an upper bound for the ith eigenvalue of $G_{sym}(y, \delta)$ is given by

$$ub_i = \delta_i \frac{\partial^2 \Pi_{M_i}}{\partial y_i^2} - \frac{1}{2} \sum_{j \neq i} \left[\delta_i \frac{\partial^2 \Pi_{M_i}}{\partial y_i \partial y_j} + \delta_j \frac{\partial^2 \Pi_{M_j}}{\partial y_i \partial y_j} \right],$$

$i = 1, \ldots, n$. Therefore, $G_{sym}(y, \delta)$ is negative definite if, for all i, $ub_i < 0$. This is true if Π_{M_i} is strictly concave in y_i, and

$$2 + \sum_{j \neq i} \frac{\partial y_i^C}{\partial y_j} - \sum_{j \neq i} \frac{\delta_j}{\delta_i} \frac{\partial^2 \Pi_{M_j} / \partial y_i \partial y_j}{\partial^2 \Pi_{M_i} / \partial y_i^2} > 0 \tag{C.16}$$

for all y, where we make use of the Implicit Function Theorem

$$\frac{\partial y_i^C}{\partial y_j} = -\frac{\partial^2 \Pi_{M_i} / \partial y_i \partial y_j}{\partial^2 \Pi_{M_i} / \partial y_i^2}.$$

By choosing $\delta_i = 1/w_i > 0$ for all i, (C.16) reduces to (4.6), which proves the proposition. □

Proof of Corollary 4.1. If $\Pi_W(x)$ is jointly concave in x, then the wholesaler's optimal stocking level $x^\star(y)$ is unique for any given y. In addition, under the conditions of Proposition 4.6, the manufacturer Nash equilibrium y^c is also unique. It follows that $(x^\star(y^c), y^c)$ defines the unique Bayesian Nash-Stackelberg equilibrium in the competitive scenario of the Supply Game. □

Proof of Proposition 4.7. Assuming rational beliefs, the manufacturer's expected profit is

$$\Pi_M(y) = \sum_i \left(w_i \mu_i(y) - c_i y_i \right).$$

Taking first-order derivatives yields

$$\frac{\partial \Pi_M(y)}{\partial y_i} = w_i \frac{\partial \mu_i(y)}{\partial y_i} + \sum_{j \neq i} w_j \frac{\partial \mu_j(y)}{\partial y_i} - c_i,$$

$i = 1, \ldots, n$. Rearranging terms and satisfying the optimality conditions gives (4.8). □

Proof of Corollary 4.2. If $\Pi_W(x)$ and $\Pi_M(y)$ are jointly concave in x and y, respectively, then the wholesaler's optimal stocking level given y, $x^\star(y)$, and the manufacturer's optimal production quantity y^{nc} are both unique. Thus, in the non-competitive scenario of the Supply Game, $(x^\star(y^{nc}), y^{nc})$ defines the unique Bayesian Stackelberg equilibrium. □

Proof of Proposition 4.8. We start this proof with a preliminary result that is useful in the remainder. Let $y'_{-i} \geq y_{-i}$ and note that

$$\frac{\partial^2 \mu_i(y)}{\partial y_i \partial y_j} = -\int_0^{y_i} \frac{\partial^2 \Phi_i(\chi_i, y)}{\partial y_i \partial y_j} d\chi_i \leq 0$$

by the definition of rational beliefs. It follows that for arbitrarily fixed $\tilde{y}_i$

$$\left.\frac{\partial \mu_i(y_i, y'_{-i})}{\partial y_i}\right|_{y_i=\tilde{y}_i} \leq \left.\frac{\partial \mu_i(y_i, y_{-i})}{\partial y_i}\right|_{y_i=\tilde{y}_i}. \tag{C.17}$$

(i) The proof proceeds by contradiction. Assume $y^c < y^{nc}$. Now, by comparing and equating the optimality conditions (4.5) and (4.8), we require

$$\left.\frac{\partial \mu_i(y_i, y^c_{-i})}{\partial y_i}\right|_{y_i=y_i^c} = \frac{c_i}{w_i} = \left.\frac{\partial \mu_i(y_i, y^{nc}_{-i})}{\partial y_i} + \sum_{j\neq i} \frac{w_j}{w_i} \frac{\partial \mu_j(y_i, y^{nc}_{-i})}{\partial y_i}\right|_{y_i=y_i^{nc}} \tag{C.18}$$

to be true. By assumption (4.9), the second term on the right-hand side of (C.18) is always non-positive. So, for (C.18) to hold, we need

$$\left.\frac{\partial \mu_i(y_i, y^c_{-i})}{\partial y_i}\right|_{y_i=y_i^c} \leq \left.\frac{\partial \mu_i(y_i, y^{nc}_{-i})}{\partial y_i}\right|_{y_i=y_i^{nc}}.$$

By (C.17) and concavity of μ_i with respect to y_i, this can only be true if $y_i^c \geq y_i^{nc}$, a contradiction to our initial assumption.

(ii) An example provides the proof. Assume manufacturers' beliefs about the wholesaler's stocking levels for products $j \neq i$ are independent of the production quantity of product i, i.e., $\mu_j(y_i, y_{-i}) = \mu_j(y_{-i})$ for all $j \neq i$. Hence, $\partial\mu_j/\partial y_i = 0$ for all $j \neq i$. Assume further that $\partial^2\Phi_i(\chi_i, y)/\partial y_i \partial y_j > 0$ for all $j \neq i$. Then, the inequality in (C.17) becomes strict.

Comparing the optimality conditions (4.5) and (4.8) for product i gives

$$\left.\frac{\partial \mu_i(y_i, y^c_{-i})}{\partial y_i}\right|_{y_i=y_i^c} = \frac{c_i}{w_i} = \left.\frac{\partial \mu_i(y_i, y^{nc}_{-i})}{\partial y_i}\right|_{y_i=y_i^{nc}}. \tag{C.19}$$

Now, assume $y^c_{-i} \geq y^{nc}_{-i}$; otherwise the proof would already be complete. By (C.17) and concavity of μ_i with respect to y_i, (C.19) can only be true if $y_i^c < y_i^{nc}$. □

Proof of Proposition 4.9. (i) The proof proceeds by contradiction. Let $y' \geq y$ and suppose $I(y') < I(y)$. Then, for arbitrary i,

$$y'_{-i} - x^\star_{-i}(y') < y_{-i} - x^\star_{-i}(y). \tag{C.20}$$

As an immediate consequence of (C.20), we know that $x^\star_{-i}(y') > x^\star_{-i}(y)$. Now, by repeatedly applying Lemma 4.2(i),

$$\hat{x}_i(x^\star_{-i}(y')) \leq \hat{x}_i(x^\star_{-i}(y)), \tag{C.21}$$

and recall that $x^\star_i(y) = \min\{\hat{x}_i(x^\star_{-i}(y)), y_i\}$.

If $\hat{x}_i(x^\star_{-i}(y)) \geq y_i$, then $I_i(y) = y_i - y_i = 0$, and thus $I_i(y') \geq I_i(y)$. If, to the contrary, $\hat{x}_i(x^\star_{-i}(y)) < y_i$, then applying (C.21) yields

$$I_i(y) = y_i - \hat{x}_i(x^\star_{-i}(y)) \leq y'_i - \hat{x}_i(x^\star_{-i}(y')) = I_i(y').$$

Accordingly, $I_i(y') \geq I_i(y)$; a contradiction to our initial assumption that $I(y') < I(y)$.

(ii) The proof is an application of Proposition 4.2. Suppose $y' = y + \varepsilon e_j$, $\varepsilon > 0$, for arbitrary j. Then, by Proposition 4.2(iii), there exist situations where $x^\star_i(y') > x^\star_i(y)$ for some $i \neq j$. Thus,

$$I_i(y') = y'_i - x^\star_i(y') < y'_i - x^\star_i(y) = y_i - x^\star_i(y) = I_i(y).$$

□

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