

# **The Interface of Operations and Finance in Global Supply Chains**

*by*

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**Dissertation**

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# Table of Contents

1. Introduction.....	1
1.1 Motivation .....	1
1.2 Research Scope.....	2
2. The Interface of Operations and Finance: State of The Art .....	5
2.1 Introduction.....	5
2.2 A Roadmap to Integrated Risk Management.....	9
2.3 Risk Identification .....	12
2.4 Specify Integration Conditions: When to Integrate – or Not .....	15
2.5 Select Operational Hedging and Financial Flexibility.....	19
2.6 Integrated Optimization of Operations and Finance .....	23
2.6.1 Relationship Analysis: Complements or Substitutes?.....	23
2.6.2 Approach Choice: Centralization or Decentralization? .....	26
2.6.3 Link of Relationship Analysis and Approach Choice .....	28
2.7 Conclusions .....	29
3. Capacity Investment, Backup Production, Switching Options, and Financial Hedging in a Global Supply Chain under Mean-CVaR.....	31
3.1 Introduction.....	31
3.2 Literature Review .....	33
3.3 Global Supply Chain Model with Backup Production, Switching Options, and Financial Hedging .....	37
3.3.1 Formulation and Assumptions.....	37
3.3.2 Optimal Financial Hedging Strategy .....	44
3.3.3 Optimal Operational Flexibility Strategy .....	47
3.4 Interplay between Operations and Finance.....	50
3.4.1 Relationship between Backup Production and Switching Options .....	50
3.4.2. Interaction between Operational Flexibility and Financial Hedging.....	51
3.5 Robustness Analysis.....	56
3.5.1 Impact of Exchange Rate Variability .....	57
3.5.2 Impact of Demand Variability .....	59
3.6 Conclusions .....	61

3.7 Appendices to Chapter 3 .....	62
Appendix 3A: Proofs.....	62
Appendix 3B: Input Parameters for Robustness Analysis.....	75
4. Mitigating Supplier Distress: Purchase Order Finance, Advance Payment Discount, and Backup Production .....	76
4.1 Introduction.....	76
4.2 Literature Review .....	78
4.3 A Supply Chain with Purchase Order Finance, Advance Payment Discount, and Backup Production.....	80
4.3.1 Formulation and Assumptions.....	80
4.3.2 Centralized and Decentralized Benchmarks .....	85
4.3.3 Base Case and Backup Production Only .....	86
4.4 Financing with Purchase Order Finance or Advance Payment Discount.....	89
4.4.1 Purchase Order Finance.....	89
4.4.2 Advance Payment Discount.....	93
4.4.3 Financing Equilibrium between POF and APD .....	95
4.5 Interaction of Pre-shipment Finance and Backup Production.....	97
4.5.1 Dual Financing: Pecking Order of POF and APD.....	97
4.5.2 Relationship between Pre-shipment Finance and Backup Production.....	99
4.6 Robustness Analysis.....	104
4.6.1 Impact of Demand Variability .....	105
4.6.2 Impact of the Retailer’s Internal Capital Level.....	107
4.7 Conclusions .....	108
4.8 Appendix to Chapter 4 .....	110
Appendix 4: Proofs.....	110
5. Managerial Insights.....	117
Bibliography.....	120

## List of Figures

Figure 1.1. Research Topology.....	3
Figure 2.1. Closed-loop View of Operations and Finance .....	10
Figure 2.2. A Roadmap to Integrated Risk Management .....	11
Figure 3.1. The Global Supply Chain Network.....	38
Figure 3.2. Timeline of Events .....	41
Figure 3.3. Operational Flexibility Strategies in Domains of Uncertainty.....	48
Figure 3.4. Efficient Frontier Analysis: Interplay between Operations and Finance .....	54
Figure 3.5. Effect of Exchange Rate Volatility on (a) Optimal Capacity; (b) Expected Profit; (c) and (e) CVaR; (d) and (f) Expected Utility .....	58
Figure 3.6. Effect of Demand Volatility on (a) Optimal Capacity; (b) Expected Profit; (c) and (e) CVaR; (d) and (f) Expected Utility.....	60
Figure 4.1. Trade Finance Arrangements by Market Share .....	77
Figure 4.2. The Physical and Financial Supply Chain Network .....	80
Figure 4.3. Timeline of Events .....	82
Figure 4.4. Effect of Demand Volatility on (a) Offshore Supplier Delivered Quantity; (b) Retailer Expected Profit; (c) Offshore Supplier Expected Profit; and (d) Supply Chain Expected Profit.....	105
Figure 4.5. Effect of Retailer's Internal Capital Level on (a) Offshore Supplier Delivered Quantity; (b) Retailer Expected Profit; (c) Offshore Supplier Expected Profit; and (d) Supply Chain Expected Profit .....	107

## List of Tables

Table 2.1. Risk Identification.....	13
Table 2.2. Integration Conditions of Operations and Finance .....	16
Table 2.3. Categorization of Operational Hedging.....	21
Table 2.4. Categorization of Financial Flexibility.....	22
Table 2.5. Overview of Relationship Analysis.....	24
Table 2.6. Overview of Approach Choice .....	27
Table 2.7. Link of Relationship Analysis and Approach Choice .....	29
Table 3.1. Summary of the Literature on Integrated Operational Flexibility and Financial Hedging and New Contribution .....	35
Table 3.2. Summary of Notation and Assumptions .....	44
Table 3.3. Optimal Production Quantities in Stage 2 .....	48
Table 3.4. Capacity Shadow Prices in Stage 1.....	49
Table 3.5. Relative Effectiveness of Operational Flexibility and Financial Hedging .....	56
Table 3.6. Optimal Production Quantities: Switching Options Only.....	72
Table 3.7. List of Input Parameters .....	75
Table 4.1. Summary of Notation and Assumptions .....	84
Table 4.2. Relative Effectiveness of Pre-shipment Finance and Backup Production .....	104
Table 5.1. Summary of Supply Chain Models in Chapters 3 and 4.....	118

# Chapter 1

## Introduction

### 1.1 Motivation

The dynamic global economy exposes companies to multiple and high magnitude risks. The set of the normal business risks is expanded as companies are now often facing unfamiliar and uncertain demand and supply markets, currency exchange rate fluctuations and working capital constraints. Recognizing the multifunctional nature of the challenges faced by business, this growing area of Operations Management and Finance Interface, fully embraces a multidisciplinary approach that exploits recent development in supply chain management, finance theory, and operations research to manage the complex, highly interacting, and diverse global supply chain risks. In this arena, integrated operations and finance management plays a key role in providing the physical and financial network structure for developing, processing and delivering the company's value-adding activities.

Our work on the interfaces of operations and finance is driven by both academic research and industry practice. In the supply chain and operations management literature, a recent research stream addresses the joint operational flexibility and financial hedging and explores the value of integrated risk management. For example, a focused issue of *Management Science* (Dec. 2011) compiles a number of state-of-the-art researches on Interfaces of Operations and Finance; while a special issue of *International Journal of Production Economics* (Nov. 2011) focuses on Enterprise Risk Management (ERM) in Operations. Moreover, research proceedings on the Interface of Finance, Operations, and Risk Management (iFORM) are presented in a special interest group conference of the *Manufacturing and Service Operations Management* (MSOM) society. In addition, Kouvelis et al. (2012a) provide a textbook-level exposition on the integrated risk management in global supply chains; while Sodhi and Tang (2012) present systematically the concepts, frameworks and strategies in Supply Chain Risk Management (SCRM). The researchers who investigate the interface between the two fields propose conditions under which integrating both functions leads to higher value creation; as well as approaches to joint operational hedging and financial flexibility under intricate risk exposures (Birge et al. 2007).

In the meanwhile, industrial practice calls for the integrated operational and financial approach to risk management. For instance, a 2010 survey of Global Supply Chain Trends 2010–2012 by the consulting company PRTM shows “the end-to-end risk management” as one of the major supply chain trends: between 65% and 75% of the respondents list end-to-end supply chain practices at the top of their agenda, which calls for the joint operational and financial risk management (PRTM 2010). Moreover, citing a negative effect of exchange rate amounting to €2.4 billion from 2005 to 2009, the BMW group has adopted the joint operational diversification (or “natural hedge”) with 44% overseas production and financial hedging (Xu and Liu 2012). Another investigation conducted by a number of European purchasing institutes on supply risk management finds that practice is characterized by sub-optimization—69% have commodity risk coordinated by purchasing and 65% economic risk by finance. Only approximately 30% have a joint approach, which further emphasizes the importance of integrating procurement, finance, and operations to mitigate supplier risks (Valcon et al. 2011).

## 1.2 Research Scope

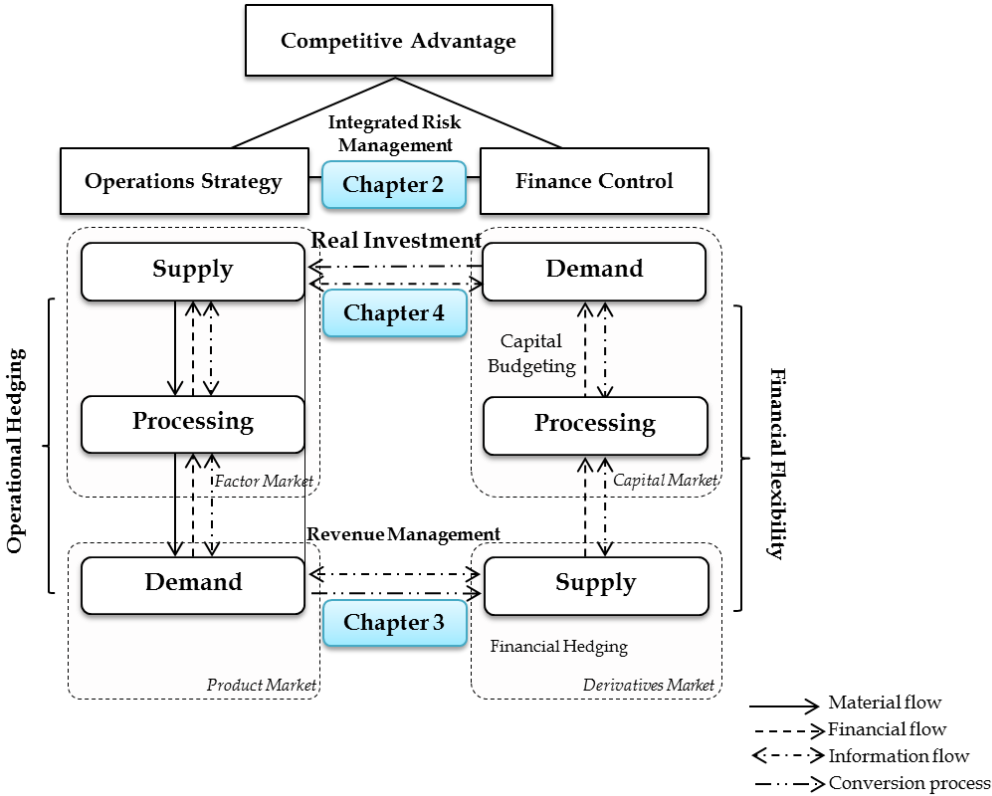
This dissertation consists of three essays addressing the interface of operations and finance in global supply chains. Chapter 2 reviews the OR models that integrate operational hedging and financial flexibility in risk management. We introduce a closed-loop view (Figure 1.1) of two supply–demand matching processes under uncertainty to link operations and finance. In this setting, two conversion processes—revenue management and real investment—bridge physical and financial supply chains and close the loop, which are analytically examined in Chapters 3 and 4, respectively. A roadmap to integrated risk management including categorizations of operational strategies and financial instruments is proposed in Chapter 2. It is shown that: first, zero interaction effects (separation) of operations and finance lead to decentralization. Second, operational hedging and financial flexibility should be centralized even if they are partial substitutes.

Chapter 3 considers a risk-averse multinational corporation that manages exchange rate risk and supply–demand mismatches via (i) ex ante capacity investment and financial hedging and (ii) ex post backup production and switching options. Our mean-conditional value-at-risk (CVaR) analysis establishes three main results. First, backup production and switching options are complements (resp., substitutes) when used to fulfill foreign (resp., domestic)



demand. Operational flexibility and financial hedging are substitutes for reducing risk, but for enhancing profit they are complements—provided that financial hedging enlarges the feasible set of capacity portfolios by relaxing the CVaR constraint. Hence information exchange between operations and finance is crucial. Second, given operational flexibility, financial hedging is viable only under rare and extreme exchange rates; otherwise, real options are relatively more successful at generating above-target expected profits. Overall, the integration of these two strategies can create significant value because its expected utility is strictly greater than that of either one. Third, switching options and financial hedging are more effective at reducing risk in exchange rate volatility than in demand volatility, though the risk reduction effect of hedging is decreasing in both types of volatility. For risk reduction, operational flexibility is more effective than financial hedging.

Figure 1.1. Research Topology



In Chapter 4, we examine a supply chain consisting of one retailer and two suppliers, where both the retailer and the offshore supplier may be capital-constrained. To manage supplier financial distress and supply–demand mismatch risk, the retailer chooses among three strategies: purchase order finance (POF), advance payment discount (APD), and dual sourcing via a backup supplier. When the retailer chooses either POF or APD only, the

unique equilibrium is POF (resp., APD) if her internal asset level is below a certain threshold (resp., otherwise). The POF equilibrium region is decreasing in demand variability and in the retailer's internal capital level. POF can alleviate the credit risk of an offshore supplier by outsourcing capital from a creditor; in contrast, APD may coordinate the channel by transferring financial flow from voluntary to binding positions within the supply chain. When both POF and APD are employed, there is a "pecking order" as regards pre-shipment finance: the retailer first uses internal capital to fund APD and then may adopt POF to finance the offshore supplier under certain conditions. For the retailer, pre-shipment finance and capacity hedging (via a backup supplier) can be complements or partial substitutes depending on demand variability. Overall, the expected profit from integrating pre-shipment finance and backup supply is strictly greater than that from following any single strategy.

## Chapter 2

### The Interface of Operations and Finance: State of The Art<sup>1</sup>

#### 2.1 Introduction

Operations and finance are two sides of the same coin. Material needs capital, and sales generate cash (Li et al. 2013). Recently, a survey of global manufacturing outlook “Growth while managing volatility” (KPMG 2011a) calls for a rigorous approach to risk, cost, and demand management. Moreover, Henkel (a European home care manufacturer) has enacted a cross-divisional continuous improvement to maintain its financial flexibility with a cash focus, while optimizing its global manufacturing footprint (Rorsted and Knobel 2012). Meanwhile, a growing body of literature has focused on the interface between operations and finance. This research proposes conditions under which integrating both functions within an enterprise and across a supply chain—which are the aims of enterprise risk management (ERM) and supply chain risk management (SCRM), respectively—leads to higher value creation; it also proposes ways to approach both operational hedging and financial flexibility under intricate risk exposures (Birge et al. 2007).

Motivated by the emerging literature on the interface of operations, finance, and risk management, this chapter attempts to provide an overview of the OR models that integrate operational hedging and financial flexibility in risk management. A number of interesting research questions may arise from literature and practice: (i) under which (generic) conditions should a company adopt integrated risk management of operations and finance? (ii) How to categorize operational hedging and financial flexibility strategies/instruments? (iii) How are the decision criteria for relationship analysis (complements/substitutes) and approach choice (centralization/decentralization) connected?

To answer these questions, we mainly review the analytical works on integrated risk management<sup>2</sup> of operational hedging and financial flexibility from our personal (and perhaps biased) perspective. We shall articulate a closed-loop view of two supply – demand matching processes under endogenous and exogenous uncertainties to integrate operations

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<sup>1</sup> The content of Chapter 2 is based on Zhao and Huchzermeier (2013).

<sup>2</sup> Provided the vast literature on the interface of operations management and finance, we restrict our attention to recent and representative analyses on integrated risk management to provide an overview.

and finance in an enterprise and across a supply chain. A roadmap of integrated risk management is proposed, which incorporates continuous review and improvement as well as classifications of operational strategies and financial instruments. Based on the existing literature, we conclude that: (i) zero interaction effects (separation) of operations and finance lead to decentralization. (ii) Operational hedging and financial flexibility should be centralized even if they are *partial* substitutes.

The research on integrated operational hedging and financial flexibility<sup>3</sup> is closest to our work. Global supply chain management has focused on the integration of production flexibility and currency hedging. Mello et al. (1995) consider the optimal financial hedging of a multinational corporation with production flexibility under exchange rate uncertainty. Chowdhry and Howe (1999) study the value of financial hedging and operational flexibility in the presence of exchange rate and demand risk. Hommel (2003) extends that model to joint operational flexibility/diversification and financial hedging in a multinational context. Ding et al. (2007) explore how a risk-averse multinational firm hedges both operationally and financially under uncertain demand and exchange rates. Zhu and Kapuscinski (2011) compare the benefits of operational and financial hedging both separately and jointly in a dynamic finite-capacity newsvendor setting.

The relationship of operational hedging and financial flexibility<sup>4</sup> has also been analyzed by examining their interaction effects in value creation. Chod et al. (2010) investigate a value-maximizing firm that hedges demand risk by combining product or postponement flexibility with financial hedging. Dong and Tomlin (2012) examine how a firm manages disruption risk via inventory mitigation, emergency sourcing, and insurance. The interdependence of operations strategy and (financial) market imperfections provides another incentive for joint management of financing and operations. Boyabatli and Toktay (2011) analyze how a budget-constrained monopolist decides on product flexibility and capacity/borrowing level under demand uncertainty, and Gamba and Triantis (2014) present a dynamic structural model in which a value-maximizing firm incorporates operational flexibility, liquidity management, and financial hedging. Altogether, the scope of operational strategies and

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<sup>3</sup> For textbook expositions of integrated risk management in the fields of operations management, international finance, and strategic management, please refer to Sodhi and Tang (2012, chap. 8), Shapiro (2003, chap. 11), and Lessard and Nohria (1990), respectively.

<sup>4</sup> For empirical research on the relationship between operational and financial hedging, please see Allayannis et al. (2001) and Kim et al. (2006), among others.

financial instruments analyzed by this integration literature contains only a subset of strategy – instrument portfolios proposed in the research on operational hedging or financial flexibility. Next we review these two streams of literature, respectively.

Operational hedging (or flexibility) in global supply chain management under uncertainty is an emerging field. One active focus is identifying the optimal global supply chain network configuration under exchange rate uncertainty and/or demand uncertainty. Huchzermeier and Cohen (1996) present a classical modeling perspective and show the value of operational hedging (via excess capacity and switching options) in global supply chains for mitigating currency risk. Dasu and Li (1997) examine the allocation of production among plants in a multifacility network when costs are influenced by exchange rates. Kouvelis (1999) considers global sourcing flexibility in a multisupplier setting under price and exchange rate uncertainty. Kazaz et al. (2005) demonstrate the expected benefits from production hedging via excess capacity and postponed allocation for a profit-maximizing firm under exchange rate uncertainty. Van Mieghem (2007) explains how a risk-averse firm can configure newsvendor networks through resource diversification, sharing, and flexibility to hedge demand risk.

One substream of research concentrates on operational hedging and diversification under supply uncertainty. Tomlin (2006) investigates the value of dual-sourcing, inventory mitigation, and contingent rerouting in a two-supplier supply chain with disruption risk. Dada et al. (2007) formulate the newsvendor's supplier selection problem by applying a general model of supplier reliability. Wang et al. (2010) explore the benefits of dual sourcing and supplier reliability improvement under random capacity or yield. Sting and Huchzermeier (2012) focus on setting up responsive capacity via dual-sourcing under correlated supply and demand uncertainty. For overviews of operational hedging (or real options) in global supply chains, please see Cohen and Huchzermeier (1999), Boyabatli and Toktay (2004), and Van Mieghem (2012). The works cited here yield an extensive portfolio of operational strategies for integrated risk management.

The research on joint finance and operations management has been expanding rapidly. Financial hedging of operational risk is explored by Gaur and Seshadri (2005), who study a risk-averse newsvendor that adopts financial hedging of inventory risk when demand is correlated with asset price. Caldentey and Haugh (2006) explore the problem further by

dynamically hedging corporate profits that are correlated with financial market returns under different informational structures. Chen et al. (2007) investigate risk aversion and financial hedging through security trading in multiperiod inventory and pricing models. Kouvelis et al. (2012b) propose an integrated risk management that incorporates long-term supply contract, short-term trading, and financial hedging of storable commodities.

Supply chain finance has addressed how material flows under budget constraints can be financed to achieve channel coordination. Dada and Hu (2008) consider the inventory procurement of a capital-constrained newsvendor borrowing from a bank that sets interest rate to coordinate the channel in Stackelberg equilibrium. Caldentey and Haugh (2009) examine the performance of a supply chain consisting of a producer and a budget-constrained retailer. Lai et al. (2009) consider short-term bank financing when bankruptcy costs exist in a capital-constrained supply chain. Kouvelis and Zhao (2012) and Yang and Birge (2013) analyze the role of trade credit in channel coordination and inventory financing.

The conditions under which it is optimal to centralize or decentralize operational and financing decisions<sup>5</sup> have also been examined in various settings. Buzacott and Zhang (2004) focus on a newsvendor model to study joint financing and inventory management. Babich and Sobel (2004) jointly optimize capacity-expansion, production and loan financing decisions to maximize a firm's expected present value of initial public offering (IPO). Babich (2010) describes conditions under which a manufacturer can render its capacity ordering independently of supplier subsidies in a dynamic and stochastic setting. Alan and Gaur (2012) characterize the order quantity, probability of bankruptcy, and capital structure in equilibrium for an asset-based lender and a business owner. Li et al. (2013) consider a capital constrained manufacturer that optimizes its long-term dividends in a multiperiod dynamic newsvendor model. This research offers an extensive portfolio of financial instruments for integrated risk management.

Various frameworks for ERM and SCRM have been developed in literature, respectively. Enterprise risk management focuses on the cross-functional integration of a firm's operational and financial risk management. Miller (1992) categorizes uncertainties and outlines financial and operational strategies in international business. Froot et al. (1993, 1994)

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<sup>5</sup> For more finance papers that focus on joint financing and operational decisions, please see, e.g., Childs et al. (2005), Mello and Parsons (2000), and Mauer and Triantis (1994).

illustrate how financial hedging increases firm value by ensuring internal funds for investment opportunities under costly external financing. Meulbroek (2002) integrates firm wide operational strategies, financial instruments, and capital structure adjustments to manage total risk exposure. Triantis (2005) explains the procedure and aspects of synthesizing real options and financial hedging. Nocco and Stulz (2006) discuss the value and implementation of ERM in corporate finance. Tripp et al. (2008) review the existing ERM frameworks from a general insurance actuarial perspective.

SCRM have proposed cross-organizational approaches to enhance the agility and resilience of supply chains. Tang (2006) reviews perspectives on risk management in supply chains. Ritchie and Brindley (2007) propose a framework for managing risk and evaluating performance in supply chains. Tang and Tomlin (2008) highlight and quantify the value of operational flexibility in SCRM. Blome and Schoenherr (2011) investigate supply risk management in financial crises and use case studies to establish a link between ERM and SCRM. Nevertheless, the research on ERM and SCRM are mostly disconnected. Hence our work proposes a closed-loop view of integrated risk management, in which ERM and SCRM can be linked by cross-functional and cross-organizational integration of operations and finance.

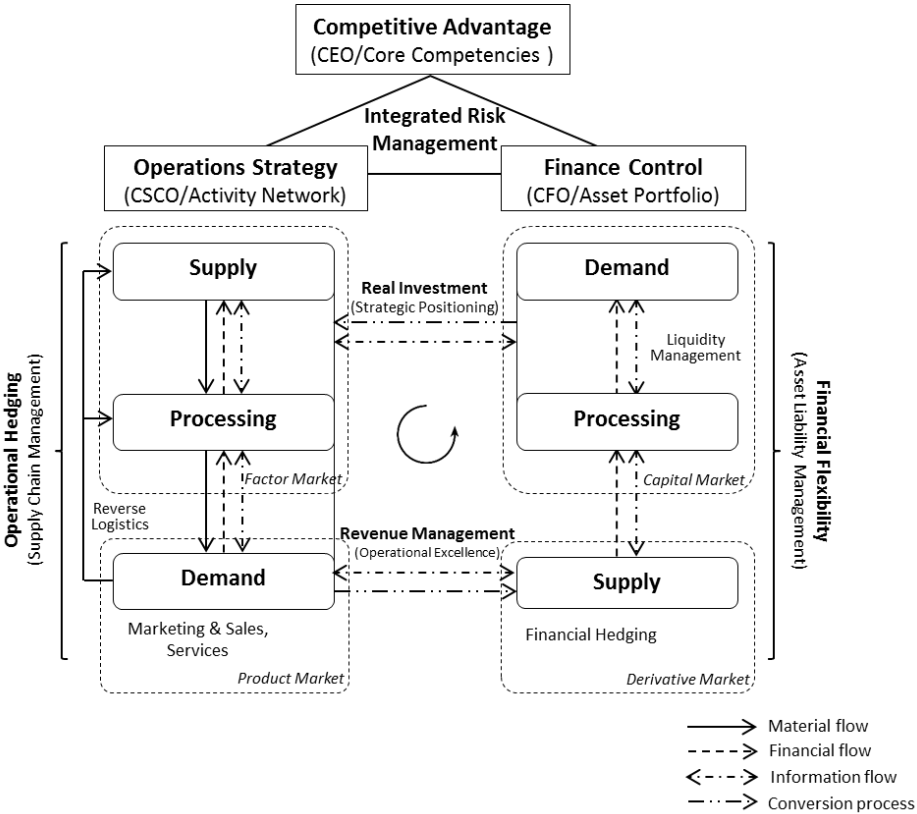
The remainder of the chapter is organized as follows. In Section 2.2, we introduce a closed-loop view and a roadmap of integrated risk management. Sections 2.3–2.6 critically review the literature on the interface of operations and finance following a four-step process: identify operational and financial risks, specify (generic) integration conditions, select operational hedging and financial flexibility, and integrated optimization. We conclude in Section 2.7 by discussing possible directions for future research.

## **2.2 A Roadmap to Integrated Risk Management**

There are direct links between operations and finance. Operational strategy sets the backbone of financial performance by revenue generation, and finance supports real investment in operations. This chapter adopts a closed-loop view (Figure 2.1), which connects two supply–demand matching processes under uncertainty in a cycle of material, financial, and information flows. These three types of resource flow can be called the Three Bs: boxes, bucks, and bytes. Operations strategy matches supply with demand of material

flows in an activity network (physical supply chain) to achieve profit optimization (Cachon and Terwiesch 2011). Meanwhile, finance control enables a better alignment between supply and demand of monetary flows in an asset portfolio (financial supply chain) to fund value-enhancing investments (Froot et al. 1994). In addition, managing information flows can improve the supply–demand matching processes of material and financial flows. Two conversion processes—real investment and revenue management—bridge physical and financial supply chains and close the loop. *Real investment* in infrastructure, human resources, technology, R&D, procurement, marketing, and growth can transform capital into material to enhance a firm’s strategic positioning (Porter 1985, 1996); *revenue management* converts product demand into cash flow via sales and services to achieve operational excellence. Various endogenous and exogenous uncertainties (see Section 2.3) may lead to mismatches in the closed-loop. Hence, a firm can adopt both operational hedging and financial flexibility to match supply with demand and generate a “virtuous” cycle (marked in Figure 2.1 by counterclockwise arrow) of operational excellence and strategic positioning. In other words, integrating operations and finance in risk management can improve a firm’s core competencies to create a sustainable competitive advantage (Porter 1985) by boosting the “metabolism” of the closed-loop.

Figure 2.1. Closed-loop View of Operations and Finance

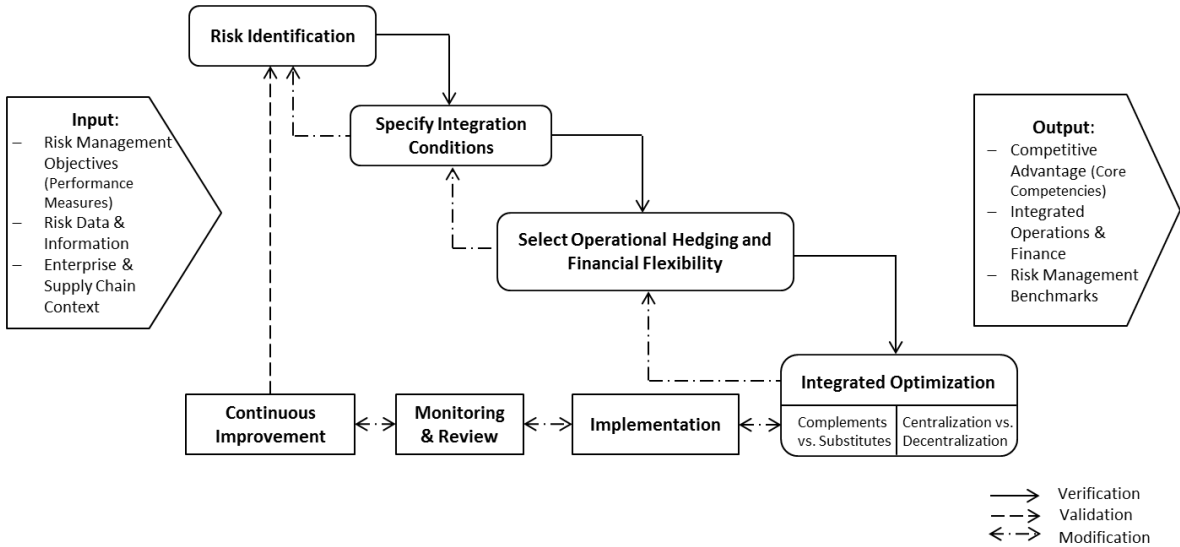




The closed-loop view of operations and finance can be interpreted from two perspectives. On the one hand, resources flow across operational and financial units in an enterprise; on the other hand, resources flow across operational and financial partners in a supply chain. The former view can lead to *enterprise risk management*, or “the ongoing proactive process of adopting a holistic approach across the enterprise to all the uncertainty which may affect either positively or negatively the achievement of its key purposes and objectives, leading to action to achieve greater business robustness and flexibility, efficient risk taking and an appropriate risk-reward balance” (ICE/FIA 2009). In contrast, the latter view can result in *supply chain risk management*, i.e., “the management of supply chain risks through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity” (Tang 2006). In this chapter, we define *integrated risk management* as “the joint analysis, synthesis, and optimization of operational and financial risk management across functional units in an enterprise and across supply chain partners”. Here, *integration* refers to (i) the joint identification/analysis of operational and financial risks; (ii) the synthesis of operations strategy and financial control; and (iii) the unification of value-based management (flexibility/growth) and risk management (hedging/mitigation).

Integrated risk management is traditionally the domain of a firm’s CEO and CFO (Buehler et al. 2008). Recently, a SCM World survey (Lee et al. 2012) reports that chief supply chain officer (CSCO) positions have been created and have become an integral part of corporate risk management; which can lead to a C-level trilateral interaction (see Figure 2.2) in joint optimization of operations and finance to enhance the firm’s competitive advantage.

Figure 2.2. A Roadmap to Integrated Risk Management



For the purpose of this review, we propose a (logical) roadmap to integrated risk management (Figure 2.2) with continuous review and improvement, which also illustrates the connections of the remaining sections. Integrated risk management starts by defining risk management objectives in enterprise and supply chain context. Toward that end, along with data collection and information updates, several performance measures can be employed—for example, organic sales growth, adjusted earnings before interest and taxes (EBIT) margin, and adjusted earnings per share (EPS) growth (Rorsted and Knobel 2012). Sections 2.3–2.6 review the relevant literature taking four steps: (i) identify operational and financial risks, (ii) specify (generic) integration conditions, (iii) select operational hedging and financial flexibility, and (iv) integrated optimization with relationship analysis (complements/substitutes) and approach choice (centralization/decentralization). *Implementation* carries out the integrated risk management in the firm’s strategies, tactics, and operations. Responsibilities and performance measures at the corporate, business unit, and functional level are specified to *monitor and review* integrated risk management. *Continuous improvement* is a top-down and bottom-up iterative approach that uses verification, validation, and modification to ensure efficiency and effectiveness of risk management. *Verification* adjusts the realized risk management process in accordance with risk management objectives and specifications; *validation* ensures the consistency with updated inputs; and *modification* enhances previous procedures in response to feedback from subsequent steps. Integrated risk management can result in competitive advantage, as the firm’s core competencies are optimized by the integration of operations and finance, as well as established risk management benchmarks.

## **2.3 Risk Identification**

The objectives of risk identification are to identify, categorize, and document the causes and types of risk. In this chapter, we concentrate on two major types of risk that may affect corporate performance: operational risk and financial risk (Table 2.1). *Operational risk* refers to uncertain time, quantity, and profit in supply, processing, and demand management; *financial risk* is uncertain payoff that may deviate from the expected outcome because of exogenous and endogenous factors. *Exogenous* financial risk results from the uncertain prices due to volatile external economic and financial variables (e.g., financial market risk); *endogenous* financial risk includes credit and liquidity risks, which are uncertainties in a firm’s internal financing that stem from market imperfections.

**Table 2.1. Risk Identification**

Operational Risk		Financial Risk	
Supply risk	Supply disruption risk <sup>iii</sup>	Endogenous financial risk <sup>i</sup>	Budget constraints
	Uncertain supply capacity		Financial distress costs
	Supply yield risk		Bankruptcy risk
	Uncertain input prices		Tax deductions
	Uncertain lead times		External debt costs
Processing risk	Processing disruption risk <sup>iii</sup>		Agency and transaction costs
	Uncertain processing capacity		
	Technological risk		
	Processing yield risk		
	Uncertain processing costs		
Demand risk	Product demand risk	Exogenous financial risk <sup>ii</sup>	Interest rate risk
	Market demand risk		Exchange rate uncertainty <sup>iii</sup>
	Uncertain output prices		Asset price uncertainty
	Uncertain service cost		Commodity price risk <sup>iii</sup>
	Marketing and sales risks		Derivative price uncertainty
	Distribution risk		

- i. Financial constraints on operations in real investment that are caused by endogenous financial risk and result in supply/processing risks.
- ii. Correlation between demand risk and exogenous financial risk in revenue management.
- iii. Alternative risk mitigation via operational hedging of financial risk and/or financial hedging of operational risk.

Interdependence among operational and financial risks provides incentives for firms to employ integrated risk management. Three types of interdependence between operations and finance (marked in Table 2.1 by superscripts i, ii, and iii, respectively) can be detected: (i) financial constraints on operations, (ii) correlation between operational and financial risks, and (iii) alternative risk mitigation. The first two types are embedded in the two conversion processes of material and financial flows in the closed-loop (see Figure 2.1): real investment and revenue management, while the third type lies in the possibilities of mitigating financial risk operationally and/or hedging operational risk financially.

*Financial constraints on operations* due to market imperfections connect operations and finance in real investment, which may cause bottlenecks in the process of transforming capital into material supply. Given market imperfections—including budget constraints and costs associated with taxes, financial distress, bankruptcy, and external debt—a firm may choose suboptimal operational strategies (e.g., underinvestment). Hence, financial hedging or liquidity management can enable operations management to maximize firm value by addressing these restrictions. For instance, capital constraints on newsvendor procurement can be alleviated by bank loans that achieve channel coordination (Dada and Hu 2008).

Financial distress and bankruptcy risk can be mitigated by joint liquidity management and operational hedging (Gamba and Triantis 2014). External loan financing and production technology decisions can be jointly optimized with respect to budget constraints and a fixed bankruptcy cost (Boyabatli and Toktay 2011).

*Correlation between operational and financial risks* may lead to a stronger link between operations and finance in revenue management, which affects the volatility in product demand and cash flow. The correlation between demand distribution and an economic or financial variable can result in joint operational and financial hedging under demand uncertainty. For example, the correlated demand uncertainty with asset prices enables financial hedging of inventory risk, where the magnitude of correlation determines the reduction in profit variance due to hedging (Gaur and Seshadri 2005). Another type of correlation can be detected between operational price risk and economic or financial variables. Price risk can be operational and/or financial because it may influence either type of costs. *Operational* price risk refers to uncertain input and output prices that influence operational costs, whereas *financial* price risk is the price uncertainty of assets and derivatives in financial markets. The dependence of input price on financial market movements can lead to joint procurement and financial hedging (Caldentey and Haugh 2009).

*Alternative risk mitigation* consists of the operational hedging of financial risk and/or financial hedging of operational risk. In the first place, financial risk—for instance, exchange rate uncertainty—can be hedged both operationally via real options and financially by currency derivatives in global supply chains (Ding et al. 2007). Second, operational risk that is commonly verifiable can be mitigated financially by insurance, which argues for joint insurance and operations management. Disruption risk can be managed by incorporating contingent supply, inventory, and business interruption insurance (Dong and Tomlin 2012). Third, price uncertainty that is both operational and financial motivates integrated risk management; for example, commodity price risk can be managed by long- and short-term contracting and by financial hedging via commodity derivatives (Kouvelis et al. 2012b).

## 2.4 Specify Integration Conditions: When to Integrate – or Not

Based on risk identification, a firm can consider integrating operational hedging and financial flexibility. Hence, multiple dimensions (feasibility, trade-offs, and structure issues, see Table 2.2) are examined to specify the (generic) conditions under which it is appropriate to integrate operations and finance.

To start with, a firm can jointly select operational strategies and financial instruments by considering *feasibility* issues, i.e., source of uncertainty, timing, and availability. *Source of uncertainty* determines the choice of operational hedging and financial flexibility, and the type of interdependence between operational and financial risks (see Section 2.3) can affect the feasibility of a strategy – instrument portfolio. Operational strategy is more effective in mitigating operational or competitive risks, whereas financial instruments can provide a better hedge against financial and transactional risks. For instance, the presence of uncertain demand and exchange rates can lead to integrated production flexibility and financial hedging (Chowdhry and Howe 1999). Market risk can be fully hedged even in a partially complete financial market; however, demand uncertainty is private risk that can be hedged only by inventory management, not by financial instruments (Chen et al. 2007). Similar results are derived by comparing the relative effectiveness of operational and financial hedging in mitigating demand and currency risks (Ding et al. 2007).

*Timing* of operational and financial decisions can affect the feasibility of integrated risk management. Operational flexibility takes time to develop, whereas shorter maturities allow financial hedging to be implemented in a timelier manner. Thus, a financial instrument can serve as a buffer before implementing the operational strategies under risk exposure (Hommel 2003). Integrated risk management typically requires that the planning horizons of operational flexibility and financial hedging be aligned; this can be accomplished by dynamic financial hedging in each period within long-term operational planning (Zhu and Kapuscinski 2011). The type of interdependence between operational and financial risks (see Table 2.1) can influence the relative timing of operational and financial decisions: (i) financial constraints on operations in real investment can result in an ex ante or simultaneous financing via cash or supply chain instruments (see Table 2.4), such as bank loan, trade credit, and factoring (Yang and Birge 2013). (ii) Correlation of operational and financial risks in revenue management typically requires ex post or simultaneous financial hedging (Ding et al.

2007). (iii) Alternative risk mitigation can result in financial decisions that are ex ante in the case of business interruption insurance (Dong and Tomlin 2012).

**Table 2.2. Integration Conditions of Operations and Finance**

Category	Dimension	Operational Hedging	Financial Flexibility	Integration Conditions <sup>a</sup>	References
Feasibility	Source of uncertainty	More effective in operational/competitive risk mitigation	More effective to manage financial/transactional risks	Detected interdependence <sup>b</sup> between operations and finance	Chowdhry and Howe (1999), Chen et al. (2007), Ding et al. (2007)
	Timing	Long-term	Short-term	Alignment of planning horizons; timing based on detected interdependence	Hommel (2003), Zhu and Kapuscinski (2011), Yang and Birge (2013)
	Availability	Determined by capacity investment	Dependent on financial market (e.g., derivatives for major currencies)	Both operational and financial hedging are feasible	Boyabatli and Toktay (2011), Huchzermeier and Cohen (1996), Alan and Gaur (2012)
Trade-offs	Value	$\mathbb{E}[V] > 0$	$\mathbb{E}[V] > 0$ (market imperfections/value max.), $\mathbb{E}[V] = 0$ (arbitrage-free)	Neither operational nor financial strategy achieves value maximization	Triantis (2005), Stulz (1996)
	Risk	Increase or decrease	Decrease	Neither operational nor financial strategy achieves risk (e.g., variance) minimization	Mello et al. (1995), Ding et al. (2007), Gamba and Triantis (2014)
	Cost	Costly, may decrease in time and volatility	Less costly, may increase in time and volatility	Integration is cost efficient	Huchzermeier and Cohen (1996), Triantis (2005)
Structure	Organizational structure	Operational unit	Financial department	Centralization benefits dominate coordination costs	Kleindorfer and Saad (2005), Glaum (2005)
	Supply chain structure	Competitive positions, (de)centralization	Decentralized hedging, competitive positions	Operational and financial resources available to supply chain partners	Froot et al. (1994), Kouvelis and Zhao (2012)
	Information structure	Supply chain information, market (price) information	Market information, enterprise information	Aligned incentives; optimality depends on information structure	Lee et al. (1997), Caldentey and Haugh (2006), Alan and Gaur (2012)
	Capital structure	Feasible strategy set subject to capital structure	Decreases financial distress, increases debt capacity	Optimality depends on capital structure	Mello et al. (1995), Stulz (1996), Gamba and Triantis (2014)

a. These can be model-specific and/or case-specific. b. See Section 2.3 for details.

*Availability* of a strategy – instrument portfolio can alter the feasible set of risk management mechanisms. For instance, operational hedging depends on real investments in technology choices: product flexibility requires initial investment in dedicated or flexible production technologies (Boyabatli and Toktay 2011). Note that financial hedging may be restricted in that, for example, currency derivatives are available only for major currencies (Huchzermeier and Cohen 1996). Moreover, debt financing may be subject to loan limits, such as those inherent in asset-based lending (Alan and Gaur 2012).

Operational hedging and financial flexibility can be optimized by managing the *trade-offs* among value, risk, and cost effects. The expected *value* (denoted in Table 2.3 as  $E[V]$ ) of an operational strategy is typically positive because real options can limit downside risks while exploring upside potential (Triantis 2005). The value-enhancing effects of financial hedging depend largely on market assumptions and hedging objectives. In an efficient (arbitrage-free) market, the expected value of financial hedging is zero; this is known as a “self-financing” trading strategy. Under market imperfections (e.g., budget constraints and the costs associated with taxes, financial distress, bankruptcy, and external debt), the expected value of financial hedging can be positive if there are cost-reduction effects. In addition, the objective of financial hedging is value maximizing when the aim is to avoid “lower-tail outcomes” while preserving upside potential (Stulz 1996).

A closely related issue is the *risk* mitigation effect of operational strategies and financial instruments under risk aversion. Global supply chain network options may exploit the cash flow volatility (Huchzermeier and Cohen 1996); while allocation option can decrease the unit profit variance in global production (Ding et al. 2007). The variance effects of production flexibility reflect the extent of correlation of output price and exchange rate; thus, positive (negative) correlation leads to decreased (increased) variance (Mello et al. 1995). The variance reduction effects of financial hedging depend on the firm’s objective. In an efficient market, financial hedging can be used to minimize volatility. In the presence of market imperfections, the objective of hedging can be either to maximize value or to minimize variance (Gamba and Triantis 2014).

*Cost* of a risk management strategy/instrument varies as a function of availability, time, and volatility. Operational flexibility can be more costly because it requires an initial investment. For example, production flexibility depends on investments in multicountry facilities, and multisourcing flexibility depends on switching costs and development of the supplier base. In contrast, financial hedging is less costly because of lower or insignificant transaction costs. One must bear in mind that the costs of operational and financial hedging can evolve over time. Depending on the type of options and the type of hedging, the cost of real options may decrease over time (e.g., the switching costs can be spread across additional periods), whereas the cost of financial hedging may increase as the time horizon extends (Huchzermeier and Cohen 1996). Finally, greater volatility may result in more cost-effective operational flexibility and increase the cost of financial hedging; the reason is that the cost of

production capacity is less sensitive to volatility than is the cost of financial derivatives (Triantis 2005).

The third category in Table 2.2 illustrates how integrated risk management incorporates the mutual adjustment of strategy – instrument portfolio and various structures: organizational, supply chain, information, and capital. On the one hand, the selected strategy – instrument portfolio can be tailored to reflect these structures; on the other hand, firms that are flexible enough to adapt a given structure can enhance the effectiveness of their strategy – instrument portfolio. *Organizational structure* in an enterprise plays an important role in mitigating risk, because the various risk exposures must be addressed by cross-functional centralization, collaboration, and coordination (the Three Cs) in ERM. In addition to avoiding suboptimal solutions by balancing the interaction of operations and finance, integration can also lead to synergistic benefits – for example, economies of scale can arise from a firm’s (cross-functional) overall hedging positions to avoid costly non-cooperative strategies (Kleindorfer and Saad 2005). However, integrated risk management involves costs stemming from the coordination of local or functional units with regard to legal and operational restrictions (Glaum 2005). The firm’s optimal structure thus depends on a trade-off between the benefits of centralization and the costs of coordination.

*Supply chain structure* determines not only a firm’s competitive position but also its exposure to the risks entailed by cooperating with other chain members; hence this structure can affect the optimality of integrated risk management. The Three Cs across supply chain partners are also required for successful SCRM. For instance, a decentralized supply chain with optimal financing and contracting under capital constraints can be coordinated via trade credit and bank financing (Kouvelis and Zhao 2012). At the same time, a firm’s competitive position can influence its optimal risk management strategy. Firms need not mimic the risk mitigation strategies of their rivals. If a competitor’s weakness (due, e.g., to insufficient hedging) reduces the likelihood of industry overcapacity, then the benefits of investing in foreign countries may increase; this, in turn, incentivizes the firm to hedge more via currency derivatives (Froot et al. 1994).

*Information structures* in the supply chain, financial markets and an enterprise can alter the optimal strategies of integrated risk management. Information asymmetry among operational and financial partners in supply chain naturally affects the coordinated



mitigation of risk. Information sharing may reduce the bullwhip effects and thus help to match supply with demand of material flows (Lee et al. 1997); in a financial supply chain, information asymmetry effects can be ameliorated by the design of financing mechanisms. For instance, asset-based lending can be adopted to reduce information distortion along the financial chain (Alan and Gaur 2012). We remark that a financial market's information structure can shape the optimality of joint operational and financial hedging. Complete versus partial information in financial markets yields different solutions to joint newsvendor procurement and financial hedging (Caldentey and Haugh 2006). Finally, the enterprise information structure (with respect to managers and shareholders) is a key concern of capital structure theories; that concern has spawned such notions as "separation property", "static trade-off", and "pecking order" (see Section 2.6.2).

*Capital structure* can determine the feasibility of operational strategies and financial instruments in the face of shareholder equity concerns, thereby affecting the optimality of integrated risk management. For instance, the liability structure of a multinational firm shapes the interaction between production flexibility and financial hedging under agency costs of debt and bankruptcy risk. Greater flexibility reduces the number of hedging contracts needed for a given debt level but increases that number if the leverage ratio is fixed (Mello et al. 1995). Since risk management can be viewed as a substitute for equity capital, it increases the firm's debt capacity under financial distress (Stulz 1996). The choice of capital structure is affected by whether the objective is to maximize firm value or equity value – as is the optimality of operations, hedging, and liquidity management (Gamba and Triantis 2014).

## **2.5 Select Operational Hedging and Financial Flexibility**

Once the (generic) integration conditions are aligned, a firm can proceed to jointly select its portfolio of operations and finance. Given the sheer variety of operational strategies and financial instruments, we categorize operational hedging and financial flexibility to facilitate the firm's portfolio selection. *Operational flexibility* typically adapts the type, timing, and quantity of the material flows in an activity network contingent on realizations of uncertainty. Operational hedging is defined as "real (compound) options that are exercised in response to demand, price and exchange rate contingencies faced by firms in a global supply chain context" (Huchzermeier 1991), where real options consist of the ability to "defer, expand, contract, abandon, or otherwise alter a project at different stages during its

useful operating life” (Trigeorgis 1993). Another definition of operational hedging is “mitigating risk by counterbalancing actions in the processing network that do not involve financial instruments...may include various types of processing flexibility” (Van Mieghem 2003). In this chapter, we use the terms operational hedging and operational flexibility interchangeably.

Adopting a process view, we present six categories of operational strategies for integrated risk management (Table 2.3). *Supply flexibility* incorporates multisourcing, contingent supply, backup supply, supplier improvement, and inventory mitigation to manage supply uncertainty. *Processing flexibility* includes production flexibility, product flexibility, modularization, and launch flexibility to match supply and demand of material flows. *Demand flexibility* uses demand shifting, allocation options, after-sales services, and entry/exit options to mitigate demand risk. *Network flexibility* accounts for how supply chain network options, network configuration, coordination options, integration options, and reverse logistics are used to optimize supply chain networks. *Timing flexibility*, which includes both advance flexibility and postponement flexibility, focuses on the time dimension of supply chain processes. Finally, our concept of *flexibility mix* integrates the preceding five flexibilities within a category or across categories.

Next we describe the categories of *financial flexibility*, which is “the ability of a firm to access and restructure its financing at a low cost” (Gamba and Triantis 2008). Financial flexibility enables monetary flows to be transferred across time, markets, and organizations from voluntary to binding conditions via the choice of financial instruments. A financial instrument is a contract that gives rise to a financial asset of one entity and a financial liability or equity instrument of another entity. Financial flexibility also incorporates recapitalization to match supply with demand of monetary flows and financial hedging of cash flow volatility, where financial hedging is “hedging that uses counterbalancing positions in financial derivative instruments” (Van Mieghem 2003) and a financial derivative is “an instrument whose value depends on, or is derived from, the value of another asset” (Hull 2012).

Distinguishing by valuation mechanisms, we illustrate three categories of financial instruments for integrated risk management (Table 2.4). A *cash instrument* is one whose value

**Table 2.3. Categorization of Operational Hedging**

Category	Operational strategy	Mechanism	Trade-offs	Reference
Supply flexibility	Multisourcing	Purchasing one product from multiple suppliers	Supplier diversification/ competition benefits vs. Setup costs	Kouvelis (1999), Babich et al. (2007), Dada et al. (2007)
	Contingent supply	Reserving the right (capacity) to purchase a certain number of units from a supplier by quantity-flexible contracts	Contingency benefits vs. Reservation costs	Tomlin (2006)
	Backup supply	Sourcing from an alternative internal (backup production) or external supply (backup supplier) in case of shortage/disruption	Marginal revenue vs. Unit supply cost	Yang et al. (2009), Sting and Huchzermeier (2010)
	Supplier improvement	Investing in suppliers to improve production processes	Improvement benefit vs. Investment costs	Wang et al. (2010)
	Inventory Mitigation	Holding inventory to fulfill demand under supply shortage/disruption	Expected prot vs. Holding costs	Tomlin (2006)
Processing flexibility	Production flexibility	Shifting production between plants in different countries	Flexibility benefits vs. Switching costs	Kazaz et al. (2005), Ding et al. (2007)
	Product flexibility	Producing multiple products from a common resource	Marginal value vs. Unit capacity cost	Van Mieghem (2007)
	Modularization	Assembling final product from a set of standardized components	Modularization value vs. Configuration cost	Ernst and Kamrad (2000)
	Launch flexibility	Introducing new products and product varieties	Launch benefits vs. R&D/marketing costs	Vickery et al. (1999)
Demand flexibility	Demand shifting	Shifting demand across time, markets and products	Flexibility value vs. Shifting costs	Tang (2006)
	Allocation option	Delivering products to markets cost effectively and responsively	Expected profit vs. Allocation costs	Ding et al. (2007)
	After-Sales service option	Providing customized services and maintenance after sales	Service benefits vs. Operating costs	Kim et al. (2007)
	Entry/exit options	Expanding new market; holding back products, stopping production, or exiting market	Flexibility value vs. Options costs	Van Mieghem and Dada (1999), Gamba and Triantis (2014)
Network flexibility	Supply chain network options	Designing supply chain network by altering supply, production and distribution options	Flexibility value vs. Switching costs.	Huchzermeier and Cohen(1996)
	Network configuration	Configuring networks that allow for multiple supply, products, processing, and storage points	Configuration benefits vs. Resource investment	Tomlin and Wang (2005), Van Mieghem (2007)
	Coordination option	Coordinating decisions among supply chain members via contracting or information sharing	Coordination value vs. Coordination cost	Chen(2003), Cachon (2003)
	Integration option	Integrating information, material, and financial flows of supply chain via merger/acquisition or IT	Integration benefits vs. Integration investment	Nagurney(2009), Rai et al. (2006)
	Reverse logistics	Operating a closed-loop supply chain over the product life cycle with value recovery from returns	Return benets vs. Operating costs	Guide and Van Wassenhove (2009)
Timing flexibility	Advance flexibility	Placing orders in advance using quick response, supply contracts, and/or dual sourcing from forward and spot markets	Flexible timing value vs. Implementation costs	Fisher and Raman(1996), Donohue (2000), Kouvelis et al. (2012b)
	Postponement flexibility	Postponing capacity, production, and/or pricing decisions after the realization of uncertainty		Lee(1996), Van Mieghem and Dada (1999)
Flexibility mix	Inter-category mix	Combining flexibilities across various categories	Flexibility value vs. Operational costs	Ernst and Kamrad (2000)
	Intra-category mix	Combining flexibilities within a certain category		Tomlin (2006)

**Table 2.4. Categorization of Financial Flexibility**

Category	Financial instrument	Mechanism	Trade-offs	Reference
Cash instruments	Loans	A certain amount of cash borrowed at a fixed interest rate from a creditor (e.g., asset-based or technology-specific)	Operational benefits vs. Interests payments	Boyabatlı and Toktay (2011), Alan and Gaur (2012)
	Stocks	A security that represents ownership in a firm and has claims on part of the firm's assets and earnings	Bid price vs. Ask price	Caldentey and Haugh (2006)
	Liquidity management	A reserve fund that consists of cash holdings in a base currency or other highly liquid assets	Liquidity benefits vs. Holding costs	Gamba and Triantis (2014)
	Foreign currency	A monetary reserve of a firm in foreign currency	Reserve benets vs. Currency risk	Chowdhry and Howe (1999)
	Insurance	An equitable transfer of the risk of a loss (e.g., business interruption) from one entity to another in exchange for payment	Insurance coverage vs. Insurance premium	Dong and Tomlin (2012)
Supply chain instruments	Supplier subsidy	A buyer provides financial aid to a supplier to increase its asset or reduce its liability	Supplier reliability vs. Subsidy costs	Babich (2010)
	Trade credit	A buyer purchases goods from a supplier with optional postponed payment (extended credit)	Early payment discount vs. Postponed payment price	Kouvelis and Zhao (2012)
	Factoring	A supplier sells account receivables to a third party at a discount for immediate cash	Liquidity benefits vs. Factoring discount	Yang and Birge (2013)
	Reverse factoring	A creditor buys accounts receivable from a supplier under an acceptance from a reputable buyer who commits to pay the creditor on the due date	Liquidity benefits vs. Interest rate costs	Klapper (2006)
	Invoice discounting	A supplier draws loans from a creditor using accounts receivable as collateral at a discount	Liquidity benefits vs. Invoice discount	Cosh et al. (2009)
Derivative instruments	Currency risk sharing	A contract that allows exchange rate gains/ losses to be shared equally by a supplier and a buyer.	Expected payoff vs. Currency uncertainty	Kouvelis (1999)
	Futures	A standardized agreement to buy an amount of an asset at a fixed price at a standardized delivery time in the future		Kouvelis (1999)
	Forwards	A customized agreement to buy an asset at a fixed price at a specific time in the future		Hommel (2003)
	Call/put options	An agreement that gives holder the right to buy/sell a certain asset by a certain date for a certain strike price	Hedging benefits vs. Financial uncertainty	Ding et al. (2007)
	Swaps	An agreement to exchange cash flows at specified future times according to certain specified rules		Gamba and Triantis (2014),Hull (2012)

is determined directly by markets; these instruments may include bonds, loans, stocks, liquidity management, foreign currency reserves, and insurance. The *supply chain instrument* is an agreement among operational and/or financial partners for transferring financial flows in a supply chain; it can take the form of a supplier subsidy, trade credit, factoring, reverse factoring, invoice discounting, or currency risk sharing. Finally, a *derivative instrument* derives its price from the value of some other financial instrument or variables (e.g., futures, forwards, call and put options, swaps). Derivative markets exist for various underlying

assets, including currency and interest rates, equity, credit, stocks, commodities, and even the weather.

## 2.6 Integrated Optimization of Operations and Finance

Given the selected portfolio of operational hedging and financial flexibility, a firm jointly optimizes its real and financial assets. Two interesting issues have been addressed in literature: (i) are operational hedging and financial flexibility complements or substitutes? (ii) When it is optimal to centralize or decentralize operational and financial decisions? Next we review the two related topics of integrated risk management.

### 2.6.1 Relationship Analysis: Complements or Substitutes?

Explorations of the relationship between operations and finance began with the Modigliani and Miller (1958) theorem, which states the *separation property* between operations and finance in perfect markets. According to this theorem, financial hedging can enhance firm value only through (i) taxes, (ii) contracting costs, or (iii) the impact of hedging on real investments in operations (Smith and Stulz 1985). Moreover, there might be value creation by financial hedging of operational risks in (iv) revenue management that transforms product demand into cash flow in the closed-loop (see Figure 2.1). Each of these avenues has motivated the relationship analysis of operations and finance.

For ease of discussion, we define a (generic) value function,<sup>6</sup>  $V$ , as the firm's optimization objective. Hence the value of integration,  $V(\mathbf{O}, \mathbf{F}) = V(\mathbf{O}) + V(\mathbf{F}) + V(\text{IE})$ ; where the adopted operational strategies,  $\mathbf{O} \in \mathbb{O}$  (Table 2.3) and financial instruments,  $\mathbf{F} \in \mathbb{F}$  (Table 2.4), and  $V(\text{IE})$  refers to the interaction effects of operations and finance. Based on the existing literature, the following four cases of relationship analysis can be delineated: (i) if  $V(\mathbf{O}, \mathbf{F}) > V(\mathbf{O}) + V(\mathbf{F})$ , i.e.,  $V(\text{IE}) > 0$ , operational hedging and financial flexibility are complements. (ii) If  $V(\mathbf{O}, \mathbf{F}) = V(\mathbf{O}) + V(\mathbf{F})$ , i.e.,  $V(\text{IE}) = 0$ , operational strategy and financial instrument are separate. Moreover, when  $V(\mathbf{O}, \mathbf{F}) < V(\mathbf{O}) + V(\mathbf{F})$ , i.e.,  $V(\text{IE}) < 0$ , operational hedging and financial flexibility are substitutes. Two cases are present in this setting: (iii) if  $V(\mathbf{O}, \mathbf{F}) > \max\{V(\mathbf{O}), V(\mathbf{F})\}$ , operational strategy and financial instrument are *partial* substitutes; (iv) if  $V(\mathbf{O}, \mathbf{F}) \leq \max\{V(\mathbf{O}), V(\mathbf{F})\}$ , operational hedging and financial flexibility are *perfect* substitutes. In case (iii), the value of integration is less than the sum of two mechanisms, yet

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<sup>6</sup> For an overview of various objective formulations, please refer to Choi et al. (2011).

integration can still add value to the firm because its value is strictly larger than the value of any single strategy. In case (iv), either operational hedging or financial flexibility can achieve the first-best solution in the firm's objective, i.e., if the value increment of integration (defined as  $\Delta V = V(\mathbf{O}, \mathbf{F}) - \max\{V(\mathbf{O}), V(\mathbf{F})\}$ ) is negative or zero, operational strategy and financial instrument are redundant and mutually exclusive.

**Table 2.5. Overview of Relationship Analysis**

Interdependence <sup>a</sup>			Operational Strategy	Financial Instrument	Compl.	Separ.	Partial Subst.	Perfect Subst.	Reference
Correlation	Constraint	Alternative							
√	√	√	Production flexibility, real investment	Currency derivatives	√				Froot et al. (1993)
√	√	√	Production flexibility	Currency bonds, swaps, forwards	√		√		Mello et al. (1995)
√		√	Production flexibility	Currency forwards, options	√		√		Chowdhry and Howe (1999)
	√	√	Production diversification and flexibility	Currency forwards, options	√		√		Hommel (2003)
√		√	Capacity plan, allocation option	Currency forwards, options	√				Ding et al. (2007)
√			Product/postponement flexibility	Weather derivatives	√		√	√	Chod et al. (2010)
	√		Capacity ordering, inventory	Supplier subsidy	√	√	√		Babich (2010)
		√	Capacity, production, and allocation	Bonds, currency derivatives	√	√			Zhu and Kapuscinski (2011)
	√		Product flexibility	Technology-specific loans	√				Boyabatlı and Toktay (2011)
		√	Inventory, emergency sourcing	Business interruption insurance	√		√	√	Dong and Tomlin (2012)
√	√		Production entry/exit	Cash, swaps	√		√		Gamba and Triantis (2014)

<sup>a</sup> See Section 2.3 for details.

Global supply chain management has focused on the integration of production flexibility and currency hedging. Production hedging by shifting production in different countries can be adopted as a "value driver", while currency hedging via financial derivatives can tailor the variance (Hommel 2003, Ding et al. 2007). Although production flexibility and currency hedging are typically found to be complementary, they may exhibit substitution effects if operational hedging increases expected profit and reduces variance (Mello et al. 1995, Ding et al. 2007). Provided the integration of both mechanisms can lead to a positive value increment in the firm's objective, they are partial substitutes and should be adopted simultaneously and optimized jointly. Whereas both production and financial hedging are

effective in managing currency risk, operational hedging is typically more effective in mitigating demand risk. It has been shown that financial hedging is more efficient when the firm is strongly averse to risk than otherwise (Zhu and Kapuscinski 2011). Furthermore, a firm's liability structure (e.g., debt level) can be part of what determines the optimal joint operational and financial hedging under market imperfections (Mello et al. 1995).

Relationships among various operational strategies and financial instruments can be analyzed by examining the marginal value increment of an additional strategy/instrument, though conclusions will differ according to model assumptions and variable changes. For instance, operational flexibility and financial hedging via weather derivatives can be jointly adopted to manage weather-dependent demand risk. Product flexibility and financial hedging are complements or substitutes depending on whether there is (respectively) a positive or negative correlation between demand and weather variable; postponement flexibility and financial hedging are substitutes (Chod et al. 2010). Insurance and operational strategies (inventory and emergency sourcing) can be complements or substitutes, depending on whether their net-premium interaction dominates penalty-reduction in managing disruption risk (Dong and Tomlin 2012). Supplier subsidies and inventory can be substitutes with back orders; capacity ordering and subsidies are substitutes under proportional random yield; and the relationship between order quantities and subsidies depends on how convex the manufacturer's cost function is with upfront capacity costs (Babich 2010).

In addition, market imperfections can affect the optimality and relative effectiveness of operational hedging and financial flexibility. Operational strategies and financial instruments are typically found to be complementary, yet they may behave as partial substitutes when being jointly optimized. Ensuring monetary supply via operational flexibility, financial hedging, and liquidity management can enhance firm value through real investments and/or reduce the costs of market imperfections. The optimality of joint financing and real investment depends on the risk exposure of real investments and revenues, market competition, and the hedging strategies of competitors (Froot et al. 1993), as well as on the interplay of operational diversification, capacity pooling, and loan financing (Boyabatli and Toktay 2011). Liquidity management is critical to integrated risk management motivated by market imperfections (Gamba and Triantis 2014). Table 2.5 presents an overview of analytical explorations in relationship analysis.

### 2.6.2 Approach Choice: Centralization or Decentralization?

In addition to the relationship analysis of operations and finance, a firm is faced with the choice of a centralized versus decentralized approach to integrated risk management. Three theories of capital structure<sup>7</sup>—separation property, static trade-off, and pecking order—are invoked in literature for the firm's approach choice.

Modigliani and Miller (1958) argue that a firm's capital structure and financial decisions are independent of the optimal investment and operational decisions under perfect markets. This is referred to as the *separation property* of operations and finance, which should hold in the absence of information asymmetry and incentive misalignments between shareholders and managers. Subsequent research has incorporated various market frictions and information structures, which has resulted in two competing theories of capital structure: static trade-off theory and pecking order theory. In *static trade-off* theory proposed by Modigliani and Miller (1963), a firm optimizes its liability structure by trading off the benefits and costs of external debt under complete information. The benefits of external debt include, for instance, the tax shield and fewer free cash flow problems; the costs of debt include the costs associated with, inter alia, financial distress, bankruptcy risk, and agency problems. In contrast, Myers and Majluf (1984) and Myers (1984) propose a *pecking order* theory that incorporates manager—shareholder information asymmetry and in which firms prefer internal to external financing because of transaction and adverse selection costs. Even though managers are supposedly better informed than shareholders, the former are assumed to act in the best interests of the latter. Given these assumptions, a firm sources its capital by the following pecking order: from cash flow (internal equity), straight debt, convertible debt (with equity option), to external equity.

The separation property of operations and finance, static trade-off theory, and pecking order theory have been applied to choose a centralized versus decentralized approach to integrated risk management. To start with, recall that the *separation property* refers to the case where operational strategies and financial instruments are adopted simultaneously but optimized separately (decentralization) with zero interaction effects (Section 2.6.1). The separation of operations and finance is typically derived under *strong* modeling assumptions (e.g., perfect market conditions). This property does not imply that the optimality of operational and

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<sup>7</sup> For extensive reviews of capital structure research, please see Harris and Raviv (1991), Myers (2003), and Graham and Leary (2011).



financial decisions is irrelevant; in fact, optimizing operational and financial decisions separately can create significant value. For instance, a given operational strategy can lead to a determinate firm value independently of financial hedging. Meanwhile, currency hedging affects the feasible set of production strategies under bankruptcy risk and agency costs of debt (Mello et al. 1995). Optimal inventory can be independent of a firm's wealth, market position, and financial hedging in a multiperiod inventory model featuring a partially complete financial market (Smith and Nau 1995), whose incompleteness stems from private demand risk (Chen et al. 2007). Optimal capacity reservation and supplier subsidy decisions can be made separately under conditions of independent supply and demand shocks, no inventory, random capacity, and zero upfront costs (Babich 2010). Under perfect (competitive) capital market assumptions, capital constrained firms can decouple its operational and bank financing decisions (Boyabatli and Toktay 2011, Kouvelis and Zhao 2012).

**Table 2.6. Overview of Approach Choice**

Interdependence <sup>a</sup>			Market Assumptions	Information Stru.		Separ. Property	Static Trade-off	Pecking Order	References
Correlation	Constraint	Alternative		Symmetric	Asymmetric				
√	√	√	Agency costs of debt, bankruptcy costs	√		√			Mello et al. (1995)
	√	√	Efficient market, diversification/ flexibility costs	√				√	Hommel (2003)
	√		Financial constraints on capacity expansion	√				√	Babich and Sobel (2004)
√	√		Perfect/imperfect market (tax, bankruptcy)	√			√		Xu and Birge (2004)
√			Partially complete financial market	√		√			Chen et al. (2007)
√	√		Cash holding costs, loan limits, external financing costs	√				√	Bolton et al. (2009)
	√		Independent supply and demand shocks, no inventory, random capacity, zero upfront costs	√		√			Babich (2010)
	√		Loan limits, competition, transaction costs		√			√	Babich et al. (2012)
	√		Asset-based lending, tax, bankruptcy		√		√		Alan and Guar (2012)
	√		Perfect (competitive) capital market			√			Kouvelis and Zhao (2012)
	√		Perfect capital market	√		√			Boyabatli and Toktay (2011)
	√		Zero long-term debt, bankruptcy costs		√			√	Li et al. (2013)

<sup>a</sup> See Section 2.3 for details.

Moreover, joint production and financing decisions can be optimized simultaneously as a *static trade-off* between tax benefits of debt and financial distress costs under demand uncertainty and market imperfections (Xu and Birge 2004). The trade-off between investing in an external market and a newsvendor business with asset-based lending shapes the business owner's capital structure under tax codes, bankruptcy costs, and information asymmetry (Alan and Gaur 2012).

Finally, the *pecking order* theory as applied in integrated risk management suggests that financial instruments and operational strategies are partial substitutes with different execution priorities due to various costs. For example: if production diversification and flexibility incur additional costs, then financial instruments will be preferred over operational strategies (Hommel 2003). When financing expansion of pre-IPO production capacity under a budget constraint, the firm can first consume internal assets as the cheapest capital and then turn to bank loans (Babich and Sobel 2004). In the presence of cash holding costs, loan limits, and/or external financing costs; real investment may be financed by a pecking order among internal funds, credit lines, and external equity (Bolton et al. 2009). To finance inventory in a budget-constrained supply chain, a retailer first chooses internal capital, then employs the cheapest trade credit, and finally diversifies external financing between trade credit and bank loan (Yang and Birge 2013). The manufacturer can choose the less expensive financing option (bank loan versus trade credit) in a supply chain under random yield, fixed supplier costs, financial constraints, and information asymmetry (Babich et al. 2012). Moreover, the pecking order theory holds when it is optimal for a manufacturer to borrow the smallest amount from bank that satisfies the liquidity constraint (Li et al. 2013). Table 2.6 summarizes the applications of capital structure theory in optimizing integrated risk management.

### **2.6.3 Link of Relationship Analysis and Approach Choice**

Linking the relationship analysis (Section 2.6.1) and approach choice (Section 2.6.2) of integrated risk management, the following result can be derived: the interaction effects and value increment can jointly determine the relationship (complements/substitutes) and compatibility of operations and finance, as well as the approach (centralization/decentralization) to integrated risk management (Table 2.7).

Table 2.7. Link of Relationship Analysis and Approach Choice

Case	Interaction Effects	Value Increment	Relationship	Compatibility	Approach
I	$V(IE) > 0$	$\Delta V > 0$	complements	compatible	centralization
II	$V(IE) = 0$	$\Delta V > 0$	separation	compatible	decentralization
III	$V(IE) < 0$	$\Delta V > 0$	partial substitutes	compatible	centralization
IV	$V(IE) < 0$	$\Delta V \leq 0$	perfect substitutes	incompatible	decentralization, exclusion

The link of relationship analysis and approach choice in integrated operations and finance can be represented by three causal relations in Table 2.7: (i) the interaction effects of operational hedging and financial flexibility shape their relationship, (ii) the value increment in the firm's objective determines their compatibility, and (iii) the interaction effects and value increment can jointly set the optimal approach to integrated risk management.

Intuitively, one may expect that operational hedging and financial flexibility should be optimized in a centralized (decentralized) manner if they are complements (substitutes). However, this one-to-one correspondence does not always hold when linking the relationship analysis with approach choice of integrated risk management. Two counterintuitive results are evident (Table 2.7): (i) if the interaction effects are zero (separation), operational strategies and financial instruments should be adopted simultaneously yet optimized separately (decentralization). (ii) Operational hedging and financial flexibility should be optimized in a centralized manner even if they are *partial* substitutes.

## 2.7 Conclusions

This chapter reviews the literature on the interface of operations and finance. A roadmap to integrated risk management including classifications of operational hedging and financial flexibility is proposed. The relationship analysis and approach choice of integrated risk management are linked in light of the value increment and interaction effects of operations and finance.

The synthesis of integrated risk management may suggest a number of research directions. First, new combinations of operational hedging and financial flexibility can be explored analytically. Given the variety of risk management strategies/instruments, integrating

operations and finance while analyzing their relationship can be an avenue with untapped potential of fruitful explorations.

Moreover, empirical research on integrated risk management can be conducted to test its effectiveness in applications. Best practices of cross-functional, cross-supply chain risk management programs can be traced, and the portfolio of operational strategies and financial instruments can be enriched. For instance, the link of ERM and SCRM is emphasized by eight case studies of European firms in supply risk management (Blome and Schoenherr 2011).

In addition, integrated risk management can be extended by incorporating the triple bottom line (3BL) of sustainability, via which optimal strategies may be found at the intersection of social, environmental, and economic performance (Carter and Rogers 2008). For example, a firm can consider the ecological and social impact of its products and services besides economic goals by “integrated reporting” of finance, operations, and sustainability (IIRC 2011).

## Chapter 3

# Capacity Investment, Backup Production, Switching Options, and Financial Hedging in a Global Supply Chain under Mean-CVaR<sup>8</sup>

### 3.1 Introduction

Switching options give multinational corporations (MNCs) the operational flexibility to shift production between different countries in response to exchange rate movements (Kogut and Kulatilaka 1994, Huchzermeier and Cohen 1996, Kazaz et al. 2005). Global firms can also manage currency exposure by financial hedging in the derivatives market (Mello et al. 1995, Ding et al. 2007, Chen et al. 2014). For example, General Electric (GE) states in its annual report that “when countries or regions experience currency and/or economic stress, we often have increased exposure to certain risks, but also often have new profit opportunities .... New profit opportunities include, among other things, more opportunities for lower cost outsourcing [i.e., switching production from domestic to foreign regions]”. Moreover, “as a matter of policy, we generally hedge the risk of fluctuations in foreign currency exchange rates” via “selective use of derivatives” (General Electric 2010). Recently, in response to the rising risks of outsourcing, “GE is spending some \$800 million ... to re-establish manufacturing in its giant facility ... at Appliance Park, in Louisville, Kentucky .... In March 2012, GE started a second assembly line to make new high-tech French-door refrigerators” (Denning 2012). Such newly (re-)established domestic capacity is typically more reliable yet more expensive than outsourcing. In our setting, we call such alternatives *backup production* (cf. Yang et al. 2009, Chen 2014), because they constitute excess capacity that can be used when lower-cost capacities are fully utilized. A question that naturally arises is: how does backup production interact with switching options and financial hedging in the MNC’s management of risk?

By and large, the literature on integrated operational flexibility and financial hedging has examined the interaction between switching/allocation options and financial hedging in a risk-neutral context (Mello et al. 1995), using variance-based risk measures (Chowdhry and

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<sup>8</sup> The content in Chapter 3 is based on Zhao and Huchzermeier (2014a). This chapter was presented at the 2013 INFORMS MSOM Conference in Fontainebleau, France.

Howe 1999, Hommel 2003, Ding et al. 2007, Chen et al. 2014), or via expected utility models (Zhu and Kapuscinski 2011). However, variance-based risk measures obscure both upside potential and downside risk, a characteristic known as “nonmonotonicity” in the literature on coherent risk measures (Artzner et al. 1999). The optimal decision according to mean-variance (MV) models can be extremely sensitive to the covariance matrix and especially to the mean, and the model’s proposed portfolio may be stochastically dominated by another portfolio (Black and Litterman 1992). Moreover, the optimal solution in MV models varies with unit rescaling (i.e., from US dollars to cents; see Choi et al. 2011). And although the expected utility approach exhibits certain theoretical elegance, it describes risk attitude indirectly; hence it is rarely adopted in practice (Zhu and Fukushima 2009). In light of these limitations, it makes sense to examine the interaction between operational flexibility and financial hedging by way of a mean-downside risk model.

Among downside risk measures, value-at-risk (VaR) has become popular in financial risk management since the middle 1990s. However, VaR has been subject to three particular criticisms. First, VaR is not subadditive in the general distribution case—in other words, the sum of two portfolios may not return a VaR less than or equal to the sum of the VaRs of each portfolio. Hence this risk measure is not coherent in the sense of Artzner et al. (1999). Second, VaR may exhibit multiple local extrema for discrete distributions as a function of the portfolio positions; that possibility may render it inconvenient for purposes of optimization (Zhu and Fukushima 2009). Third, VaR captures only the percentile of loss distribution and thus does not account for the magnitude (severity) of incurred damage (Acerbi and Tasche 2002). The Basel Committee on banking supervision therefore recommends using *conditional* value-at-risk (CVaR), which is defined as the average value of expected profit falling below a certain quantile level (or VaR), because it accounts for both the magnitude and probability of risk (Heaney 2012).

Since CVaR is also a coherent risk measure (Choi et al. 2011), we adopt it as the downside risk measure in our mean-risk model. In practice, a CVaR constraint can accommodate three cases: (i) the internal capital required for an investment opportunity (Froot et al. 1993); (ii) the lower bound of profitability imposed by shareholders (Hommel 2003); and (iii) a standing loan that is tied to default risk (Gamba and Triantis 2014).

This chapter aims at making two contributions to the literature on integrated operational flexibility and financial hedging. First, we incorporate backup production and explore its interactions with switching options and financial hedging in a global supply chain network. Second, we examine the relationship between operational flexibility and financial hedging under a mean-CVaR criterion. For a more detailed positioning of our research within the relevant literature, see Section 3.2.

We model a risk-averse MNC that makes ex ante capacity investment and financial hedging decisions and executes ex post backup production and switching options to manage both exchange rate uncertainty and mismatch risk.<sup>9</sup> We employ a mean-CVaR analysis and arrive at three principle findings. First, backup production and switching options are complements when both are used to fulfill foreign demand but are substitutes when used to fulfill domestic demand. Operational flexibility and financial hedging are substitutes in risk reduction, yet they can be complements in profit enhancement if financial hedging alters the feasible set of capacity portfolios by relaxing the CVaR constraint; hence the exchange of information between operations and finance is crucial. Second, given operational flexibility, financial hedging is viable only under rare and extreme exchange rates; otherwise, real options are expected to generate greater profits. Overall, the integration of these strategies can create significant value because its expected utility is strictly greater than that of employing operational flexibility alone or financial hedging alone. Third, switching options are more effective than financial hedging at reducing risk. Financial hedging is better able to reduce exchange rate risk than demand volatility risk, although the reduction is decreasing in either type of volatility.

### **3.2 Literature Review**

Three streams of literature are especially relevant to our research: (i) the integration of operational flexibility<sup>10</sup> and financial hedging; (ii) operational flexibility via switching options or backup production; and (iii) the application of CVaR in financial hedging.

Most strongly related to this chapter is the research on integrated operational flexibility and financial hedging. Global supply chain management has focused on integrated production

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<sup>9</sup> Mismatch risk refers to the possibility that supply (capacity or inventory) differs from demand.

<sup>10</sup> Throughout this chapter, the terms “operational flexibility” and “operational hedging” are used interchangeably.

flexibility (i.e., switching options) and currency hedging under exchange rate uncertainty and demand risk. Mello et al. (1995) consider the optimal financial hedging policy for a MNC with production flexibility via switching options under exchange rate uncertainty. They illustrate how operational flexibility and financial hedging interact as substitute risk management mechanisms to maximize firm value, and they also discuss the complementary aspects of these mechanisms. Production flexibility acts more as a value driver than a hedging strategy, and financial hedging helps move the operating frontier to the first-best solution. The firm's liability structure (e.g., debt level) can change the relationship between operational flexibility and financial hedging. Because production flexibility shapes the contingent cost structure by increasing the debt level, more financial hedging contracts may be required to provide a shield against risk.

Chowdhry and Howe (1999) study the choice between financial hedging and operational flexibility with fixed total capacity in the presence of both exchange rate risk and demand risk. Production flexibility and financial hedging are each generalized as maximizer of a MV utility function. These authors find that firms typically employ financial instruments to hedge short-term risk exposure while relying on operational flexibility to hedge long-term exposure. Their analysis suggests that operational hedging is adopted only when both exchange rate risk and demand risk are present. Hommel (2003) extends that model and distinguishes between geographical diversification and operational flexibility in a multinational real options context under demand and currency risk, where hedging incentives are introduced by a minimum cash flow constraint. He argues that operational flexibility serves as a hedging device when both the exchange rate and demand are highly volatile; otherwise, it enhances expected profits. Financial hedging is shown to minimize the profit variance.

Ding et al. (2007) explore how risk-averse multinational firms hedge operationally (via allocation and postponement options) and financially (via currency options) under exchange rate risk and demand uncertainty. They show that the firm achieves the greatest MV utility by adopting an integrated operational and financial hedging approach. The allocation option improves expected profit and reduces profit variance by avoiding unfavorable exchange rates, while financial options alleviate the effect of exchange rate uncertainty on profit variance. Zhu and Kapuscinski (2011) compare the benefits of operational and financial hedging separately and jointly in a dynamic, finite-capacity model. These authors report that



operational hedging is preferred when demand uncertainty, transportation costs, and total capacity are high; in contrast, financial hedging is preferred when risk aversion is high. When the profit margin is small and exchange rate variations are large, joint operational and financial hedging is optimal for the multinational risk-averse newsvendor.

Gamba and Triantis (2014) consider a value-maximizing firm that incorporates operational flexibility, liquidity management, and financial hedging in a dynamic structural model. They demonstrate that liquidity management serves as a critical risk management mechanism and that distress costs are a key motivator of risk hedging. Chen et al. (2014) examine financial and operational hedging—for the case of more than two countries—via general financial hedging contracts under a MV objective in a single-period model; here operational hedging is defined as the postponement of production. These authors show that financial hedging is a partial substitute for operational flexibility but serves as a complement to total capacity when both hedges are used. Table 3.1 presents an overview of the literature discussed so far.

**Table 3.1. Summary of the Literature on Integrated Operational Flexibility and Financial Hedging and New Contribution**

Reference	Source of Uncertainty			Switching/ Allocation Options	Backup Production	Financial Hedging	Objective
	Supply	Demand	Exchange Rate				
Mello et al. (1995)			√	√		√	Value/equity maximization
Chowdhry and Howe (1999)		√	√	√		√	MV
Hommel (2003)		√	√	√		√	Value maximization, variance minimization
Ding et al. (2007)		√	√	√		√	MV
Zhu and Kapuscinski (2011)		√	√	√		√	Present certainty equivalent value
Gamba and Triantis (2014)		√		√		√	Firm equity/value maximization
Chen et al. (2014)		√	√	√		√	MV
This chapter	√	√	√	√	√	√	Mean-CVaR

Our research contributes to this literature by adding backup production and then exploring its interactions with switching options and financial hedging in a mean-CVaR model. We find that backup production and switching options are complements if both are used to fulfill foreign demand but are substitutes if both are used to fulfill domestic demand. Operational flexibility and financial hedging are substitutes in risk reduction, yet they can be

complements in profit enhancement. Contrary to the existing literature, we show that switching options are more effective at reducing risk in exchange rate volatility than in demand volatility; the effect of financial hedging on risk reduction is decreasing in both types of volatility. The difference between our results and those in the literature is driven mainly by two factors: the addition of backup production and the adoption of CVaR as a downside risk measure.

Operational flexibility in global supply chain management under uncertainty is an emerging field. One area of active interest is establishing an optimal configuration of the global supply chain network via switching and allocation options under exchange rate exposure and/or demand risk. Kogut and Kulatilaka (1994) focus on valuing the option of switching production between two of a MNC's plants under fluctuating exchange rates. Huchzermeier and Cohen (1996) take a classical modeling perspective and demonstrate the value of operational hedging (via excess capacity and network switching options) in global supply chains for mitigating currency risk. Dasu and Li (1997) examine production allocation among plants in a multifacility network when costs are influenced by exchange rates. Kouvelis (1999) considers global sourcing flexibility in a multisupplier setting under price risk and exchange rate uncertainty. Kazaz et al. (2005) describe the expected benefits of production hedging via excess capacity and postponed allocation for a profit-maximizing firm under exchange rate uncertainty. Li and Wang (2010) examine the impact of operational hedging through consideration of a switching option between an expensive domestic supplier and a low-cost offshore supplier.

One substream of research concentrates on operational flexibility via backup production under supply uncertainty. Dada et al. (2007) formulate the newsvendor's supplier selection problem by applying a general model of supplier reliability. Yang et al. (2009) assess the effect of a supplier's private information about supply disruption on the execution of manufacturer or supplier backup production options. Tang and Kouvelis (2011) consider a Cournot game between two buyers who decide whether to sole source or dual source—and from which supplier(s)—under yield uncertainty. Chen (2014) examines optimal procurement design and backup production under supply disruptions and heterogeneous beliefs between the buyer and the supplier. Sting and Huchzermeier (2014) set up responsive capacity via dual sourcing under correlated supply and demand uncertainty. Our model

complements this literature by examining how backup production hedges random yield and interacts with switching options and financial hedging in a global supply chain network.

Conditional value-at-risk<sup>11</sup> is a coherent risk measure that fulfills the five axioms of convexity, monotonicity, subadditivity, translation equivariance, and positive homogeneity (Artzner et al. 1999, Acerbi and Tasche 2002, Choi et al. 2011). Hence, CVaR has often been adopted as a risk measure in financial hedging. Föllmer and Leukert (2000) explore efficient hedging that trades off cost against expected shortfall. Rockafellar and Uryasev (2000, 2002) propose a CVaR approach to portfolio optimization that calculates VaR as a by-product. Topaloglou et al. (2008) examine a multistage stochastic program for constructing an international portfolio under CVaR in a dynamic setting. Zhu and Fukushima (2009) study the application of worst-case CVaR optimization to robust portfolio management. Our model contributes to this research by optimizing financial hedging with operational flexibility under mean-CVaR via knock-in currency options—a form of barrier option (Carr et al. 1998) on the currency exchange rate—the payoff on which is the same as a standard option if the exchange rate breaches a pre-set barrier level and is zero otherwise. These are also known as “up-and-in” and “down-and-in” options.

The remainder of this chapter is organized as follows. In Section 3.3, we formulate our model and propose the optimal solutions to integrated operational flexibility and financial hedging under exchange rate uncertainty and mismatch risk. Sections 3.4 and 3.5 use (respectively) analytical and numerical means to describe the interactions of operational flexibility and financial hedging. We conclude in Section 3.6 with a summary of main insights and directions for future research.

### **3.3 Global Supply Chain Model with Backup Production, Switching Options, and Financial Hedging**

#### **3.3.1 Formulation and Assumptions**

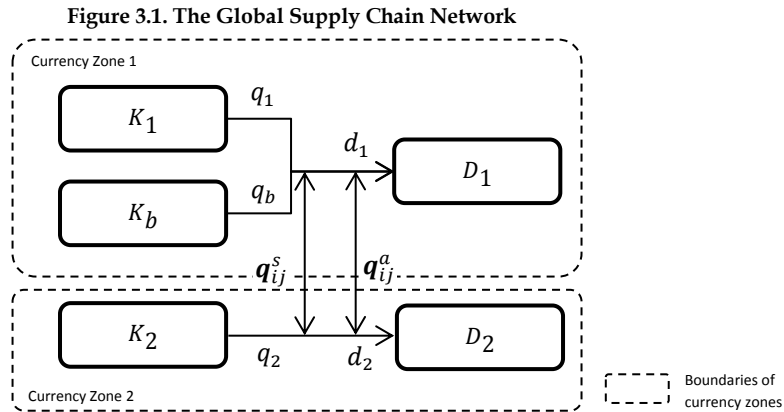
We consider a risk-averse global firm that supplies one product with three capacities for two markets located in two currency zones (see Figure 3.1). The capacities may be internal to the firm (as when it is a manufacturer) or external (as when it outsources production to a contract manufacturer; see Sting and Huchzermeier 2010, Swinney et al. 2011). The foreign

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<sup>11</sup> For continuous distributions, this risk measure is known also as *expected shortfall*, *mean excess loss*, *tail value at risk*, and *average value at risk*.

currency exchange rate  $s = \frac{\text{domestic currency}}{\text{foreign currency}}$ , where  $s \in [\underline{s}, \bar{s}]$  with a probability density function (PDF) of  $e(\cdot)$  that is assumed to be independent of demand rates  $D_i$ . We define *domestic currency* as the “home” currency—that is, the currency in which the global firm’s financial statements are denominated.

Ordinary capacities  $K_i$  in currency zones  $i = 1, 2$  are unreliable, with endogenous production functions  $K_i = Q_i R_i$  (cf. Dada et al. 2007, Federgruen and Yang 2009, Tang and Kouvelis 2011); here  $R_i \in (0, 1]$  are random variables distributed on  $\mathbb{R}_+^2$ . In contrast, backup production capacity is perfectly reliable; that is,  $K_b = Q_b$ . Market demand in currency zone  $i = 1, 2$  is stochastic with a PDF of  $g_i(\cdot)$ . The joint distribution of exchange rate and supply–demand matching states (i.e.,  $s, K_i, D_i$ ) has density function  $f(\cdot, \cdot)$  with finite support  $\Omega_i$  ( $i = 1, 2, \dots, 10$ ); probabilities of the respective states are known ex ante. We assume that the global firm is able to estimate the distribution of uncertainty factors. In practice, the MNC can resolve demand uncertainty in various ways—for example, by performing extensive market research, employing consumer focus groups, and/or working with retailers to improve forecasts econometrically using estimated demands (Van Miegham 2003, Swinney et al. 2011). Furthermore, exchange rate forecasts can be improved by a better understanding of the firm’s exposure and by anticipating possible exchange rate scenarios (Wright 2008). The market (unit) price  $p_i$  in currency zone  $i = 1, 2$  is assumed to be exogenous; also, the conditions  $p_1 > c_b > c_1$  and  $p_2 > c_2$  ensure the profitability of unit production in each market.



The MNC first decides on capacity installment quantities  $\mathbf{Q} = (Q_1, Q_b, Q_2) \in \mathbb{R}_+^3$ . It then decides on production quantities  $q_i$  at unit capacity cost  $c_i^k$  and unit production cost  $c_i$  for resource  $i = 1, 2, b$ . We assume that  $c_1^k < c_b^k$  and  $c_1 < c_b$ , given that backup capacity and production are more expensive than ordinary domestic capacity and production. The MNC then makes output quantity decisions  $d_i$  with regard to market  $i = 1, 2$ . The global firm has

access to three risk management strategies: operational flexibility by reliable (domestic) backup capacity  $K_b$ ; switching and allocation options  $\mathbf{q}_{ij}^s$  and  $\mathbf{q}_{ij}^a$ <sup>12</sup> for  $i, j = 1, 2$  with  $i \neq j$ ; and financial hedging via currency derivatives  $\mathbf{h} \in \mathbb{R}^n$ . The execution of a switching or allocation option incurs (respectively) a unit switching cost  $c_{ij}^s$  or a unit allocation cost  $c_{ij}^a$  in that one production unit or product unit is shifted from currency zone  $i$  to  $j$  in the destination zone's currency ( $j$ ). We assume  $c_{ij}^s \leq c_{ij}^a$  to ensure that the global firm prefers switching options (the focus of our research) over allocation options when rerouting its material flows. If the switching cost is constant, linear, or convex in adjusted sourcing quantities, then the optimal structure of sourcing policy—that is, the “hysteresis band”—is essentially unchanged (Kogut and Kulatilaka 1994, Dasu and Li 1997, Kouvelis 1999). We distinguish between switching and allocation options as follows. Switching options  $\mathbf{q}_{ij}^s$  capture the flexibility to minimize cost by adjusting (ex post) production quantities  $q_i$  derived from domestic and foreign resources. In contrast, allocation options  $\mathbf{q}_{ij}^a$  enable profit maximization by adjusting output levels  $d_i$  in domestic and foreign markets contingent on realized profit margins. In practice, allocation options typically incur higher transportation costs and custom charges whereas switching options may lead to a higher configuration cost in terms of labor and machines. Hence, switching and allocation options are not perfect substitutes.

The MNC is assumed to be risk-averse, and it seeks to maximize its objective function:

$$U(\Pi) = \mathbb{E}[\Pi] - \lambda \text{CVaR}_\beta.$$

Here  $\mathbb{E}[\cdot]$  is the expectation operator taken on the joint distribution of the exchange rate and supply–demand matching states (i.e., the realizations of random yield and stochastic demand);  $\text{CVaR}_\beta$  denotes the conditional value-at-risk for a given confidence interval  $\beta$ ; and the risk parameter  $\lambda \geq 0$  represents the rate at which decision makers substitute CVaR for expected profit, which is also referred to as the “coefficient of risk aversion”.

Following the abstract approach of Rockafellar and Uryasev (2000), we present a formal definition of the CVaR. Let  $(\Omega; \mathbb{F}; P)$  be a probability space with filtration  $\mathbb{F}$  and probability measure  $P$ . In our setting,  $\Omega$  is the probability space on which  $f(\cdot, \cdot)$  is defined and  $\mathbb{F}$  is the set of exchange rates and supply–demand state realizations. An uncertain outcome (i.e., loss function) is represented by a measurable function  $L: \Omega \rightarrow \mathbb{R}$ . We specify the vector space  $\mathcal{Q}$  of

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<sup>12</sup> Throughout the chapter, we use boldface letters to denote (row or column) vectors.

possible functions, where it is sufficient to consider  $\mathfrak{L} = \mathcal{L}_\infty(\Omega; \mathbb{F}; P)$ . Here the random vector  $\mathbf{y} \triangleq (\mathbf{K}, s, \mathbf{D}) \in \mathbb{R}_+^m$ . Given the joint operational and financial decisions  $(\mathbf{Q}, \mathbf{h})$ , we can write the probability that the loss function  $l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \triangleq -\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  does not exceed a threshold  $\alpha$  as

$$\Psi(\mathbf{Q}, \mathbf{h}, \alpha) \triangleq \int_{l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \leq \alpha} f(\mathbf{y}) d\mathbf{y}.$$

For a given confidence level  $\beta \in (0,1)$  (e.g.,  $\beta = 0.9$  or  $\beta = 0.95$ ) and fixed decisions  $(\mathbf{Q}, \mathbf{h})$ , the value-at-risk is defined as

$$\text{VaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \triangleq \min\{\alpha \in \mathbb{R}: \Psi(\mathbf{Q}, \mathbf{h}, \alpha) \geq \beta\}.$$

The corresponding conditional value-at-risk, denoted by  $\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$ , is defined as the expected value of loss that exceeds  $\text{VaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$ ; thus,

$$\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \triangleq \frac{1}{1-\beta} \int_{l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \geq \text{VaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})} l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) f(\mathbf{y}) d\mathbf{y}.$$

The worst-case CVaR (WCVaR) for decisions  $(\mathbf{Q}, \mathbf{h})$  is (cf. Zhu and Fukushima 2009)

$$\text{WCVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \triangleq \sup \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}).$$

Hence, the firm's integrated operational flexibility and financial hedging problem can be written as follows

$$\max_{\mathbf{Q} \in \mathbb{R}_+^3, \mathbf{h} \in \mathbb{R}^n} \{\mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})] - \lambda \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})\}. \quad (3.1)$$

We assume that CVaR is convex, that the mean profit function is concave, and that the decision vector set is convex. Following the approach of Krokmal et al. (2002, p. 49), we show that there are three equivalent formulations of the mean-CVaR optimization problem.

**Lemma 3.1.** *Suppose the functions  $\text{CVaR}_\beta(\mathbf{p}, \mathbf{y})$  and  $\mathbb{E}[\Pi(\mathbf{x}, \mathbf{y})]$  depend on the decision vector  $\mathbf{p} \triangleq (\mathbf{Q}, \mathbf{h}) \in \mathbf{P}$ , and consider the following three problems:*

$$\max_{\mathbf{Q} \in \mathbb{R}_+^3, \mathbf{h} \in \mathbb{R}^n} \{\mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] - \lambda \text{CVaR}_\beta(\mathbf{p}, \mathbf{y})\} \quad \text{s.t. } \mathbf{p} \in \mathbf{P} \text{ and } \lambda \geq 0; \quad (\text{P1})$$

$$\min_{\mathbf{h} \in \mathbb{R}^n} \text{CVaR}_\beta(\mathbf{p}, \mathbf{y}) \quad \text{s.t. } \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] \geq \rho \text{ and } \mathbf{p} \in \mathbf{P}; \quad (\text{P2})$$

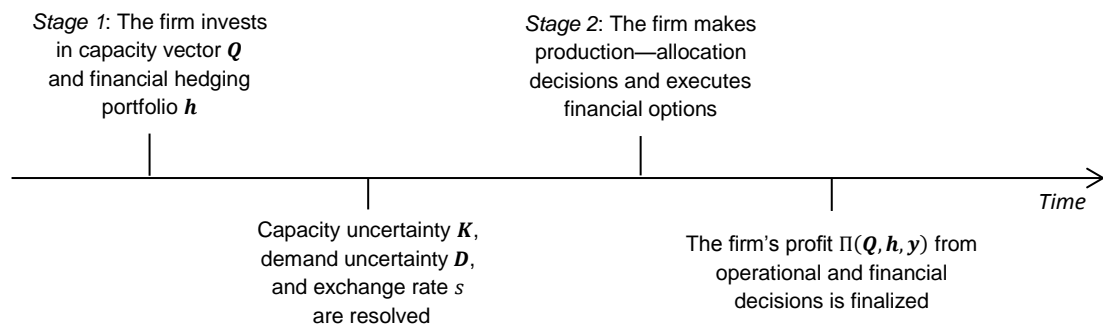
$$\max_{\mathbf{Q} \in \mathbb{R}_+^3} \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] \quad \text{s. t. } \text{CVaR}_\beta(\mathbf{p}, \mathbf{y}) \leq \omega \text{ and } \mathbf{p} \in \mathbf{P}. \quad (\text{P3})$$

Now suppose that the constraints  $\mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] \geq \rho$  and  $\text{CVaR}_\beta(\mathbf{p}, \mathbf{y}) \leq \omega$  have internal points. Then the efficient frontiers for the problems (P1)–(P3) can be traced by varying the parameters  $\lambda$ ,  $\rho$ , and  $\omega$  accordingly. Given our assumptions that  $\text{CVaR}_\beta(\mathbf{p}, \mathbf{y})$  is convex,  $\mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})]$  is concave, and the decision vector set  $\mathbf{P}$  is convex, the problems (P1)–(P3) are equivalent in that they generate the same efficient frontier.

*Proof.* All proofs are given in Appendix 3A.

Lemma 3.1 establishes that a mean-CVaR optimization is equivalent to minimizing CVaR with a minimum expected profit and also to maximizing the expected profit subject to a CVaR constraint (based on generating the same efficient frontier). Therefore, the global firm's optimization problem (P1) can be decomposed into CVaR minimization via financial hedging with a minimum expected profit (P2) and expected profit maximization by operational flexibility subject to a CVaR constraint (P3). This decomposition enables one to implement a mean-CVaR optimization within a centralized functional structure, via (P1), or within a decentralized functional structure via (P2) and (P3). MV and expected utility models both require the MNC to act as one *centralized* planner of operations and finance using the same objective function; such models are inappropriate for a MNC with decentralized functional structure because they ignore the incentive misalignments between operational and financial departments. In contrast, a mean-CVaR objective can be implemented within a *decentralized* structure: operational strategy focuses on maximizing expected profit subject to a CVaR constraint while financial hedging focuses on minimizing CVaR subject to a minimum expected profit, and the interactions between operations and finance are represented by the minimum expected profit and the CVaR constraint.

Figure 3.2. Timeline of Events



We use a two-stage stochastic program to characterize the MNC's operational strategies and financial decisions (see Figure 3.2). In Stage 1, the global firm invests in domestic and foreign capacities  $\mathbf{Q}$  subject to a CVaR constraint; that is,  $\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \leq \omega$ . The MNC purchases financial hedging contracts consisting of forwards or put options on foreign currency,  $\mathbf{h}_i$  ( $i = f, p$ ),<sup>13</sup> to optimize the CVaR of its cash flow under minimum expected profit:  $\mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})] \geq \rho$ . The firm has postponement flexibility (Van Mieghem and Dada 1999) when planning production and allocation contingent on the realization of uncertainty. In Stage 2—after observing realized capacities  $\mathbf{K} = (K_1, K_b, K_2)$ , demands  $\mathbf{D} = (D_1, D_2)$ , and exchange rate  $s$ —the global firm makes its production and allocation decisions,  $\mathbf{q} = (q_1, q_b, q_2, q_{12}^s, q_{21}^s, q_{12}^a, q_{21}^a)$ . In other words, the firm first decides on both regular and backup production quantities (after uncertainty realization), and then decides on the execution of switching and allocation options. In our setting, backup capacity differs from ordinary capacity by offering higher *reliability*; therefore the lead time of backup and ordinary production is assumed to be identical. Moreover, the payoff from financial hedging is assumed to be zero (the no-arbitrage condition):  $\mathbb{E}[H(\mathbf{h})] = 0$ . Thus the MNC's operating profit in home currency after Stage 2 is

$$\begin{aligned} \Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) &= \Pi^{\text{int}}(\mathbf{Q}, \mathbf{y}) + R(\mathbf{h}) - C(\mathbf{h})e^{\gamma t} \\ \text{s.t. } \sum q_i &= \sum d_i \leq \sum D_i, \quad \sum q_i = \sum d_i \leq \sum K_i, \\ q_i &\leq K_i, d_i \leq D_i, q_{ij}^s \leq K_j, q_{ij}^a \leq D_j, \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \leq \omega, \\ \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})] &\geq \rho, \mathbb{E}[H(\mathbf{h})] = 0. \end{aligned} \tag{3.2}$$

We use  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{y})$  to denote the cash flow derived from operational decisions,<sup>14</sup> which can take various functional forms depending on the global firm's production and allocation decisions in Stage 2 (see equation (3.10) in Section 3.3.3); note that  $i = 1, 2, b, j = 1, 2$ . The payoff from financial hedging,  $H(\mathbf{h}) = R(\mathbf{h}) - C(\mathbf{h})e^{\gamma t}$ , reflects the payout  $R(\mathbf{h})$  in Stage 2 and the overall cost of financial hedging  $C(\mathbf{h})e^{\gamma t}$  in Stage 1. The term  $\gamma$  is the risk-free interest rate in the home currency, and  $t$  is the time duration between Stage 1 and Stage 2 as well as the time to maturity of financial derivatives. The CVaR constraint should be chosen from the interval  $\omega \in [\text{VaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}), \text{WCVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})]$ : if  $\omega = \text{VaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  then not all capacity portfolios in the decision vector set  $\mathbf{P}$  are feasible, owing to the CVaR constraint,

<sup>13</sup> Here  $f$  and  $p$  denote (respectively) currency forwards and currency put options. For the sake of brevity, the vector  $\mathbf{h}_i$  is sometimes simply written as  $\mathbf{h}$  when no confusion could result.

<sup>14</sup> We shall use "bc", "bp", "sw", "op", "fh", and "int" to denote (respectively) "base case", "backup production only", "switching options only", "full operational flexibility", "financial hedging only", and "integrated risk management" (see Definition 1).



and so financial hedging can enlarge the feasible set of capacity portfolios;  $\omega = \text{WCVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  indicates that all capacity portfolios are feasible and so financial hedging is unnecessary. The minimum expected profit is similarly confined to the interval  $\rho \in [\inf \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})], \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})]]$ . If  $\rho = \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})]$ , then only the decision vectors that achieve above-average expected profit are feasible; if  $\rho = \inf \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})]$ , then all decision vectors in the set  $\mathbf{P}$  are feasible.

**Definition 3.1.** The following strategies can be distinguished in terms of their respective degrees of operational flexibility and financial hedging.

- (a) *Base case* refers to a nonflexible global firm without backup capacity, switching/allocation options, or financial hedging (i.e.,  $K_b = q_{ij}^s = q_{ij}^a = \mathbf{h} = 0$ ); ceteris paribus.
- (b) *Backup production only* denotes a partially flexible global firm with backup capacity but without switching/allocation options or financial hedging (i.e.,  $K_b > 0$ , and  $q_{ij}^s = q_{ij}^a = \mathbf{h} = 0$ ); ceteris paribus.
- (c) *Switching options only* means a partially flexible global firm with switching/allocation options yet with neither backup capacity nor financial hedging (i.e.,  $q_{ij}^s \geq 0$ ,  $q_{ij}^a \geq 0$ , and  $K_b = \mathbf{h} = 0$ ); ceteris paribus.
- (d) *Full operational flexibility* indicates a fully flexible global firm with backup capacity and switching/allocation options but without financial hedging (i.e.,  $K_b > 0$ ,  $q_{ij}^s \geq 0$ ,  $q_{ij}^a \geq 0$ , and  $\mathbf{h} = 0$ ); ceteris paribus.
- (e) *Financial hedging only* refers to a nonflexible global firm that adopts financial hedging but has neither backup capacity nor switching/allocation options (i.e.,  $\mathbf{h} > 0$ , and  $K_b = q_{ij}^s = q_{ij}^a = 0$ ); ceteris paribus.
- (f) *Integrated risk management* denotes a fully flexible global firm that employs not only backup capacity and switching/allocation options but also financial hedging (i.e.,  $K_b > 0$ ,  $q_{ij}^s \geq 0$ ,  $q_{ij}^a \geq 0$ , and  $\mathbf{h} > 0$ ); ceteris paribus.

For ease of exposition, we define  $\Pi^x(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  for  $x = \text{bc, bp, sw, op, fh, int}$  as the profit function when strategy  $x$  is adopted; this may also be written as  $\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})$ ,  $\Pi^x(\mathbf{Q}, \mathbf{h})$ , or  $\Pi^x$  for brevity. Similarly,  $\text{CVaR}_\beta^x(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  is defined as the CVaR when  $l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^x(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  for strategy  $x = \text{bc, bp, sw, op, fh, int}$ ; this term may also be denoted as  $\text{CVaR}_\beta^x$  or  $\text{CVaR}_\beta^x(\mathbf{Q}, \mathbf{h})$  for brevity. An overview of our notation and assumptions is given in Table 3.2.

Table 3.2. Summary of Notation and Assumptions

Symbol	Description	Assumptions
$s$	Exchange rate in currency zone 2	$s = \frac{\text{home currency}}{\text{foreign currency}}, s \in [\underline{s}, \bar{s}]$
$e(\cdot)$	Probability density function (PDF) of exchange rate distribution	Exogenous, stochastic; independent of $D_i$
$K_i$	Ordinary capacity in currency zone $i = 1, 2$	Unreliable with endogenous production function, $K_i = Q_i R_i$ for $i = 1, 2$
$K_b$	Backup capacity (domestic) in currency zone 1	Perfectly reliable; $K_b = Q_b$
$R_i$	Random yield factors $i = 1, 2$	Random variables distributed on $\mathbb{R}_+^2$
$Q_i$	Capacity order quantities at resource $i = 1, 2, b$	Decision variable in stage 1; $\mathbf{Q} \in \mathbb{R}_+^3$
$q_i$	Production quantities at resource $i = 1, 2, b$	Decision variable in stage 2
$c_i^k$	Unit capacity cost at resource $i = 1, 2, b$ in Stage 1	$c_j^k < c_b^k$ for $j = 1, 2$
$c_i$	Unit production cost at resource $i = 1, 2, b$ in Stage 2	$c_j < c_b$ for $j = 1, 2$
$q_{ij}^s$	Production quantity switched from currency zone $i$ to $j$	$i, j = 1, 2, i \neq j$
$q_{ij}^f$	Finished products reallocated from currency zone $i$ to $j$	$i, j = 1, 2, i \neq j$
$c_{ij}^s$	Unit switching cost of shifting a production unit from currency zone $i$ to $j$ in destination location currency ( $j$ )	Exogenous, deterministic $i, j = 1, 2, i \neq j$
$c_{ij}^a$	Unit reallocation cost of relocating one product from currency zone $i$ to $j$ in destination market currency ( $j$ )	Exogenous, deterministic $c_{ij}^s \leq c_{ij}^a; i, j = 1, 2, i \neq j$
$D_i$	Market demand in currency zone $i = 1, 2$	Exogenous, stochastic
$g_i(\cdot)$	PDF of demand distribution for market $i = 1, 2$	Exogenous; known in Stage 1
$\mathbf{y}$	Random vector $\mathbf{y} \triangleq (\mathbf{K}, s, \mathbf{D})$	$\mathbf{y} \in \mathbb{R}^m$
$f(\cdot, \cdot)$	Density function of joint distribution of exchange rate and supply–demand matching states	Exogenous, has finite support $\Omega_i$ ( $i = 1, 2, \dots, 10$ ) with respective probabilities known in stage 1
$d_i$	Product output in currency zone $i = 1, 2$	Decision variable in stage 2, $d_i \leq D_i$
$p_i$	Market (unit) price in currency zone $i = 1, 2$	Exogenous, $p_i > c_b > c_i$ for $j = 1, 2$
$H(\mathbf{h})$	Payoff of financial hedging portfolio	$\mathbb{E}[H(\mathbf{h})] = 0$
$\mathbf{h}_i$	Size vectors of currency forwards or options, $i = f, p$	Consists of currency forwards or options
$C(\mathbf{h})$	Overall cost of financial hedging	Includes commission costs, transaction fees, and margin requirements
$\alpha$	Threshold value of CVaR	Endogenous; depends on $\beta$
$\beta$	Confidence interval of CVaR	Endogenous, deterministic
$\omega$	CVaR constraint on operations	Endogenous, deterministic
$\rho$	Minimum expected profit constraint	Endogenous, deterministic

### 3.3.2 Optimal Financial Hedging Strategy

We now optimize the MNC's financial hedging strategy. Since maximizing the mean-CVaR utility is equivalent to minimizing CVaR subject to a minimum expected profit (see Lemma 3.1), the portfolio of financial hedging contracts with respect to (w.r.t.)  $\mathbf{h} \in \mathbb{R}^n$  for each  $\mathbf{p} = (\mathbf{Q}, \mathbf{h}) \in \mathbf{P}$  can be optimized by solving the following problem:

$$\begin{aligned} & \min_{\mathbf{h} \in \mathbb{R}^n} \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \\ & \text{s. t. } \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})] \geq \rho, \mathbb{E}[H(\mathbf{h})] = 0, \mathbf{p} \in \mathbf{P}. \end{aligned} \quad (3.3)$$

Here the no-arbitrage constraint  $\mathbb{E}[H(\mathbf{h})] = 0$  indicates that the overall hedging cost—which includes commission fees, transaction costs, and margin requirements—is equal to the payout from financial hedging:  $\mathbb{E}[C(\mathbf{h})] = \mathbb{E}[R(\mathbf{h})e^{-\gamma t}]$ . So for a fixed capacity portfolio  $\mathbf{Q}$ ,

the expected profit remains unaffected by financial hedging. That is, financial hedging has no direct impact on expected profit; it can affect expected profit only if it alters the feasible set of capacity portfolios by minimizing CVaR (see Proposition 3.3 in Section 3.3.3). We assume that there exist methods (e.g., Black–Scholes formulas, delta–gamma approximations, pricing models of barrier options) for computing the derivative values. In this setting, the financial hedging contracts are “fairly priced” (Froot et al. 1993):

$$\mathbb{E}[C(\mathbf{h})] = \mathbb{E}[R(\mathbf{h})e^{-\gamma t}] = \begin{cases} \int_{\underline{s}}^{\bar{s}} \mathbf{h}_f^T (s_f - s) e(s) ds e^{-\gamma t} & \text{for } l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{fn}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}), \\ \int_{\underline{s}}^{s_b} \mathbf{h}_p^T [\mathbf{s}_p - \mathbf{s}]^+ e(s) ds e^{-\gamma t} & \text{for } l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}); \end{cases} \quad (3.4)$$

here  $[t]^+ = \max\{t, 0\}$ ,  $s_f$  is the contractual rate of the currency forwards,  $\mathbf{s}_b$  and  $\mathbf{s}_p$  denote (respectively) barrier and strike vectors of down-and-in puts, and superscript T denotes transposition. The global firm thus tailors its CVaR through a hedge portfolio of forwards or down-and-in put options (Carr et al. 1998). Hence the magnitude of monetary flow transferred via financial hedging is

$$\int_{\underline{s}}^{s_i} (R(\mathbf{h})e^{-\gamma t} - C(\mathbf{h}))e(s) ds = \int_{\underline{s}}^{\bar{s}} (R(\mathbf{h})e^{-\gamma t} - C(\mathbf{h}))e(s) ds, \quad (3.5)$$

where  $i = f$  for  $l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{fn}}(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  and  $i = b$  for  $l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y})$ . The left-hand side of equation (3.5) represents the expected positive payoff from financial hedging when there is a shortfall in operating cash flow (e.g., when the knock-in options exceed the stipulated barriers); the right-hand side represents the expected negative payoff (i.e., the costs and losses) of financial hedging when there is no shortfall in operating profit. Equation (3.5) indicates that financial hedging optimizes CVaR by transferring monetary flows from voluntary to binding positions across the probability space (cf. Caldentey and Haugh 2009).

For financial hedging only (i.e., financial hedging without operational flexibility), the loss function is

$$\begin{aligned} l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) &= -\Pi^{\text{fn}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{bc}} - H(\mathbf{h}) \\ &= -\sum s_i (p_i - c_i) \min(D_i, K_i) - R(\mathbf{h}) + \left( s_i \mathbf{c}_i^k \mathbf{Q}^T + C(\mathbf{h}) \right) e^{\gamma t}, \end{aligned}$$

where  $i = 1, 2$  and  $s_i = \begin{cases} 1, & \text{if } i = 1 \\ s, & \text{if } i = 2 \end{cases}$ . This loss function is *continuous* and linear w.r.t.  $\mathbf{h}$ . Hence CVaR can be calculated by minimizing the following auxiliary function with respect to the variable  $\alpha \in \mathbb{R}$  (Rockafellar and Uryasev 2000, 2002):

$$F_\beta(\mathbf{Q}, \mathbf{h}, \alpha) \triangleq \alpha + \frac{1}{1-\beta} \int_{\mathbf{y} \in \mathbb{R}^m} [l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) - \alpha]^+ f(\mathbf{y}) d\mathbf{y}. \quad (3.6)$$

Therefore,

$$\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \min_{\alpha \in \mathbb{R}} F_\beta(\mathbf{Q}, \mathbf{h}, \alpha).$$

In this case, the optimal financial hedging portfolio consists of forward contracts with expected payout  $\mathbb{E}[R(\mathbf{h})e^{-\gamma t}] = \int_{\underline{s}}^{\bar{s}} \mathbf{h}_f^T (s_f - s) e(s) ds e^{-\gamma t}$ .

For integrated risk management (i.e., financial hedging with operational flexibility), real options lead to multiple *discrete* loss functions (see Proposition 3.2 in Section 3.3.3) whose corresponding probabilities arise from the finite support of continuous uncertainty domains (see Table 3.3). In this case, operational flexibility can enlarge the feasible decision vector set w.r.t. the minimum expected profit. The multiple discrete loss functions imply that the  $\Psi(\mathbf{Q}, \mathbf{h}, \alpha)$  can have jumps at  $\alpha$  and that  $\text{CVaR}_\beta$  may “split the atom” of probability associated with the loss function in specific domains. In that case, the CVaR is the weighted average of VaR and  $\text{CVaR}^+$  (or expected shortfall):  $\text{CVaR}_\beta = \theta \text{VaR}_\beta + (1 - \theta) \text{CVaR}_\beta^+$ , for  $\theta = \frac{\Psi(\mathbf{Q}, \mathbf{h}, \alpha) - \beta}{1 - \beta}$ , and  $\text{CVaR}_\beta^+ = \mathbb{E}\{l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \mid l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) > \alpha\}$  (Rockafellar and Uryasev 2002). Hence  $\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  can be calculated as a weighted sum of the CVaR in each uncertainty domain and then optimized by sampling the probability density distribution  $f(\mathbf{y})$ ; that distribution has finite support  $\Omega_i$  ( $i = 1, 2, \dots, 10$ ) and its probabilities  $P_i$  generate a collection of vectors  $\mathbf{y}_i$ . Hence, CVaR can be minimized via the following formula (cf. Rockafellar and Uryasev 2002):

$$G_\beta(\mathbf{Q}, \mathbf{h}, \alpha) \triangleq \alpha + \frac{1}{1-\beta} \sum_{i=0}^n P_i [l(\mathbf{Q}, \mathbf{h}, \mathbf{y}_i) - \alpha]^+. \quad (3.7)$$

where  $n$  denotes the number of scenarios. The optimal financial hedging portfolio consists of deep out-of-the-money put options with expected payout  $\mathbb{E}[R(\mathbf{h})e^{-\gamma t}] = \int_{\underline{s}}^{s^b} \mathbf{h}_p^T [s_p - s]^+ e(s) ds$  when the loss distribution is fat tailed at rare and extreme low exchange rates.

**Proposition 3.1.** *The optimal financial hedging contract can be derived as follows:*

$$\mathbf{h}^* = \arg \min_{\mathbf{h} \in \mathbb{R}^n} \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \begin{cases} \arg \min_{\mathbf{h} \in \mathbb{R}^n} F_\beta(\mathbf{Q}, \mathbf{h}, \alpha) & \text{for } l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{fh}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}), \\ \arg \min_{\mathbf{h} \in \mathbb{R}^n} G_\beta(\mathbf{Q}, \mathbf{h}, \alpha) & \text{for } l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}), \end{cases}$$

$$\text{s. t. } \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})] \geq \rho, \quad \mathbb{E}[H(\mathbf{h})] = 0. \quad (3.8)$$

Moreover, if the optimal solution to financial hedging is not (necessarily) unique, then

$$(\mathbf{h}^*, C(\mathbf{h})^*) \in \arg \min_{\mathbf{h} \in \mathbb{R}^n} \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \Leftrightarrow \mathbf{h}^* \in \arg \min_{\mathbf{h} \in \mathbb{R}^n} \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}), C(\mathbf{h})^* \in \arg \min_{\mathbf{h} \in \mathbb{R}^n} C(\mathbf{h}^*).$$

According to Proposition 3.1, the MNC should adopt financial hedging whenever the operating cash flow falls below the VaR threshold that minimizes the profit shortfall (i.e., CVaR). The payoff from financial hedging aims to replicate (offset) the size of CVaR in the corresponding exchange rate interval based on a conditional expectation. In practice, the cost associated with a portfolio of knock-in barrier options—as derived using equations (3.4), (3.7), and (3.8) for integrated risk management—is typically lower than the similar currency options without a barrier. Even if the barrier options are not fully available in a derivative market, the payoff from an optimal financial hedging strategy can be replicated (or approximated) via a portfolio of forwards and simple options (Brown et al. 2001).

### 3.3.3 Optimal Operational Flexibility Strategy

In this section, we optimize the global firm's operational flexibility strategy. Since the mean-CVaR optimization is equivalent to maximizing the expected profit subject to a CVaR constraint (see Lemma 3.1), the firm's operational decisions w.r.t.  $\mathbf{Q} \in \mathbb{R}_+^3$  for  $\mathbf{p} = (\mathbf{Q}, \mathbf{h}) \in \mathbf{P}$  can be optimized by solving the following problem:

$$\max_{\mathbf{Q} \in \mathbb{R}_+^3} \mathbb{E}[\Pi(\mathbf{Q}, \mathbf{h}, \mathbf{y})] \quad (3.9)$$

$$\text{s. t. } \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) \leq \omega, \mathbf{p} \in \mathbf{P}.$$

We now use backward induction to characterize the global firm's optimal production planning and capacity investment in Stages 2 and 1, respectively.

#### Stage 2: (Ex Post) Production—Allocation Decisions.

**Proposition 3.2.** *The optimal production quantities  $\mathbf{q}_i^*$  in Stage 2 have one of the ten distinct forms listed in Table 3.3, depending on the realized capacity—demand matching states and exchange rates.*

Table 3.3. Optimal Production Quantities in Stage 2

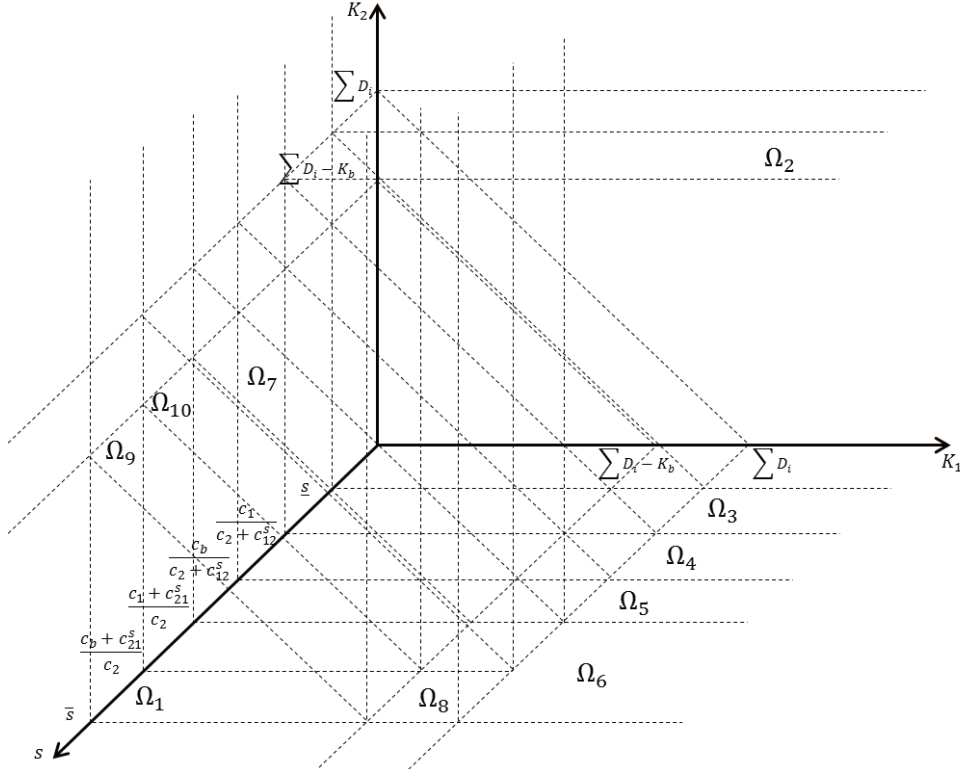
Domain	Optimal Strategy	$q_1^*$	$q_b^*$	$q_2^*$
$\Omega_1(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid \sum K_i < \sum D_i, s \in [\underline{s}, \bar{s}]\}$	Full capacity sourcing with allocation option	$K_1$	$K_b$	$K_2$
$\Omega_2(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid \sum D_i \leq K_2, s \in [\underline{s}, \frac{c_1}{c_2 + c_{12}^s}]\}$	Single sourcing from resource 2	0	0	$\sum D_i$
$\Omega_3(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid K_2 < \sum D_i \leq K_1 + K_2, s \in [\underline{s}, \frac{c_1}{c_2 + c_{12}^s}]\}$	Sourcing from resource 2 with hedge from 1	$\sum D_i - K_2$	0	$K_2$
$\Omega_4(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid \sum D_i \leq K_1 + K_2, s \in (\frac{c_1}{c_2 + c_{12}^s}, \frac{c_b}{c_2 + c_{12}^s}]\}$	Splitting with priority hedge from 2 and rerouting option	$\min(D_i, K_i) + (D_2 - K_2)^+$	0	$\min(D_2, K_2) + (D_1 - K_1)^+$
$\Omega_5(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid \sum D_i \leq K_1 + K_2, s \in (\frac{c_b}{c_2 + c_{12}^s}, \frac{c_1 + c_{21}^s}{c_2}]\}$	Splitting with priority hedge from backup capacity and rerouting option	$\min(D_i, K_i) + (D_2 - K_2)^+$	$(D_1 - K_1)^+$	$\min(D_2, K_2) + (D_1 - K_1 - K_b)^+$
$\Omega_6(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid \sum D_i \leq K_1, s \in (\frac{c_1 + c_{12}^s}{c_2}, \bar{s}]\}$	Single sourcing from resource 1	$\sum D_i$	0	0
$\Omega_7(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid K_1 < \sum D_i \leq K_1 + K_2, s \in (\frac{c_1 + c_{12}^s}{c_2}, \frac{c_b + c_{21}^s}{c_2}]\}$	Sourcing from resource 1 with hedge from 2	$K_1$	0	$\sum D_i - K_1$
$\Omega_8(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid K_1 < \sum D_i \leq K_1 + K_b, s \in (\frac{c_b + c_{21}^s}{c_2}, \bar{s}]\}$	Sourcing from resource 1 with hedge from backup capacity	$K_1$	$(\sum D_i - K_1)^+$	0
$\Omega_9(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid K_1 + K_b < \sum D_i \leq \sum K_i, s \in (\frac{c_b + c_{21}^s}{c_2}, \bar{s}]\}$	Sourcing from resource 1 and backup capacity with hedge from 2	$K_1$	$K_b$	$\sum D_i - K_1 - K_b$
$\Omega_{10}(Q) = \{\mathbf{R} \in \mathbb{R}^2 \mid K_1 + K_2 < \sum D_i \leq \sum K_i, s \in [\underline{s}, \frac{c_b + c_{21}^s}{c_2}]\}$	Sourcing from resources 1 and 2 with hedge from backup capacity	$K_1$	$\sum D_i - K_1 - K_2$	$K_2$

The cash flow in Stage 2 resulting from operational decisions is

$$\Pi^{\text{int}}(Q, y) = s_j p_j d_j^{*T} - s_i c_i q_i^{*T} - s_j c_{ij}^s q_{ij}^{*T} - s_j c_{ij}^a q_{ij}^{*T} - s_i c_i^k Q^T e^{\gamma t}, \quad (3.10)$$

where  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1 & \text{if } j = 1 \\ s & \text{if } j = 2 \end{cases}$ .

Figure 3.3. Operational Flexibility Strategies in Domains of Uncertainty



Proposition 3.2 indicates how the global firm should execute backup production and switching options in Stage 2 to form the optimal production–allocation strategies in response to uncertainty realizations. The domains of uncertainty in Table 3.3 are illustrated by Figure 3.3, where the horizontal and vertical axes depict the relative positions of supply (capacity) and demand states and where a third dimension of uncertainty is added by the exchange rates.

**Stage 1: (Ex Ante) Capacity Investment Decisions.** In the first stage, the optimal solutions to capacity investment under uncertainty can be characterized by matching capacity costs with weighted capacity shadow prices—that is, the marginal profit obtained by adding one unit of capacity. Using the necessary and sufficient Kuhn–Tucker conditions, we formalize the optimal ex ante capacity investment decisions.

**Proposition 3.3.** A capacity vector  $\mathbf{Q}^* \in \mathbb{R}_+^3$  is optimal if and only if there exists a  $\boldsymbol{\delta} \in \mathbb{R}_+^3$  such that

$$\begin{aligned} \mathbf{c}^k e^{\gamma t} - \boldsymbol{\delta} &= \sum P(\Omega_i(\mathbf{Q}^*)) \boldsymbol{\mu}(\mathbf{Q}, \Omega_i), \quad \boldsymbol{\delta}^T \mathbf{Q}^* = 0, \\ \text{s. t. } \text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y}) &\leq \omega. \end{aligned} \quad (3.11)$$

Table 3.4. Capacity Shadow Prices in Stage 1

Domain	$\boldsymbol{\mu}(\mathbf{Q}, \Omega_i)$				
	a	b	c	d	e
$\Omega_1(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid \sum K_i < \sum D_i, s \in [\underline{s}, \bar{s}]\}$	$p_1 - c_1$ $p_1 - c_b$ $s(p_2 - c_2)$	$p_1 - c_1$ $p_1 - c_b$ $p_1 - sc_2 + sc_{12}^s$	$sp_2 - c_1 - sc_{12}^s$ $sp_2 - c_b - sc_{12}^s$ $s(p_2 - c_2)$	$sp_2 - c_1 + c_{21}^s$ $sp_2 - c_b + c_{21}^s$ $s(p_2 - c_2)$	$p_1 - c_1$ $p_1 - c_b$ $p_1 - sc_2 - c_{21}^s$
$\Omega_2(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid \sum D_i \leq K_2, s \in [\underline{s}, \frac{c_1}{c_2 + c_{12}^s}]\}$			0	0	0
$\Omega_3(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid K_2 < \sum D_i \leq K_1 + K_2, s \in [\underline{s}, \frac{c_1}{c_2 + c_{12}^s}]\}$			0	0	0
$\Omega_4(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid \sum D_i \leq K_1 + K_2, s \in (\frac{c_1}{c_2 + c_{12}^s}, \frac{c_b}{c_2 + c_{12}^s}]\}$	a 0 0 0	b 0 0 $c_1 + c_{21}^s - sc_2$	$c_1 - sc_2 - sc_{12}^s$ or $c_1 - sc_2 + sc_{21}^s$	c $sc_{12}^s + sc_2 - c_1$ 0	c 0 0
$\Omega_5(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid \sum D_i \leq K_1 + K_2, s \in (\frac{c_b}{c_2 + c_{12}^s}, \frac{c_1 + c_{21}^s}{c_2}]\}$	a $c_b - c_1$ or 0 0	b 0 0 $c_1 + c_{21}^s - sc_2$	0 0 0	$sc_{12}^s + sc_2 - c_1$ $sc_{12}^s + sc_2 - c_b$ 0	c 0 0
$\Omega_6(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid \sum D_i \leq K_1, s \in (\frac{c_1 + c_{12}^s}{c_2}, \bar{s}]\}$			0 0 0	0 0 0	0 0 0
$\Omega_7(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid K_1 < \sum D_i \leq K_1 + K_2, s \in (\frac{c_1 + c_{12}^s}{c_2}, \frac{c_b + c_{21}^s}{c_2}]\}$			$sc_2 - c_1 - c_{21}^s$ or $sc_2 - c_1 + sc_{12}^s$	0 0 0	0 0 0
$\Omega_8(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid K_1 < \sum D_i \leq K_1 + K_b, s \in (\frac{c_b + c_{21}^s}{c_2}, \bar{s}]\}$			$c_b - c_1$ 0 0	0 0 0	0 0 0
$\Omega_9(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid K_1 + K_b < \sum D_i \leq \sum K_i, s \in (\frac{c_b + c_{21}^s}{c_2}, \bar{s}]\}$			$sc_2 - c_1 - c_{21}^s$ or $sc_2 - c_1 + sc_{12}^s$ $sc_2 - c_b - c_{21}^s$ or $sc_2 - c_b + sc_{12}^s$	0 0 0	0 0 0
$\Omega_{10}(\mathbf{Q}) = \{\mathbf{R}\epsilon \mathbb{R}^2 \mid K_1 + K_2 < \sum D_i \leq \sum K_i, s \in [\underline{s}, \frac{c_b + c_{21}^s}{c_2}]\}$			$c_b - c_1$ 0 0	0 0 0	0 0 0
			$c_b - sc_2 - sc_{12}^s$ or $c_b - sc_2 + c_{21}^s$		

Here  $P(\Omega_i(\mathbf{Q}^*))$  denotes the respective (positive) probability of each uncertainty domain; the capacity shadow prices  $\mu_j(\mathbf{Q}, \Omega_i)$  ( $j = 1, 2, b$ ) that correspond to the uncertainty space partitions are given in Table 3.3. Capacity shadow prices can be weighted by the probabilities of each scenario being realized in Stage 2. Depending on production – allocation plans in Stage 2, there are subcases of domains  $\Omega_1, \Omega_4$ , and  $\Omega_5$  (denoted in Table 3.4 as a, b, c, d, e) that differ in their capacity shadow prices (see proof of Proposition 3.2). Furthermore, the CVaR constraint  $\omega$  indicates that the adoption of optimal financial hedging (see Section 3.3.2) can affect operations strategy by altering the feasible set of capacity portfolios.

### 3.4 Interplay between Operations and Finance

We next explore the relationships among backup production, switching options, and financial hedging when there are mean-CVaR trade-offs.

#### 3.4.1 Relationship between Backup Production and Switching Options

In order to determine whether backup production and switching options are complements or substitutes, we first examine the joint and respective values of switching options and backup production.

**Definition 3.2.** The *value* of operational flexibility is the increment in the mean-CVaR utility it creates – relative to the base case – via backup production and/or switching options.

**Proposition 3.4.** *The value of backup production only is*

$$\Delta U[\Pi^{\text{bp}}] = (1 + \lambda) \sum P(\Omega_i(\mathbf{Q}^*)) (q_b^* (p_1 - c_b) - c_b^k K_b).$$

*The value of switching options only is*

$$\Delta U[\Pi^{\text{sw}}] = (1 + \lambda) \sum P(\Omega_i(\mathbf{Q}^*)) q_{ij}^{s^*} (s_i c_i - s_j c_j - s_j c_{ij}^s);$$

where  $i \neq j$ ,  $s_i = \begin{cases} 1, & i = 1 \\ s, & i = 2 \end{cases}$  and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .



The value of full operational flexibility is

$$\Delta U[\Pi^{\text{op}}] = (1 + \lambda)(\mathbb{E}[\Pi^{\text{op}}] - \mathbb{E}[\Pi^{\text{bc}}]).$$

**Definition 3.3.** Backup production and switching options are complements, separate, or substitutes according as whether (respectively)  $\Delta U[\Pi^{\text{op}}] > \Delta U[\Pi^{\text{sw}}] + \Delta U[\Pi^{\text{bp}}]$ ,  $\Delta U[\Pi^{\text{op}}] = \Delta U[\Pi^{\text{sw}}] + \Delta U[\Pi^{\text{bp}}]$ , or  $\Delta U[\Pi^{\text{op}}] < \Delta U[\Pi^{\text{sw}}] + \Delta U[\Pi^{\text{bp}}]$ .

Because backup production and switching options both represent excess capacity that hedges mismatch risk and exchange rate uncertainty, one might well expect them to be substitutes. However, the following theorem shows that they can also be complements.

**Theorem 3.1.** Backup production and switching options are complements if both are used to fulfill foreign demand, whereas they are substitutes when both are used to fulfill domestic demand. The interaction effects between backup production and switching options (i.e., the value increment in the firm's utility) are

$$\begin{aligned} \Delta U[\text{sw, bp}] &= P\left(\frac{p_1 + c_{21}^s}{p_2} < s \leq \bar{s}\right) \min(q_b^*, q_{21}^{s*}) |sc_2 - c_b - c_{21}^s| \\ &+ P\left(\frac{c_b}{c_2 + c_{12}^s} \leq s < \frac{p_1}{c_{12}^s + p_2}\right) \{\min([D_1 - K_1 - K_b]^+, K_2) - \min([D_1 - K_1]^+, K_2)\} (p_1 - sp_2 - sc_{12}^s) + \\ &P\left(s_t \leq s < \frac{c_b}{c_2 + c_{12}^s}\right) \{\min([D_1 - K_1 - K_2]^+, K_b) - \min([D_1 - K_1]^+, K_b)\} (p_1 - c_b) + (1 + \\ &\lambda) P(\underline{s} \leq s < s_t) \{\min([D_1 - K_1 - K_2]^+, K_b) - \min([D_1 - K_1]^+, K_b)\} (p_1 - c_b). \quad (3.12) \end{aligned}$$

Here  $s_t = \max\{s \in [\underline{s}, \bar{s}] : l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) < \alpha\}$ . The first term on the right-hand side of (3.12) is nonnegative and represents the complementary effects when switching options use domestic backup capacity to fulfill foreign demand  $D_2$ . In contrast, the second, third, and fourth terms on the right-hand side of (3.12) are nonpositive; they capture the substitution effects when both backup capacity and switching options are used to fulfill domestic demand  $D_1$ . In sum, the relationship between backup production and switching options depends on whether the complementary or substitutive effects are more significant.

### 3.4.2. Interaction between Operational Flexibility and Financial Hedging

We now assess the relationship between financial hedging and operational flexibility by examining the value of financial hedging in the absence of operational flexibility (i.e., w.r.t. the base case) and also in its presence (i.e., w.r.t. full operational flexibility).

**Definition 3.4.** The *value* of financial hedging in the absence (resp., presence) of operational flexibility is the increment in the mean-CVaR utility relative to the base case (resp., to full operational flexibility) created via currency derivatives.

**Proposition 3.5.** *The value of optimal financial hedging in the absence of operational flexibility is*

$$\Delta U[\text{FH}^{\text{bc}}] = \lambda(\text{CVaR}_{\beta}^{\text{bc}} - \text{CVaR}_{\beta}^{\text{fh}}) + (\mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]). \quad (3.13)$$

*The value of optimal financial hedging in the presence of operational flexibility is*

$$\Delta U[\text{FH}^{\text{op}}] = \lambda(\text{CVaR}_{\beta}^{\text{op}} - \text{CVaR}_{\beta}^{\text{int}}) + (\mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}]). \quad (3.14)$$

Proposition 3.5 implies that the value of financial hedging with or without operational flexibility consists of two factors: (i) risk reduction effects, as described by the first term on the right-hand side of equation (3.13) or (3.14); and (ii) profit enhancement effects, as described by the second term on the right-hand side of those equations.

**Definition 3.5.** Operational flexibility and financial hedging are complements, separate, or substitutes according as whether (respectively)  $\Delta U[\text{FH}^{\text{op}}] > \Delta U[\text{FH}^{\text{bc}}]$ ,  $\Delta U[\text{FH}^{\text{op}}] = \Delta U[\text{FH}^{\text{bc}}]$ , or  $\Delta U[\text{FH}^{\text{op}}] < \Delta U[\text{FH}^{\text{bc}}]$ .

**Theorem 3.2.** *Operational flexibility and financial hedging are substitutes in risk reduction. These two mechanisms can be complements in profit enhancement only if financial hedging increases the feasible set of capacity portfolios by relaxing the CVaR constraint. Their interaction effects (i.e., the value increment in the firm's utility) are given as follows:*

$$\Delta U[\text{fh, op}] = \lambda(\text{CVaR}_{\beta}^{\text{op}} - \text{CVaR}_{\beta}^{\text{bc}} + \text{CVaR}_{\beta}^{\text{fh}} - \text{CVaR}_{\beta}^{\text{int}}) + (\mathbb{E}[\Pi^{\text{bc}}] - \mathbb{E}[\Pi^{\text{fh}}] + \mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}]).$$

This theorem states that the interaction effects between operational flexibility and financial hedging are determined by two factors, the first of which is the risk reduction interaction:  $\lambda(\text{CVaR}_{\beta}^{\text{op}} - \text{CVaR}_{\beta}^{\text{bc}} + \text{CVaR}_{\beta}^{\text{fh}} - \text{CVaR}_{\beta}^{\text{int}}) < 0$ . Therefore, operational flexibility and financial hedging are substitutes with respect to risk reduction. The second factor is the profit enhancement interaction:  $\mathbb{E}[\Pi^{\text{bc}}] - \mathbb{E}[\Pi^{\text{fh}}] + \mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}] > 0$  if and only if  $\mathbb{E}[\Pi^{\text{int}}] -$

$\mathbb{E}[\Pi^{\text{op}}] > \mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]$  (see Appendix 3A). Operational flexibility and financial hedging can therefore be complements with respect to profit enhancement.

In order to demonstrate the interactions of operational flexibility and financial hedging, we next conduct an efficient frontier analysis (Figure 3.4) following the approach of Van Mieghem (2003, p. 295). This demonstration is motivated by our understanding that optimizing mean-CVaR is equivalent to minimizing CVaR with a minimum expected profit and also to maximizing the expected profit subject to a CVaR constraint based on generating the same efficient frontier (see Lemma 3.1).

**Definition 3.6.** A portfolio of real and financial assets  $\mathbf{p} = (\mathbf{Q}, \mathbf{h})$  is *efficient* if and only if there does not exist another portfolio  $\mathbf{p}'$  such that  $U[\Pi(\mathbf{p}')] > U[\Pi(\mathbf{p})]$ .

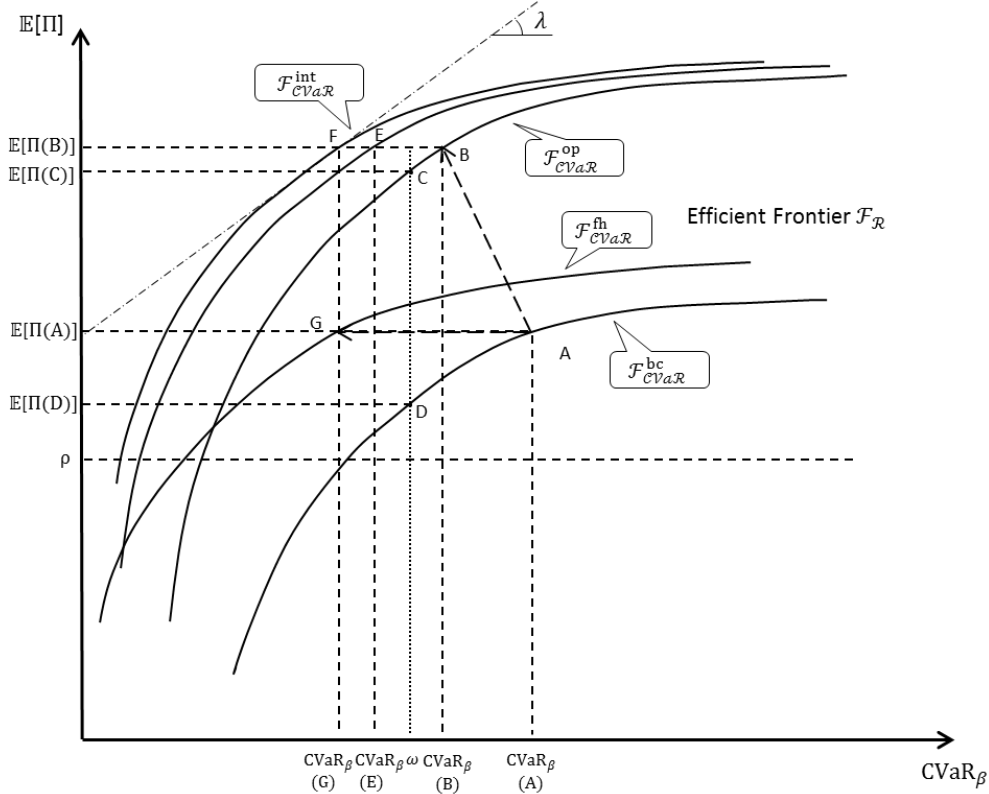
**Definition 3.7.** The efficient frontier  $\mathcal{F}_{\text{CVaR}}^x$  for strategy  $x = \text{bc, bp, sw, op, fh, int}$  (Definition 3.1) is the set of mean-CVaR pairs of efficient portfolios:

$$\mathcal{F}_{\text{CVaR}}^x = \{(\mathbb{E}[\Pi^x(\mathbf{p})], \text{CVaR}_\beta^x(\mathbf{p})) \mid \mathbf{p} \text{ is efficient}\}.$$

The global firm's initial frontier of its mean-CVaR objective is denoted by  $\mathcal{F}_{\text{CVaR}}^{\text{bc}}$  in Figure 3.4, where point A denotes the optimal value of the MNC's portfolio in the base case. Adopting operational flexibility and/or financial hedging enables the firm to improve its objective function by shifting northwest the efficient (Pareto-optimal) frontier of its portfolio  $\mathbf{p}$  of real and financial assets. The expected profit  $\mathbb{E}[\Pi(\text{B})]$  represents the maximum expected profit attainable by full operational flexibility (e.g., at points B, E, and F); here  $\mathbb{E}[\Pi(\text{B})] > \mathbb{E}[\Pi(\text{C})] > \mathbb{E}[\Pi(\text{A})] > \mathbb{E}[\Pi(\text{D})] > \rho$ . Observe that  $\text{CVaR}_\beta(\text{G})$  and  $\text{CVaR}_\beta(X)$  for  $X = \text{E, F}$  denote the minima of CVaR attainable via, respectively, financial hedging only (at point G) and integrated risk management (at points E or F).

In the base case we see that, even though the firm's expected profit can be maximized at point A, the risk-averse decision maker would choose point D by virtue of the CVaR constraint because  $\text{CVaR}_\beta(\text{D}) = \omega$  and  $\mathbb{E}[\Pi(\text{D})] > \rho$ . In the case of financial hedging only, the efficient frontier is shifted *due west* to  $\mathcal{F}_{\text{CVaR}}^{\text{fh}}$  by vector  $\overrightarrow{\text{AG}}$ , where  $\text{CVaR}_\beta(\text{G}) < \omega$ ; in this case, the profit-maximizing point G can then be selected. Hence the value of optimal financial

Figure 3.4. Efficient Frontier Analysis: Interplay between Operations and Finance



hedging without operational flexibility is  $\Delta U[\text{FH}^{\text{bc}}] = \lambda(\text{CVaR}_\beta^{\text{bc}} - \text{CVaR}_\beta^{\text{fh}}) + \mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]$  (see Proposition 3.5). Under full operational flexibility, real options shift the efficient frontier northwest to  $\mathcal{F}_{\text{CVaR}}^{\text{op}}$  by vector  $\overrightarrow{\text{AB}}$ , where the firm's expected profit can be maximized at point B; in this case the decision maker would similarly choose point C subject to the CVaR constraint, where  $\text{CVaR}_\beta(\text{C}) = \omega$ .

For integrated risk management, we distinguish two cases as follows. First, if financial hedging decreases the firm's CVaR to point E, where  $\text{CVaR}_\beta(\text{E}) = \text{CVaR}_\beta^{\text{int}} > \text{CVaR}_\beta(\text{G}) = \text{CVaR}_\beta^{\text{fh}}$ , then operational flexibility and financial hedging are substitutes in risk reduction because of their interaction effects with respect to CVaR:  $\lambda(\text{CVaR}_\beta^{\text{op}} - \text{CVaR}_\beta^{\text{bc}} + \text{CVaR}_\beta^{\text{fh}} - \text{CVaR}_\beta^{\text{int}}) < 0$ . Second, if financial hedging decreases CVaR to point F, where  $\text{CVaR}_\beta(\text{F}) = \text{CVaR}_\beta^{\text{int}} = \text{CVaR}_\beta(\text{G}) = \text{CVaR}_\beta^{\text{fh}}$ , then operational flexibility and financial hedging are substitutes in risk reduction given their interaction effects in CVaR:  $\lambda(\text{CVaR}_\beta^{\text{op}} - \text{CVaR}_\beta^{\text{bc}}) < 0$ . Yet the profit enhancement interaction,  $\mathbb{E}[\Pi^{\text{bc}}] - \mathbb{E}[\Pi^{\text{fh}}] + \mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}]$ , depends on the expected profit increments from financial hedging with and without operational flexibility. If  $\mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}] > \mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]$ , then operational flexibility and financial hedging are

complements in profit enhancement; if  $\mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}] \leq \mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]$ , then operational flexibility and financial hedging are strictly substitutes owing to their interaction effects (Theorem 3.2):  $\Delta U[\text{fh}, \text{op}] < 0$ .

The intuition behind this efficient frontier analysis is as follows. First, the heterogeneity of operational flexibility and financial hedging leads to their complementarity in two key aspects. On the one hand, operational flexibility enhances profitability and reduces downside risk; financial hedging reduces downside risk to a minimum and can affect profitability only if it enlarges the feasible set of capacity portfolios by relaxing the CVaR constraint (see Proposition 3.3). This result is in line with the literature on integrated risk management (Smith and Stulz 1985, Mello et al. 1995, 1996). On the other hand, operational flexibility can be viewed as a portfolio of “knock-out” (a term that alludes to the level of flexibility being subject to capacity investment) call/put real options written on costs in foreign/home currency. In contrast, a financial hedging portfolio of “knock-in” put options on foreign currency mitigates the impact of rare and extreme low exchange rates on the MNC’s cash flow.

Second, given operational flexibility, financial hedging is viable only in the event of rare and extreme exchange rates; the reason is that real options are expected to generate greater profits otherwise. In contrast, under financial hedging only, the result is larger risk reduction effects; that outcome reflects the substitution effects between operational flexibility and financial hedging in reducing risk. This result is consistent with empirical evidence on the interaction between financial and operational hedging, which shows a marked decrease in the use of financial derivatives as firms adopt more real options to manage currency risk exposure (Aabo and Simkins 2005, Kim et al. 2006).

Third, even though a mean-CVaR optimization problem can be decomposed into CVaR minimization via financial hedging with a minimum expected profit and expected profit maximization by operational flexibility subject to a CVaR constraint (see Lemma 3.1), collaboration and coordination between operations and finance is needed to minimize substitution effects in the mean-CVaR utility (see Theorem 3.2)—especially with respect to risk reduction. Hence information exchange between operations and finance is crucial: efficient financial hedging relies on a rigorous estimation of the probability distribution of

cash flow as shaped by operational flexibility, while the feasible set of capacity portfolios depends on financial hedging by virtue of the CVaR constraint.

### 3.5 Robustness Analysis

This section examines the robustness of our main results (Theorems 3.1 and 3.2) by means of an extensive numerical study. Examples are provided to demonstrate the relative effectiveness of operational flexibility and financial hedging as well as the effects of exchange rate volatility, demand volatility, and the CVaR confidence interval on firm performance. Unless stated otherwise, the figures illustrating our numerical results are representative of all parameter combinations that we examined.

The numerical study relies on optimization via simulation using Palisade @RISK software with 32,000 uncertainty scenarios (supply – demand matching and exchange rates) and the following benchmark parameter values:  $p_i = 10$ ,  $c_i = 7$ ,  $c_b = 7.5$ ,  $c_{ij}^a = c_{ij}^s = 1$ ,  $c_i^k e^{\gamma t} = 0.6$ ,  $c_b^k e^{\gamma t} = 1.2$ ,  $\lambda = 0.5$ , and  $R_i \sim \text{Unif}(0.91, 1)$  for  $i, j = 1, 2$  with  $i \neq j$ . Because the difference between VaR and CVaR as a risk measure is negligible for normal distributions (Sarykalin et al. 2008, p. 280), for exchange rate we choose a uniform distribution,  $s \sim \text{Unif}(0.55, 1.45)$  (cf. Chowdhry and Howe 1999; see also Appendix 3B), whose interval varies with its coefficient of variation. Demands  $D_1$  and  $D_2$  are each uniformly distributed,  $D_i \sim \text{Unif}(25, 125)$  for  $i = 1, 2$  (see Appendix 3B), where again the interval varies with the coefficient of variation. Demand and exchange rates are independent and jointly represent the ten uncertainty domains defined in Table 3.3, whose probabilities  $P_i$  ( $i = 1, 2, \dots, 10$ ) are assumed to be equal.

Table 3.5. Relative Effectiveness of Operational Flexibility and Financial Hedging

Base case			Full operational flexibility			$(\mathbf{T}^{\text{op}} - \mathbf{T}^{\text{bc}})/\mathbf{T}^{\text{bc}}$ ( $\mathbf{T} = U_{0.95}^*, E^*, \text{CVaR}_{0.95}^*$ )		
$U_{0.95}^*$	$E^*$	$\text{CVaR}_{0.95}^*$	$U_{0.95}^*$	$E^*$	$\text{CVaR}_{0.95}^*$	$U_{0.95}^*$	$E^*$	$\text{CVaR}_{0.95}^*$
253.59	205.17	-96.83	300.86	234.39	-132.93	18.64%	14.24%	37.29%
Financial hedging only			Integrated risk management			$(\mathbf{T}^{\text{int}} - \mathbf{T}^{\text{fh}})/\mathbf{T}^{\text{fh}}$		
264.95	209.57	-110.76	306.97	238.73	-136.49	15.86%	13.91%	23.22%
$(\mathbf{T}^{\text{fh}} - \mathbf{T}^{\text{bc}})/\mathbf{T}^{\text{bc}}$			$(\mathbf{T}^{\text{int}} - \mathbf{T}^{\text{op}})/\mathbf{T}^{\text{op}}$			$(\mathbf{T}^{\text{int}} - \mathbf{T}^{\text{bc}})/\mathbf{T}^{\text{bc}}$		
4.48%	2.14%	14.39%	2.03%	1.85%	2.67%	21.05%	16.36%	40.96%

Table 3.5 verifies Theorem 3.2 by showing that operational flexibility and financial hedging are substitutes in risk reduction: both risk management strategies increase expected utility and decrease the CVaR. In this benchmark example, operational flexibility increases the expected profit by 14.24%, whereas financial hedging has little effect (+2.14%) owing to the

no-arbitrage assumption, given that financial hedging can enhance expected profit only if it enlarges the feasible set of capacity portfolios by relaxing the CVaR constraint. As discussed in Section 3.4.2, operational flexibility provides the benefits of profit enhancement and risk reduction; financial hedging minimizes risk, yet its profit enhancement depends on whether the CVaR constraint is binding in its absence. When the firm adopts only one of these two risk management strategies, their relative effectiveness depends on the relative magnitudes of the resulting profit enhancement and risk reduction, which in turn are a function of the magnitude of the switching/allocation costs and the degree of the firm's risk aversion. The risk reduction effect from integrated risk management (40.96%) is less than the sum of full operational flexibility and financial hedging only (37.29% + 14.39% = 51.68%) because of their interaction effects. However, integrated risk management improves the firm's expected utility more significantly: by 21.05%, as compared with using full operational flexibility (18.64%) or financial hedging only (4.48%). These results are consistent with the empirical findings of Allayannis et al. (2001), Aabo and Simkins (2005), and Kim et al. (2006).

### 3.5.1 Impact of Exchange Rate Variability

We next examine how exchange rate volatility affects the global firm's capacity investment and performance for the six strategies described in Definition 3.1. When adjusting the exchange rate's volatility, we allow its coefficient of variation  $\delta(s)$  to vary between 0.17 and 0.26; while keeping the expectation  $\mathbb{E}[s]$  at a constant level of 1.05 (In our one-period setting, exchange rate variability is assumed to move within a certain range—for example, 30%; cf. De Grauwe 1988). The effect of increasing volatility in the exchange rate is illustrated in Figures 3.5(a)–(f).

Figure 3.5(a) shows that optimal total capacity is decreasing in exchange rate volatility. Absent financial hedging, a capacity hedge (via real options) is the only risk management instrument; this explains why, given the CVaR constraint, the optimal capacity decreases quickly as exchange rate volatility increases. When financial hedging is employed—that is, under financial hedging only or integrated risk management (see Figure 3.5)—optimal total capacity is less sensitive to exchange rate volatility because the currency exposure in CVaR is significantly reduced by financial hedging. Figure 3.5(b) shows that: the firm's expected profit is increasing in exchange rate volatility under full operational flexibility or integrated risk management, that the expected profit is much less affected under financial hedging only

or switching options only, and that the expected profit is decreasing in exchange rate volatility both for the base case and backup production only. These findings highlight that a higher level of flexibility and/or hedging increases the firm's ability to mitigate currency risk.

Figure 3.5. Effect of Exchange Rate Volatility on (a) Optimal Capacity; (b) Expected Profit; (c) and (e) CVaR; (d) and (f) Expected Utility

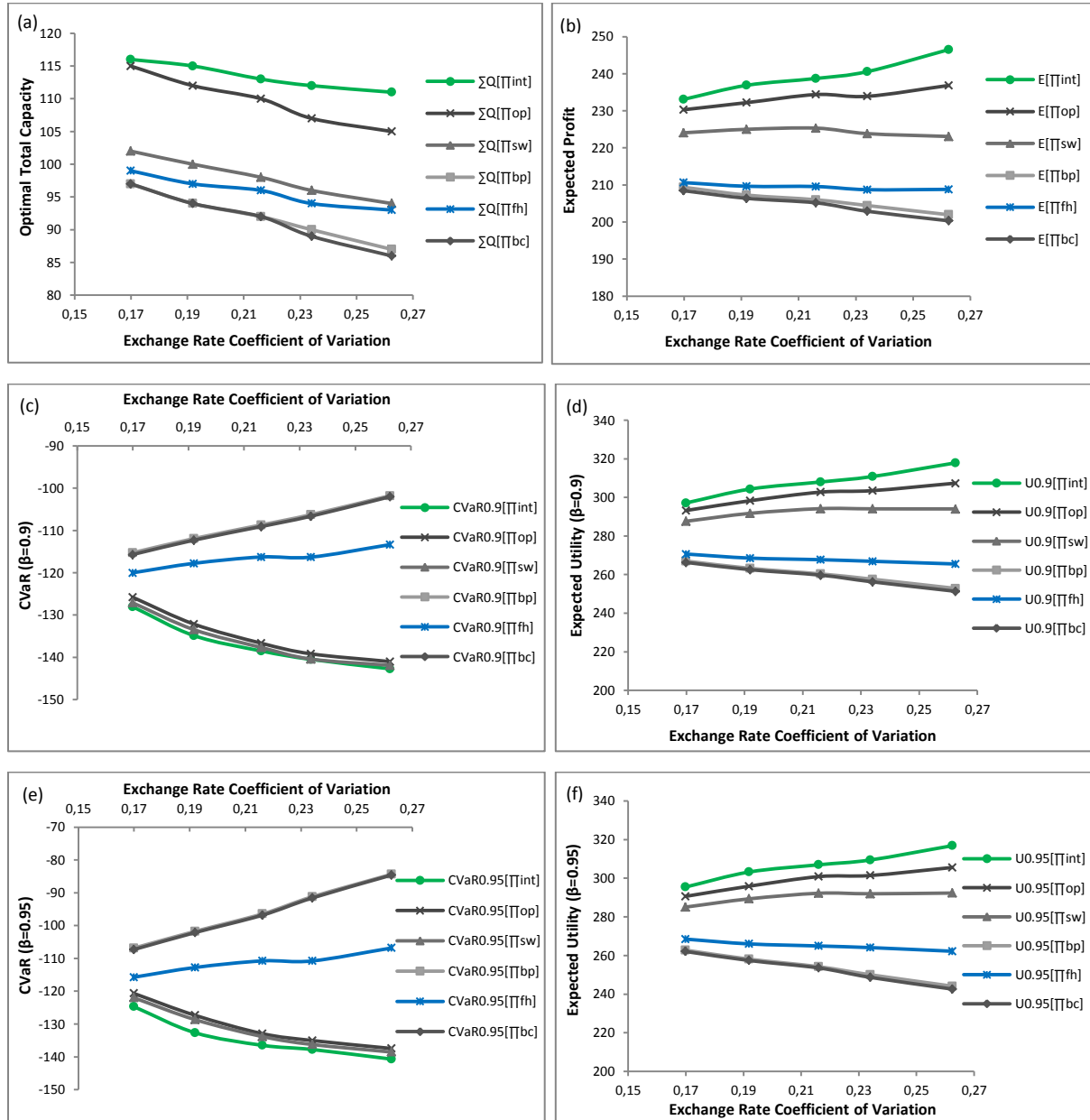


Figure 3.5(c) illustrates the risk reduction effects of financial hedging and real options with respect to increasing exchange rate volatility. The CVaR is increasing significantly in exchange rate volatility for the base case and for backup production only; the increase is much less under financial hedging only. In contrast, the CVaR is significantly decreasing in exchange rate volatility for firms that employ switching options only, full operational



flexibility, or integrated risk management. These results indicate that switching options become more effective at reducing risk as exchange rate volatility increases. That the CVaR is slightly increasing in exchange rate volatility under financial hedging only is consistent with results reported in Ding et al. (2007), who find that financial hedging makes profit variance less sensitive to a decrease in optimal capacity and hence slightly increasing in a MV model. However, the result that CVaR is *decreasing* in exchange rate volatility under integrated risk management differs from the findings of Ding et al. (2007), where profit variance is increasing under joint operational and financial hedging in a MV model. This difference stems from three key factors: we have incorporated the possibility of backup production, we assume that financial hedging is arbitrage-free, and we use CVaR for our downside risk measure. The expected utilities of firms that use switching options increase with exchange rate volatility but decrease (albeit at a slower rate) without switching options (i.e., for the base case, financial hedging only, and backup production only); see Figure 3.5(d). Figures 3.5(e) and 3.5(f) demonstrate that the confidence interval of CVaR (i.e., the level of risk aversion) has little influence on the relative effectiveness of financial hedging and real options with respect to CVaR and expected utilities.

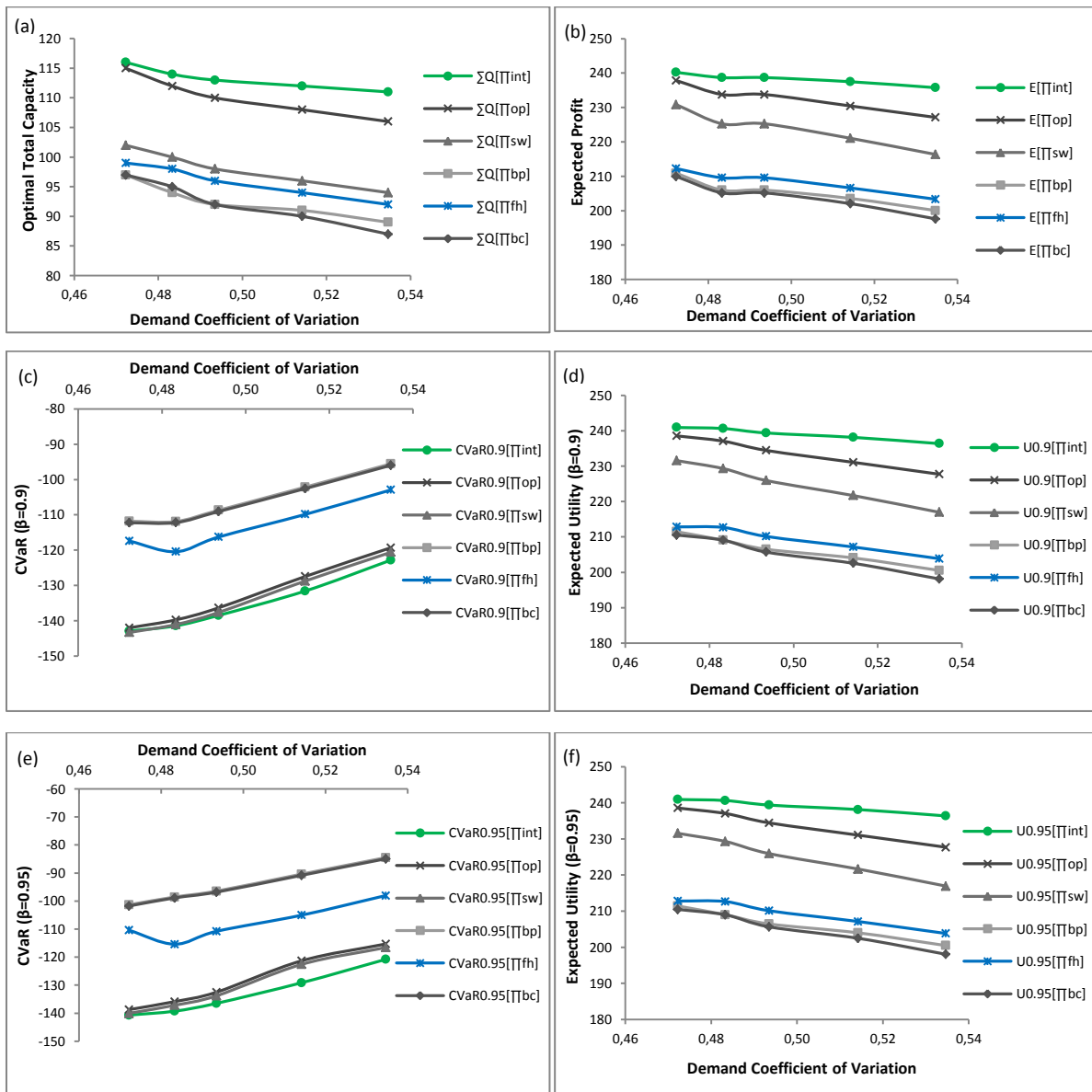
### 3.5.2 Impact of Demand Variability

In order to study the effect of demand volatility, we vary the coefficient of variation of demand,  $\delta(D_i)$ , from 0.47 to 0.53 while keeping its expectation,  $\mathbb{E}[D_i]$ , at a constant level of 41.8. Figure 3.6(a) illustrates that optimal total capacity is decreasing in demand volatility whereas financial hedging makes capacity investment (slightly) less sensitive to demand volatility. The latter result follows because financial hedging reduces currency risk and thereby alters the feasible set of capacity portfolios with respect to the CVaR constraint; hence demand volatility will have less of an impact on optimal total capacity. Figure 3.6(b) demonstrates that expected profit decreases owing to the decrease in optimal capacity under all six strategies—an effect that differs from the one shown in Figure 3.5(b).

Contrary to Figure 3.5(c) and the observations in Ding et al. (2007), Figure 3.6(c) shows that CVaR increases in demand volatility for the six strategies. This increase is slightly less significant with than without financial hedging, which is consistent with demand uncertainty being a *private* risk that cannot be hedged in the financial market (as argued by Chen et al. 2007). Figure 3.6(c) reveals that, in comparison with Figure 3.5(c), financial

hedging and switching options are less effective in reducing demand volatility risk than in reducing exchange rate risk. Figure 3.6(d) illustrates that the net effect on expected utility is decreasing in demand volatility. The presence of financial hedging slows down the decrease in mean-CVaR utility because optimal total capacity becomes relatively insensitive to demand volatility. Figures 3.6(e) and 3.6(f) show that the change in the CVaR's confidence interval,  $\beta$ , has little effect on the structure of results involving CVaR and expected utility.

Figure 3.6. Effect of Demand Volatility on (a) Optimal Capacity; (b) Expected Profit; (c) and (e) CVaR; (d) and (f) Expected Utility



### 3.6 Conclusions

This chapter contributes to the literature on integrated operational flexibility and financial hedging by exploring the relationships among backup production, switching options, and financial hedging in a mean-CVaR model. The three principle findings of our study are as follows. First, backup production and switching options are complements when both are used to fulfill foreign demand but are substitutes when both are used to fulfill domestic demand. Operational flexibility and financial hedging are substitutes in risk reduction, yet they can be complements in profit enhancement if financial hedging enlarges the feasible set of capacity portfolios by relaxing the CVaR constraint. It is therefore crucial that the MNC ensures effective information exchange between operations and finance. Second, with operational flexibility, financial hedging is viable only under rare and extreme exchange rates; otherwise, real options are relatively more effective at generating above-target expected profit. Overall, the integration of these strategies creates value because its expected utility is strictly greater than that of any single strategy. Third, switching options and financial hedging are better able to reduce the risk associated with exchange rate volatility than in that with demand volatility; however, the risk reduction effect of financial hedging is decreasing in both types of volatility. For risk reduction, operational flexibility is more effective than financial hedging.

Our proposed model of integrated risk management points to a number of research directions. First, its one-period, two-stage program could be extended to accommodate multiperiod settings in which dynamic financial hedging is adopted concurrently with long-term capacity investments. Second, since our model focuses on the case of two currency zones, it may be worthwhile to consider a multicurrency model. Third, we have focused on a MNC that acts as a central planner of a global supply chain; hence a decentralized supply chain could be examined from the perspective of channel coordination and that of diversification effects. Fourth, the global firm's pricing decisions (e.g., an exchange rate pass-through) might be incorporated into various competitive settings. Finally, empirical research can be conducted to test the relative effectiveness of operational flexibility and financial hedging in MNCs; for example, Kim et al. (2006) investigate the relationship of these strategies in terms of mitigating currency risk.

### 3.7 Appendices to Chapter 3

#### Appendix 3A: Proofs

**Proof of Lemma 3.1.** Following the approach of Krokhmal et al. (2002), the proof is based on the Kuhn–Tucker necessary and sufficient conditions stated in the following theorem.

**Theorem 3A1** (Kuhn–Tucker, Theorem 2.5; see Pshenichnyi 1971). *Let  $\mathbf{p} \in \mathbf{P}$  and consider the problem*

$$\begin{aligned} \min \Phi_0(\mathbf{p}) \\ \Phi_i(\mathbf{p}) \leq 0 \text{ for } i = -m, \dots, -1, \\ \Phi_i(\mathbf{p}) = 0 \text{ for } i = 1, \dots, n. \end{aligned}$$

*Let  $\Phi_i(\mathbf{p})$  be functional on a vector space  $\mathbf{\Gamma}$  such that the  $\Phi_i(\mathbf{p})$  are convex for  $i \leq 0$  and linear for  $i \geq 0$ , and let  $\mathbf{P}$  be a convex subset of  $\mathbf{\Gamma}$ . Then, for  $\Phi_0(\mathbf{p})$  to achieve its minimum point at  $\mathbf{p}^* \in \mathbf{\Gamma}$  there must exist constants  $\gamma_i$ ,  $i = -m, \dots, n$ , such that*

$$\sum_{i=-m}^n \gamma_i \Phi_i(\mathbf{p}^*) \leq \sum_{i=-m}^n \gamma_i \Phi_i(\mathbf{p})$$

*for all  $\mathbf{p} \in \mathbf{P}$ . Furthermore,  $\gamma_i \geq 0$  for each  $i \leq 0$  and  $\gamma_i \Phi_i(\mathbf{p}_0) = 0$  for each  $i \neq 0$ . If  $\gamma_0 \geq 0$ , then the conditions are also sufficient.*

We now specify the necessary and sufficient Kuhn–Tucker conditions for problems (P1), (P2), and (P3). After some equivalent transformations, these conditions can be stated as follows.

*Kuhn–Tucker conditions for (P1):*

$$\mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})] - \lambda \text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) \geq \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] - \lambda \text{CVaR}_\beta(\mathbf{p}, \mathbf{y}), \quad \mathbf{p} \in \mathbf{P}, \lambda \geq 0. \quad (\text{KT1})$$

*Kuhn–Tucker conditions for (P2):*

$$\begin{aligned} \gamma_0^2 \text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) + \gamma_1^2 (\rho - \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})]) \leq \gamma_0^2 \text{CVaR}_\beta(\mathbf{p}, \mathbf{y}) + \gamma_1^2 (\rho - \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})]), \\ \gamma_1^2 (\rho - \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})]) = 0, \gamma_0^2 > 0, \gamma_1^2 > 0, \mathbf{p} \in \mathbf{P} \end{aligned}$$

$$\begin{aligned}
& \Downarrow \\
& \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})] - \lambda_2 \text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) \geq \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] - \lambda_2 \text{CVaR}_\beta(\mathbf{p}, \mathbf{y}), \\
& \lambda_2 = \frac{\gamma_0^2}{\gamma_1^2}, \frac{1}{\lambda_2}(\rho - \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})]) = 0, \lambda_2 \geq 0, \mathbf{p} \in \mathbf{P}. \tag{KT2}
\end{aligned}$$

*Kuhn-Tucker conditions for (P3):*

$$\begin{aligned}
& \gamma_0^3 \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})] - \gamma_1^3 (\text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) - \omega) \geq \gamma_0^3 \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] - \gamma_1^3 (\text{CVaR}_\beta(\mathbf{p}, \mathbf{y}) - \omega), \\
& \gamma_1^3 (\text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) - \omega) = 0, \gamma_0^3 > 0, \gamma_1^3 > 0, \mathbf{p} \in \mathbf{P} \\
& \Downarrow \\
& \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})] - \lambda_3 \text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) \geq \mathbb{E}[\Pi(\mathbf{p}, \mathbf{y})] - \lambda_3 \text{CVaR}_\beta(\mathbf{p}, \mathbf{y}), \\
& \lambda_3 = \frac{\gamma_1^3}{\gamma_0^3}, \lambda_3 (\text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y}) - \omega) = 0, \lambda_3 \geq 0, \mathbf{p} \in \mathbf{P}. \tag{KT3}
\end{aligned}$$

The term  $\frac{1}{\lambda_2}$  in (KT2) is the so-called optimal reward multiplier, and  $\lambda_3$  in (KT3) is the risk multiplier. Using conditions (KT1) and (KT2), we show that a solution of problem (P1) is also a solution of (P2) and likewise that a solution of problem (P2) is also a solution of (P1).

**Lemma 3A1.** *If a point  $\mathbf{p}^*$  is a solution of (P1), then that point is a solution of (P2) with parameter  $\rho = \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})]$ . Also, if  $\mathbf{p}^*$  is a solution of (P2) and if  $\frac{1}{\lambda_2}$  is the optimal reward multiplier in (KT2), then  $\mathbf{p}^*$  is a solution of (P1) with  $\lambda = \lambda_2$ .*

**Proof of Lemma 3A1.** If  $\mathbf{p}^*$  is a solution of (P1) then it satisfies condition (KT1). Evidently, this solution  $\mathbf{p}^*$  satisfies (KT2) with  $\rho = \mathbb{E}[\Pi(\mathbf{p}^*, \mathbf{y})]$  and  $\lambda_2 = \lambda$ . Suppose that  $\mathbf{p}^*$  is a solution of (P2) and that (KT2) is satisfied. Then (KT1) is satisfied with parameter  $\lambda = \lambda_2$  and so  $\mathbf{p}^*$  is a solution of (P1).  $\square$

**Lemma 3A2.** *If a point  $\mathbf{p}^*$  is a solution of (P1), then that point is a solution of (P3) with the parameter  $\omega = \text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y})$ . Also, if  $\mathbf{p}^*$  is a solution of (P3) and if  $\lambda_3$  is a positive risk multiplier in (KT3), then  $\mathbf{p}^*$  is a solution of (P1) with  $\lambda = \lambda_3$ .*

**Proof of Lemma 3A2.** If  $\mathbf{p}^*$  is a solution of (P1) then it satisfies condition (KT1). If  $\lambda > 0$ , then this solution  $\mathbf{p}^*$  satisfies (KT3) with  $\lambda_3 = \lambda$  and  $\omega = \text{CVaR}_\beta(\mathbf{p}^*, \mathbf{y})$ . Suppose that  $\mathbf{p}^*$  is a

solution of (P3) and that (KT3) is satisfied with  $\lambda_3 > 0$ . Then (KT1) is satisfied with parameter  $\lambda = \lambda_3$  and so  $\mathbf{p}^*$  is a solution of (P1).  $\square$

Lemma 3A1 implies that the efficient frontiers of problems (P1) and (P2) coincide. Similarly, Lemma 3A2 implies that the efficient frontiers of problems (P1) and (P3) coincide. Consequently, efficient frontiers of problems (P1), (P2), and (P3) coincide. This completes the proof of Lemma 3.1.  $\square$

**Proof of Proposition 3.1.** Our solution is based on the optimization principle that minimization with respect to  $(\mathbf{h}^*, C(\mathbf{h})^*)$  can be achieved by first minimizing  $\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  w.r.t.  $\mathbf{h}$  and then minimizing  $C(\mathbf{h})$  w.r.t.  $\mathbf{h}^*$ ; this approach conforms with the trade-off between cost and shortfall risk (Föllmer and Leukert 2000). In the cases of financial hedging only and integrated risk management, we invoke formulas (6) and (7), respectively, to derive the minimum of  $\text{CVaR}_\beta(\mathbf{Q}, \mathbf{h}, \mathbf{y})$  w.r.t.  $\mathbf{h}$ .  $\square$

**Proof of Proposition 3.2.** Given that the impact of a unit increment in expected profit on CVaR does not exceed zero in Stage 2, it is sufficient to consider operational decisions that solve for  $\max_{\mathbf{Q} \in \mathbb{R}_+^3} \mathbb{E}[\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y})]$ . The optimal strategies of operational flexibility for the ten given domains of uncertainty in Stage 2 are handled as follows.

*Domain  $\Omega_1$ : Full capacity sourcing with allocation option*

If aggregate market demand exceeds overall capacity,  $\sum D_i > \sum K_i$ , then the global firm fully utilizes all three resources in manufacturing; that is,  $q_i^* = K_i$  for  $i = 1, 2, b$ . In this case, the production switching option is not viable owing to lack of excess capacity, yet the allocation option can be used to achieve higher margins contingent on the exchange rate.

(a) If the exchange rate falls in the allocation “hysteresis band”,  $s \in [\frac{p_1 - c_{21}^a}{p_2}, \frac{p_1}{p_2 - c_{12}^a}]$ , then the allocation option is not profitable owing to the unit reallocation cost; hence  $d_1 = K_1 + K_b$ , and  $d_2 = K_2$ . In this case, capacity shadow prices (i.e., the marginal profit of additional unit capacity; see Proposition 3.3) can be written as  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_1) = (p_1 - c_1, p_1 - c_b, s(p_2 - c_2))$  for  $j = 1, 2, b$ .

(b) If  $s > \frac{p_1}{p_2 - c_{12}^a}$  and  $D_2 \leq \sum K_i$ , then product inventory is shipped to market 2 with higher priority than market 1. That is,  $d_1^* = \sum K_i - D_2$ ,  $d_2^* = D_2$ , and  $q_{12}^{a*} = D_2 - K_2$ ; also,  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_1) = (p_1 - c_1, p_1 - c_b, p_1 - sc_2 + sc_{12}^a)$  for  $j = 1, 2, b$ .

(c) If  $s > \frac{p_1}{p_2 - c_{12}^a}$  and  $D_2 > \sum K_i$ , then all the products are allocated to fulfill demand in market 2:  $d_1^* = 0$ ,  $d_2^* = \sum K_i$ , and  $q_{12}^{a*} = K_1 + K_b$ ; we have  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_1) = (sp_2 - c_1 - sc_{12}^a, sp_2 - c_b - sc_{12}^a, s(p_2 - c_2))$  for  $j = 1, 2, b$ .

(d) If  $s < \frac{p_1 - c_{21}^a}{p_2}$  and  $D_1 \leq \sum K_i$ , then product inventory will be shipped to market 1 with higher priority than to market 2; hence  $d_1^* = D_1$ ,  $d_2^* = \sum K_i - D_1$ , and  $q_{21}^{a*} = D_1 - K_1$ . In this case,  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_1) = (sp_2 - c_1 + c_{21}^a, sp_2 - c_b + c_{21}^a, s(p_2 - c_2))$  for  $j = 1, 2, b$ .

(e) If  $s < \frac{p_1 - c_{21}^a}{p_2}$  and  $D_1 > \sum K_i$ , then all the products will be routed to fulfill demand in market 1:  $d_1^* = \sum K_i$ ,  $d_2^* = 0$ , and  $q_{21}^{a*} = K_2$ ; then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_1) = (p_1 - c_1, p_1 - c_b, p_1 - sc_2 - c_{21}^a)$  for  $j = 1, 2, b$ .

In sum, the cash flow resulting from operational decisions in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - \mathbf{s}_i \mathbf{c}_i \mathbf{K}_i^{*T} - \mathbf{s}_j \mathbf{c}_{ij}^a \mathbf{q}_{ij}^{a*T} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$ , where  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

*Domain  $\Omega_2$ : Single sourcing from resource 2*

If the exchange rate is low,  $s \in \left[ \underline{s}, \frac{c_1}{c_2 + c_{12}^s} \right]$ , and, if aggregate market demand is no greater than the foreign capacity,  $\sum D_i \leq K_2$ , then the MNC sources only from capacity  $K_2$  (because of its lower unit production cost) to fulfill customer orders in both markets. Thus  $q_1^* = q_b^* = 0$ ,  $q_2^* = \sum D_i$ ,  $q_{12}^{s*} = D_1$ , and  $d_i^* = D_i$  for  $i = 1, 2$ . The capacity shadow price (vector) is therefore  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_2) = (0, 0, 0)$  for  $j = 1, 2, b$ ; the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - sc_2 \sum D_i - sc_{12}^s q_{12}^{s*} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$ , where  $i = 1, 2$  and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

*Domain  $\Omega_3$ : Sourcing from resource 2 with hedge from resource 1*

If the exchange rate is low,  $s \in \left[ \underline{s}, \frac{c_1}{c_2 + c_{12}^s} \right]$ , and if aggregate market demand is greater than foreign capacity but no more than total ordinary capacity (the sum of capacities  $K_1$  and  $K_2$ ),  $K_2 < \sum D_i \leq K_1 + K_2$ , then the MNC sources primarily from capacity  $K_2$  (with capacity  $K_1$  as a backup hedge) to fulfill demand in both markets. Hence  $q_1^* = \sum D_i - K_2$ ,  $q_b^* = 0$ ,  $q_2^* = K_2$ , and  $d_i^* = D_i$  for  $i = 1, 2$ . If  $K_2 \geq D_2$ , and  $q_{12}^{s*} = K_2 - D_2$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_3) = (0, 0, c_1 - sc_2 - sc_{12}^s)$  for  $j = 1, 2, b$ ; if  $K_2 < D_2$  and  $q_{21}^{s*} = D_2 - K_2$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_3) = (0, 0, c_1 - sc_2 + c_{21}^s)$  for  $j =$

1,2,b. The operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*\text{T}} - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^{*\text{T}} - s c_{12}^s q_{12}^{s*} - s_i \mathbf{c}_i^k \mathbf{Q}^{\text{T}} e^{\gamma t}$ , where  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

*Domain  $\Omega_4$ : Splitting with priority hedge from 2 and rerouting option*

If the exchange rate falls within the range  $\left( \frac{c_1}{c_2 + c_{12}^s}, \frac{c_b}{c_2 + c_{12}^s} \right]$  and if aggregate market demand does not exceed total ordinary capacity,  $\sum D_i \leq K_1 + K_2$ , then the global firm fulfills customer order primarily by “basic” activities (i.e., serving market demand from resources in the same currency zone; cf. Van Mieghem and Rudi 2002). Both the rerouting option and the switching option can shift production quantities between manufacturing locations (so they incur the identical unit cost in local currency  $c_{ij}^s$  for  $i, j = 1, 2, i \neq j$ ); however, the rerouting option aims to mitigate the mismatch between capacity and demand in the same currency zone whereas the switching option seeks to lower production costs contingent on the exchange rate. On the one hand, in this case the rerouting option allows “nonbasic” activities to relocate production quantities contingent on the demand states in both markets; on the other hand, the switching option can be profitable when foreign capacity  $K_2$  is preferred over domestic backup capacity  $K_b$  because of its lower cost in serving excess domestic demand over ordinary capacity  $(D_1 - K_1)^+$ . (Note that domain  $\Omega_4$  becomes empty when  $\frac{c_b}{c_2 + c_{12}^s} \geq \frac{c_1 + c_{21}^s}{c_2}$ .) We have  $q_1^* = \min(D_1, K_1) + (D_2 - K_2)^+$ ,  $q_b^* = 0$ , and  $q_2^* = \min(D_2, K_2) + (D_1 - K_1)^+$ ,  $d_i^* = D_i$  for  $i = 1, 2$ :

(a) If  $D_i \leq K_i$  for  $i = 1, 2$ , then the rerouting option remains unused. That is,  $q_1^* = D_1$ ,  $q_b^* = q_{ij}^{s*} = 0$ , and  $q_2^* = D_2$ ; also  $\boldsymbol{\mu}_j^{\text{T}}(\mathbf{Q}, \Omega_4) = (0, 0, 0)$  for  $j = 1, 2, b$ .

(b) If  $D_2 > K_2$  then the rerouting option enables service of excess demand in foreign market via slack domestic (ordinary) capacity:  $q_1^* = D_1 + D_2 - K_2$ ,  $q_b^* = 0$ ,  $q_2^* = K_2$ , and  $q_{21}^{s*} = D_2 - K_2$ ; here  $\boldsymbol{\mu}_j^{\text{T}}(\mathbf{Q}, \Omega_4) = (0, 0, c_1 + c_{21}^s - s c_2)$  for  $j = 1, 2, b$ .

(c) If  $D_1 > K_1$  then the switching option enables service of excess domestic demand over ordinary capacity via slack foreign capacity. In this case,  $q_1^* = K_1$ ,  $q_b^* = 0$ ,  $q_2^* = D_2 + D_1 - K_1$ , and  $q_{12}^{s*} = D_1 - K_1$ ; we have  $\boldsymbol{\mu}_j^{\text{T}}(\mathbf{Q}, \Omega_4) = (s c_{12}^s + s c_2 - c_1, 0, 0)$  for  $j = 1, 2, b$ .

As a result, the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*\text{T}} - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^{*\text{T}} - \mathbf{s}_j \mathbf{c}_{ij}^s \mathbf{q}_{ij}^{s*\text{T}} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^{\text{T}} e^{\gamma t}$  for  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .



Domain  $\Omega_5$ : Splitting with priority hedge from backup capacity and rerouting option

If the exchange rate falls in the switching “hysteresis band”  $\left(\frac{c_b}{c_2+c_{12}^s}, \frac{c_1+c_{21}^s}{c_2}\right]$  and if the aggregate market demand does not exceed total ordinary capacity,  $\sum D_i \leq K_1 + K_2$ , then the global firm fulfills customer demand primarily via basic activities because of hysteresis effects. Here the rerouting option involves nonbasic activities to relocate production quantities contingent on the demand states in both markets. Note that, in domain  $\Omega_5$ , domestic backup capacity  $K_b$  is preferred over foreign capacity  $K_2$  to serve excess domestic demand

$$(D_1 - K_1)^+; \quad \text{hence}$$

$$q_1^* = \min(D_1, K_1) + (D_2 - K_2)^+, \quad q_b^* = (D_1 - K_1)^+, \quad q_2^* = \min(D_2, K_2) + (D_1 - K_1 - K_b)^+, \quad \text{and}$$

$$d_i^* = D_i \text{ for } i = 1, 2.$$

(a) If  $D_1 \leq K_1 + K_b$  and  $D_2 \leq K_2$ , then the rerouting option remains unused; thus  $q_1^* = \min(D_1, K_1)$ ,  $q_b^* = (D_1 - K_1)^+$ ,  $q_2^* = D_2$ , and  $q_{ij}^{s*} = 0$ . Here  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_5) = \begin{pmatrix} c_b - c_1 & \text{if } D_1 > K_1 \\ 0 & \text{if } D_1 \leq K_1 \end{pmatrix}, 0, 0$  for  $j = 1, 2, b$ .

(b) If  $D_2 > K_2$  then the rerouting option enables service of excess demand in foreign market via slack domestic (ordinary) capacity:  $q_1^* = D_1 + D_2 - K_2$ ,  $q_b^* = 0$ ,  $q_2^* = K_2$ , and  $q_{21}^{s*} = D_2 - K_2$ ; in this case,  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_5) = (0, 0, c_1 + c_{21}^s - sc_2)$  for  $j = 1, 2, b$ .

(c) If  $D_1 > K_1 + K_b$  then the rerouting option enables service of excess domestic demand over total domestic capacity via slack foreign capacity. Hence  $q_1^* = K_1$ ,  $q_b^* = K_b$ ,  $q_2^* = D_2 + D_1 - K_1 - K_b$ , and  $q_{12}^{s*} = D_1 - K_1 - K_b$ ; we have  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_5) = (sc_{12}^s + sc_2 - c_1, sc_{12}^s + sc_2 - c_b, 0)$  for  $j = 1, 2, b$ .

In sum, the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^{*T} - \mathbf{s}_j \mathbf{c}_{ij}^s \mathbf{q}_{ij}^{s*T} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$ , where  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

Domain  $\Omega_6$ : Single sourcing from resource 1

If the exchange rate is given by  $s \in \left(\frac{c_1+c_{12}^s}{c_2}, \bar{s}\right]$  and aggregate market demand is no greater than the domestic (ordinary) capacity,  $\sum D_i \leq K_1$ , then the MNC sources only from capacity  $K_1$  (because of its lower unit production cost) to fulfill customer orders in both markets. That is,  $q_1^* = \sum D_i$ ,  $q_b^* = q_2^* = 0$ ,  $q_{21}^{s*} = D_2$ , and  $d_i^* = D_i$  for  $i = 1, 2$ ; here  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_6) = (0, 0, 0)$ , for  $j = 1, 2, b$ . Hence the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - c_1 \sum D_i - c_{21}^s q_{21}^{s*} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$ , where  $i = 1, 2$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

*Domain  $\Omega_7$ : Sourcing from resource 1 with hedge from resource 2*

If the exchange rate  $s \in (\frac{c_1+c_{12}^s}{c_2}, \frac{c_b+c_{21}^s}{c_2}]$  and if aggregate market demand exceeds the domestic (ordinary) capacity but does not exceed total ordinary capacity,  $K_1 < \sum D_i \leq K_1 + K_2$ , then the global firm sources primarily from capacity  $K_1$  (with capacity  $K_2$  as a backup hedge) to fulfill demand in both markets; thus  $q_1^* = K_1$ ,  $q_b^* = 0$ ,  $q_2^* = \sum D_i - K_1$ , and  $d_i^* = D_i$  for  $i = 1, 2$ . If  $K_1 \geq D_1$  and  $q_{21}^{s*} = K_1 - D_1$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_7) = (sc_2 - c_1 - c_{21}^s, 0, 0)$  for  $j = 1, 2, b$ ; if  $K_1 < D_1$  and  $q_{12}^{s*} = D_1 - K_1$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_7) = (sc_2 + sc_{12}^s - c_1, 0, 0)$  for  $j = 1, 2, b$ . So the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^{*T} - c_{21}^s q_{21}^{s*} - s_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$  for  $i = 1, 2$ ,  $s_i = \begin{cases} 1, & i = 1 \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

*Domain  $\Omega_8$ : Sourcing from resource 1 with hedge from backup capacity*

If the exchange rate is in the range  $(\frac{c_b+c_{21}^s}{c_2}, \bar{s}]$ , and aggregate market demand is more than domestic (ordinary) capacity but no more than total domestic capacity,  $K_1 < \sum D_i \leq K_1 + K_b$ , then the MNC sources primarily from capacity  $K_1$  (with backup capacity  $K_b$  as a hedge) to fulfill product demand in both markets:  $q_1^* = K_1$ ,  $q_b^* = \sum D_i - K_1$ ,  $q_2^* = 0$ ,  $q_{21}^{s*} = D_2$ , and  $d_i^* = D_i$  for  $i = 1, 2$ ; in this case,  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_8) = (c_b - c_1, 0, 0)$  for  $j = 1, 2, b$ . Hence the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - \mathbf{c}_i \mathbf{q}_i^{*T} - c_{21}^s q_{21}^{s*} - s_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$  for  $i = 1, b$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

*Domain  $\Omega_9$ : Sourcing from resource 1 and backup capacity with hedge from resource 2*

If the exchange rate  $s \in (\frac{c_b+c_{21}^s}{c_2}, \bar{s}]$  and if aggregate market demand exceeds total domestic capacity but not total capacity,  $K_1 + K_b < \sum D_i \leq \sum K_i$ , then the global firm sources primarily from capacities  $K_1$  and  $K_b$  (with capacity  $K_2$  as a hedge) to fulfill customer orders in both markets; that is,  $q_1^* = K_1$ ,  $q_b^* = K_b$ ,  $q_2^* = \sum D_i - K_1 - K_b$ , and  $d_i^* = D_i$  for  $i = 1, 2$ . If  $K_1 + K_b \geq D_1$  and  $q_{21}^{s*} = K_1 + K_b - D_1$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_9) = (sc_2 - c_1 - c_{21}^s, sc_2 - c_b - c_{21}^s, 0)$  for  $j = 1, 2, b$ ; if  $K_1 + K_b < D_1$  and  $q_{12}^{s*} = D_1 - K_1 - K_b$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_9) = (sc_2 - c_1 + sc_{12}^s, sc_2 - c_b + sc_{12}^s, 0)$  for  $j = 1, 2, b$ . The operating cash flow in Stage 2 is thus  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*T} - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^{*T} - \mathbf{s}_j \mathbf{c}_{ij}^s \mathbf{q}_{ij}^{s*T} - s_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$ , where  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

Domain  $\Omega_{10}$ : Sourcing from resources 1 and 2 with hedge from backup capacity

If the exchange rate can be characterized as  $s \in [\underline{s}, \frac{c_b + c_{21}^s}{c_2}]$  and if aggregate market demand is greater than total ordinary capacity but not greater than total capacity,  $K_1 + K_2 < \sum D_i \leq \sum K_i$ , then the MNC sources primarily from capacities  $K_1$  and  $K_2$  (with backup capacity  $K_b$  as a hedge) to fulfill product demand in both markets:  $q_1^* = K_1$ ,  $q_b^* = \sum D_i - K_1 - K_2$ ,  $q_2^* = K_2$ , and  $d_i^* = D_i$  for  $i = 1, 2$ . If  $K_2 \geq D_2$  and  $q_{12}^{s*} = K_2 - D_2$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_9) = (c_b - c_1, 0, c_b - sc_2 - sc_{12}^s)$  for  $j = 1, 2, b$ ; if  $K_2 < D_2$  and  $q_{21}^{s*} = D_2 - K_2$ , then  $\boldsymbol{\mu}_j^T(\mathbf{Q}, \Omega_9) = (c_b - c_1, 0, c_b - sc_2 + c_{21}^s)$  for  $j = 1, 2, b$ . Hence the operating cash flow in Stage 2 is  $\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^{*\text{T}} - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^{*\text{T}} - \mathbf{s}_j \mathbf{c}_{ij}^s \mathbf{q}_{ij}^{s*\text{T}} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t}$  for  $i = 1, 2, b$ ,  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ ,  $j = 1, 2$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .  $\square$

**Proof of Proposition 3.3.** We shall employ the definition of the derivative via difference quotients to find the gradient of the operating profit.

Define  $m_i$  ( $i = 1, 2, b$ ) as the Stage 2 profit margins (unit price minus production cost in domestic currency, depending on the uncertainty domains defined in Table 3.3) of capacities  $K_i$ . Then, for  $i = 1$  and  $j = 2$ , we have

$$\begin{aligned}
\frac{\partial \Pi(\mathbf{Q})}{\partial Q_i} &= \frac{\partial \mathbb{E}[\Pi(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})]}{\partial Q_i} - c_1^k \\
&= \lim_{\theta \rightarrow 0} (\mathbb{E}[\Pi(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D})] - \mathbb{E}[\Pi(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})]) / \theta - c_1^k \\
&= \lim_{\theta \rightarrow 0} \left( \frac{\mathbb{E}[m_i q_i^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D}) + m_j q_j^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D}) + m_b q_b^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D})]}{\mathbb{E}[m_i q_i^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D}) + m_j q_j^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D}) + m_b q_b^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})]} \right) / \theta \\
&\quad - c_1^k \\
&= m_i \mathbb{E}[q_i^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D}) - q_i^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})] / \theta \\
&\quad - m_j \mathbb{E}[q_j^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D}) - q_j^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})] / \theta \\
&\quad - m_b \mathbb{E}[q_b^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D}) - q_b^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})] / \theta - c_1^k. \tag{3A1}
\end{aligned}$$

We may rewrite the first part of (3A1) as follows:

$$\begin{aligned}
\frac{\partial \mathbb{E}[q_i^*(\mathbf{Q}, R_1, R_2, \mathbf{D})]}{\partial Q_i} &= \lim_{\theta \rightarrow 0} \left( \frac{\mathbb{E}[q_i^*(Q_i + \theta, Q_j, R_1, R_2, K_b, \mathbf{D}) - q_i^*(Q_i, Q_j, R_1, R_2, K_b, \mathbf{D})]}{\theta} \right) \\
&= \lim_{\theta \rightarrow 0} \left( \frac{\mathbb{E}[\min\{\mathbf{D}, K_1, Q_i + \theta\} - \min\{\mathbf{D}, K_1, Q_i\}]}{\theta} \right).
\end{aligned}$$

To evaluate the numerator, we must consider the following six cases:

$$\begin{aligned} & \min\{\mathbf{D}, K_1, Q_1 + \theta\} - \min\{\mathbf{D}, K_1, Q_1\} = \\ & (1) \quad Q_1 + \theta - D \text{ if } Q_1 + \theta \leq D \leq \min\{\mathbf{D}, K_1, Q_1\}, \\ & (2) \quad Q_1 + \theta - K_1 \text{ if } Q_1 + \theta \leq K_1 \leq \min\{\mathbf{D}, K_1, Q_1\}, \\ & (3) \quad D - Q_1 \text{ if } Q_1 \leq D \leq Q_1 + \theta \leq K_1, \\ & (4) \quad K_1 - Q_1 \text{ if } Q_1 \leq K_1 \leq Q_1 + \theta \leq D, \\ & (5) \quad \theta \text{ if } Q_1, Q_1 + \theta \leq \min\{\mathbf{D}, K_1\}, \\ & (6) \quad 0 \text{ if } Q_1 + \theta > \min\{\mathbf{D}, K_1\}, Q_1 > \min\{\mathbf{D}, K_1\}. \end{aligned}$$

*Case 1.* As  $\theta \rightarrow 0$ , we have  $P(Q_1 + \theta \leq D \leq \min\{\mathbf{D}, K_1, Q_1\}) \rightarrow 0$ . In this case,  $|Q_1 + \theta - D| \leq |\theta|$  holds and so  $\lim_{\theta \rightarrow 0} (\mathbb{E}[Q_1 + \theta - D | (\cdot)] P(\cdot) / \theta) \rightarrow 0$ .

*Case 2.* As  $\theta \rightarrow 0$ , we have  $P(Q_1 + \theta \leq K_1 \leq \min\{\mathbf{D}, K_1, Q_1\}) \rightarrow 0$ . Here  $|Q_1 + \theta - K_1| \leq |\theta|$  holds, so  $\lim_{\theta \rightarrow 0} (\mathbb{E}[Q_1 + \theta - K_1 | (\cdot)] P(\cdot) / \theta) \rightarrow 0$ .

*Case 3.* As  $\theta \rightarrow 0$ , we have  $P(Q_1 \leq D \leq Q_1 + \theta \leq K_1) \rightarrow 0$ . In this case we have  $|D - Q_1| \leq |\theta|$ ; hence  $\lim_{\theta \rightarrow 0} (\mathbb{E}[D - Q_1 | (\cdot)] P(\cdot) / \theta) \rightarrow 0$ .

*Case 4.* As  $\theta \rightarrow 0$ , we have  $P(Q_1 \leq K_1 \leq Q_1 + \theta \leq D) \rightarrow 0$ . Here  $|K_1 - Q_1| \leq |\theta|$  holds, so  $\lim_{\theta \rightarrow 0} (\mathbb{E}[K_1 - Q_1 | (\cdot)] P(\cdot) / \theta) \rightarrow 0$ .

*Case 5.* In this case,  $P(Q_1, Q_1 + \theta \leq \min\{\mathbf{D}, K_1\}) = P(Q_1 \leq \min\{\mathbf{D}, K_1\})$ .

*Case 6.* The realized value of the numerator is always zero.

Given that Case 5 is the only one contributing to a nonzero value of the denominator, we obtain

$$\begin{aligned} \frac{\partial \mathbb{E}[q_1^*(\mathbf{Q}, R_1, R_2, \mathbf{D})]}{\partial Q_1} &= \lim_{\theta \rightarrow 0} \left( \frac{\theta \cdot P(Q_1, Q_1 + \theta \leq \min\{\mathbf{D}, K_1\})}{\theta} \right) \\ &= P(Q_1 \leq \min\{\mathbf{D}, K_1\}) \\ &= P(\Omega_1(\mathbf{Q}) + \Omega_4(\mathbf{Q}) + \Omega_5(\mathbf{Q}) + \Omega_7(\mathbf{Q}) + \Omega_8(\mathbf{Q}) + \Omega_9(\mathbf{Q}) + \Omega_{10}(\mathbf{Q})). \end{aligned}$$

Analogously, taking the differential quotient of the second part of (3A1) yields

$$\frac{\partial \mathbb{E}[q_2^*(\mathbf{Q}, R_1, R_2, \mathbf{D})]}{\partial Q_1} = P(\Omega_7(\mathbf{Q}) + \Omega_9(\mathbf{Q}) + \Omega_{4c}(\mathbf{Q}) + \Omega_{5c}(\mathbf{Q}))$$

and so the differential quotient of the third part of (3A1) is

$$\frac{\partial \mathbb{E}[q_b^*(\mathbf{Q}, R_1, R_2, \mathbf{D})]}{\partial Q_1} = P(\Omega_8(\mathbf{Q}) + \Omega_{10}(\mathbf{Q}) + \Omega_{5a}(\mathbf{Q})).$$

Thus we have

$$\begin{aligned} \frac{\partial \Pi(\mathbf{Q})}{\partial Q_i} &= m_i P(\Omega_1(\mathbf{Q}) + \Omega_4(\mathbf{Q}) + \Omega_5(\mathbf{Q}) + \Omega_7(\mathbf{Q}) + \Omega_8(\mathbf{Q}) + \Omega_9(\mathbf{Q}) + \Omega_{10}(\mathbf{Q})) - m_j P(\Omega_7(\mathbf{Q}) \\ &\quad + \Omega_9(\mathbf{Q}) \\ &\quad + \Omega_{4c}(\mathbf{Q}) + \Omega_{5c}(\mathbf{Q})) - m_b P(\Omega_8(\mathbf{Q}) + \Omega_{10}(\mathbf{Q}) + \Omega_{5a}(\mathbf{Q})). \end{aligned}$$

We can derive the following expressions analogously:

$$\begin{aligned} \frac{\partial \Pi(\mathbf{Q})}{\partial Q_j} &= m_j P(\Omega_1(\mathbf{Q}) + \Omega_3(\mathbf{Q}) + \Omega_{4b}(\mathbf{Q}) + \Omega_{5b}(\mathbf{Q}) + \Omega_{10}(\mathbf{Q})) \\ &\quad - m_i P(\Omega_3(\mathbf{Q}) + \Omega_{4b}(\mathbf{Q}) + \Omega_{5b}(\mathbf{Q})) \\ &\quad - m_b P(\Omega_{10}(\mathbf{Q})), \\ \frac{\partial \Pi(\mathbf{Q})}{\partial K_b} &= m_b P(\Omega_{5c}(\mathbf{Q}) + \Omega_9(\mathbf{Q})) - m_j P(\Omega_{5c}(\mathbf{Q}) + \Omega_9(\mathbf{Q})). \square \end{aligned}$$

**Proof of Proposition 3.4.** In the base case, the nonflexible MNC's cash flow resulting from operational decisions can be written as  $\Pi^{\text{bc}} = \sum s_i (p_i - c_i) \min(D_i, K_i) - s_i c_i^k \mathbf{Q}^T e^{\gamma t}$  for  $i = 1, 2$ , and  $s_i = \begin{cases} 1, & i = 1 \\ s, & i = 2 \end{cases}$ .

In case of backup production only, the partially flexible global firm's cash flow resulting from operational decisions can be expressed as  $\Pi^{\text{bp}} = (p_1 - c_1)q_1^* + (p_1 - c_b)q_b^* + s(p_2 - c_2)q_2^* - s_i c_i^k \mathbf{Q}^T e^{\gamma t}$ ; here  $q_1^* = \min(D_1, K_1)$ ,  $q_b^* = \min((D_1 - K_1)^+, K_b)$ ,  $q_2^* = \min(D_2, K_2)$ ,  $i = 1, 2, b$ , and  $s_i = \begin{cases} 1, & i = 1, b \\ s, & i = 2 \end{cases}$ . Given the MNC's mean-CVaR objective, we can derive the value creation of backup production only (relative to the base case) as follows:  $\Delta U[\Pi^{\text{bp}}] = U[\Pi^{\text{bp}}] - U[\Pi^{\text{bc}}] = (1 + \lambda) \sum P(\Omega_i(\mathbf{Q}^*)) (q_b^*(p_1 - c_b) - c_b^k K_b)$ .

Analogously to Proposition 3.2, for the case of switching options only the optimal production quantities  $\mathbf{q}_i^*$  ( $i = 1, 2$ ) in Stage 2 have one of the six distinct forms given in Table 3.6; these forms depend on the realized capacity – demand matching states and exchange rates.

For the strategy of switching options only, the optimal production quantities can be derived via reasoning similar to (but simpler than) that used in the proof of Proposition 3.2; we

therefore omit the details. Capacity shadow prices can be written as:  $\mu_j^T(\mathbf{Q}, \Omega_1) = (p_1 - c_1$  or  $sp_2 - c_1 - sc_{12}^a, s(p_2 - c_2)$  or  $p_1 - sc_2 - c_{21}^a)$ ;  $\mu_j^T(\mathbf{Q}, \Omega_2) = \mu_j^T(\mathbf{Q}, \Omega_5) = (0, 0)$ ;  $\mu_j^T(\mathbf{Q}, \Omega_3) = (0, c_1 - sc_2 - sc_{12}^s)$ ;  $\mu_j^T(\mathbf{Q}, \Omega_6) = (0, sc_2 - c_1 - c_{21}^s)$ ; and  $\mu_j^T(\mathbf{Q}, \Omega_4) = \begin{cases} (0, 0) & \text{if } D_i < K_i \\ (0, c_1 - sc_2 + c_{21}^s) & \text{if } D_2 \geq K_2. \\ (sc_2 - c_1 + sc_{12}^s, 0) & \text{if } D_1 \geq K_1 \end{cases}$

Table 3.6. Optimal Production Quantities: Switching Options Only

Domain	Optimal Strategy	$q_1^*$	$q_2^*$	$q_{ij}^{s*}$
$\Omega_1(\mathbf{Q}) = \{\mathbf{R}\epsilon\mathbb{R}^2 \mid \sum K_i < \sum D_i, s \in [\underline{s}, \bar{s}]\}$	Full capacity sourcing with allocation option	$K_1$	$K_2$	0
$\Omega_2(\mathbf{Q}) = \{\mathbf{R}\epsilon\mathbb{R}^2 \mid \sum D_i < K_2, s \in [\underline{s}, \frac{c_1}{c_2 + c_{12}^s}]\}$	Single sourcing from resource 2	0	$\sum D_i$	$D_1$
$\Omega_3(\mathbf{Q}) = \{\mathbf{R}\epsilon\mathbb{R}^2 \mid K_2 \leq \sum D_i \leq K_1 + K_2, s \in [\underline{s}, \frac{c_1}{c_2 + c_{12}^s}]\}$	Sourcing from resource 2 with hedge from 1	$\sum D_i - K_2$	$K_2$	$K_2 - D_2$
$\Omega_4(\mathbf{Q}) = \{\mathbf{R}\epsilon\mathbb{R}^2 \mid \sum D_i \leq K_1 + K_2, s \in (\frac{c_1}{c_2 + c_{12}^s}, \frac{c_1 + c_{21}^s}{c_2}]\}$	Splitting with rerouting option	$\min(D_1, K_1) + (D_2 - K_2)^+$	$\min(D_2, K_2) + (D_1 - K_1)^+$	$(D_i - K_i)^+$
$\Omega_5(\mathbf{Q}) = \{\mathbf{R}\epsilon\mathbb{R}^2 \mid \sum D_i < K_1, s \in (\frac{c_1 + c_{21}^s}{c_2}, \bar{s}]\}$	Single sourcing from resource 1	$\sum D_i$	0	$D_2$
$\Omega_6(\mathbf{Q}) = \{\mathbf{R}\epsilon\mathbb{R}^2 \mid K_1 \leq \sum D_i \leq K_1 + K_2, s \in (\frac{c_1 + c_{21}^s}{c_2}, \bar{s}]\}$	Sourcing from resource 1 with hedge from 2	$K_1$	$\sum D_i - K_1$	$K_1 - D_1$

As a consequence, the partially flexible firm's cash flow resulting from operational decisions is

$$\Pi^{\text{sw}} = \mathbf{s}_j \mathbf{p}_j \mathbf{d}_j^T - \mathbf{s}_i \mathbf{c}_i \mathbf{q}_i^T - \mathbf{s}_j \mathbf{c}_{ij}^s \mathbf{q}_{ij}^{sT} - \mathbf{s}_j \mathbf{c}_{ij}^a \mathbf{q}_{ij}^{aT} - \mathbf{s}_i \mathbf{c}_i^k \mathbf{Q}^T e^{\gamma t},$$

where  $i = 1, 2$ ,  $s_i = \begin{cases} 1, & i = 1 \\ s, & i = 2 \end{cases}$ ,  $i \neq j$ , and  $s_j = \begin{cases} 1, & j = 1 \\ s, & j = 2 \end{cases}$ .

Similarly, we derive the value of switching options only (relative to the base case) as

$$\Delta U[\Pi^{\text{sw}}] = U[\Pi^{\text{sw}}] - U[\Pi^{\text{bc}}] = (1 + \lambda) \sum P(\Omega_i(\mathbf{Q}^*)) q_{ij}^{s*} (s_i c_i - s_j c_j - s_j c_{ij}^s).$$

Then, by analogous reasoning, the value of full operational flexibility relative to the base case is

$$\Delta U[\Pi^{\text{op}}] = U[\Pi^{\text{op}}] - U[\Pi^{\text{bc}}] = (1 + \lambda)(\mathbb{E}[\Pi^{\text{op}}] - \mathbb{E}[\Pi^{\text{bc}}]). \square$$

**Proof of Theorem 3.1.** Suppose  $p_1 - sc_{12}^s > sp_2$  iff  $s < \frac{p_1}{c_{12}^s + p_2}$ ; then sales in the domestic market yield a higher margin and so both backup capacity and switching options are used to fulfill domestic demand  $D_1$ . In this case, when  $c_b \leq s(c_2 + c_{12}^s)$  iff  $\frac{c_b}{c_2 + c_{12}^s} \leq s < \frac{p_1}{c_{12}^s + p_2}$ , backup capacity is preferred to foreign capacity (the switching option) because its sourcing cost is lower. The value of backup production only is  $\Delta U[\Pi^{\text{bp}}] = U[\Pi^{\text{bp}}] - U[\Pi^{\text{bc}}] = \min([D_1 -$

$K_1]^+, K_b) (p_1 - c_b) - c_b^k K_b$ ; the value of switching options only is  $\Delta U[\Pi^{\text{sw}}] = U[\Pi^{\text{sw}}] - U[\Pi^{\text{bc}}] = \min([D_1 - K_1]^+, K_2) (p_1 - sp_2 - sc_{12}^s)$ ; and the value of full operational flexibility is  $\Delta U[\Pi^{\text{op}}] = U[\Pi^{\text{op}}] - U[\Pi^{\text{bc}}] = \min([D_1 - K_1]^+, K_b) (p_1 - c_b) + \min([D_1 - K_1 - K_b]^+, K_2) (p_1 - sp_2 - sc_{12}^s) - c_b^k K_b$ . Therefore, the interaction effects between backup production and switching options are  $\Delta U[\text{sw, bp}] = \Delta U[\Pi^{\text{op}}] - \Delta U[\Pi^{\text{sw}}] - \Delta U[\Pi^{\text{bp}}] = \{\min([D_1 - K_1 - K_b]^+, K_2) - \min([D_1 - K_1]^+, K_2)\} (p_1 - sp_2 - sc_{12}^s) \leq 0$ . Analogously, when  $c_b > s(c_2 + c_{12}^s)$  iff  $s_t \leq s < \frac{c_b}{c_2 + c_{12}^s}$  for  $s_t = \max\{s \in [\underline{s}, \bar{s}] : l(\mathbf{Q}, \mathbf{h}, \mathbf{y}) = -\Pi^{\text{int}}(\mathbf{Q}, \mathbf{h}, \mathbf{y}) < \alpha\}$ , it follows that  $\text{CVaR}_\beta^{\text{op}} = 0$  and foreign capacity (the switching option) is preferred to backup capacity as the former's sourcing cost is lower. The interaction effects between backup production and switching options are thus  $\Delta U[\text{sw, bp}] = \Delta U[\Pi^{\text{op}}] - \Delta U[\Pi^{\text{sw}}] - \Delta U[\Pi^{\text{bp}}] = \{\min([D_1 - K_1 - K_2]^+, K_b) - \min([D_1 - K_1]^+, K_b)\} (p_1 - c_b) \leq 0$ . When  $\underline{s} \leq s < s_t$ , (i.e.,  $\text{CVaR}_\beta^{\text{op}} > 0$ ), the interaction effects are  $\Delta U[\text{sw, bp}] = \Delta U[\Pi^{\text{op}}] - \Delta U[\Pi^{\text{sw}}] - \Delta U[\Pi^{\text{bp}}] = (1 + \lambda) \{\min([D_1 - K_1 - K_2]^+, K_b) - \min([D_1 - K_1]^+, K_b)\} (p_1 - c_b) \leq 0$ . These cases demonstrate the substitution effects if both backup capacity and switching options are used to fulfill domestic demand.

Now suppose to the contrary that  $sp_2 - c_{21}^s > p_1$  iff  $\frac{p_1 + c_{21}^s}{p_2} < s \leq \bar{s}$ , then sales in the foreign market yield a higher margin and so both backup capacity and switching options are used to fulfill foreign demand  $D_2$ . In this case, when  $c_b + c_{21}^s < sc_2$  iff  $\frac{c_b + c_{21}^s}{c_2} < s \leq \bar{s}$ , the backup capacity (the switching option) is preferred over foreign capacity because its sourcing cost is lower. The interaction effects between backup production and switching options are then  $\Delta U[\text{sw, bp}] = \Delta U[\Pi^{\text{op}}] - \Delta U[\Pi^{\text{sw}}] - \Delta U[\Pi^{\text{bp}}] = \min(q_b^*, q_{21}^{s*}) (sc_2 - c_b - c_{21}^s) \geq 0$ .

Analogously, when  $c_b + c_{21}^s \geq sc_2$  iff  $\frac{p_1 + c_{21}^s}{p_2} < s \leq \frac{c_b + c_{21}^s}{c_2}$ , the foreign capacity is preferred over backup capacity (the switching options) because its sourcing cost is lower; the interaction effects between backup production and switching options are now  $\Delta U[\text{sw, bp}] = \Delta U[\Pi^{\text{op}}] - \Delta U[\Pi^{\text{sw}}] - \Delta U[\Pi^{\text{bp}}] = \min(q_b^*, q_{21}^{s*}) (c_b + c_{21}^s - sc_2) \geq 0$ . Therefore, if  $\frac{p_1 + c_{21}^s}{p_2} < s \leq \bar{s}$  then  $\Delta U[\text{sw, bp}] = \min(q_b^*, q_{21}^{s*}) |sc_2 - c_b - c_{21}^s| \geq 0$ ; this expression captures the complementary effects when switching options use domestic backup capacity to fulfill foreign demand. In sum, the interaction effects of backup production and switching options are

$$\begin{aligned}
& \Delta U[\text{sw}, \text{bp}] = \\
& P\left(\frac{p_1 + c_{21}^s}{p_2} < s \leq \bar{s}\right) \min(q_b^*, q_{21}^{s*}) |sc_2 - c_b - c_{21}^s| + P\left(\frac{c_b}{c_2 + c_{12}^s} \leq s < \frac{p_1}{c_{12}^s + p_2}\right) \{\min([D_1 - K_1 - \\
& K_b]^+, K_2) - \min([D_1 - K_1]^+, K_2)\} (p_1 - sp_2 - sc_{12}^s) + P\left(s_b \leq s < \frac{c_b}{c_2 + c_{12}^s}\right) \{\min([D_1 - K_1 - \\
& K_2]^+, K_b) - \min([D_1 - K_1]^+, K_b)\} (p_1 - c_b) + (1 + \lambda) P(\underline{s} \leq s < s_b) \{\min([D_1 - K_1 - K_2]^+, K_b) - \\
& \min([D_1 - K_1]^+, K_b)\} (p_1 - c_b). \square
\end{aligned}$$

**Proof of Proposition 3.5.** Recall that (no-arbitrage) financial hedging yields  $\mathbb{E}[H(\mathbf{h})] = 0$ ; hence the value creation of optimal financial hedging w.r.t. the base case can be readily derived as  $\Delta U[\text{FH}^{\text{bc}}] = U[\Pi^{\text{fh}}] - U[\Pi^{\text{bc}}] = \lambda(\text{CVaR}_\beta^{\text{bc}} - \text{CVaR}_\beta^{\text{fh}})$ . The value increment of optimal financial hedging under integrated risk management (relative to full operational flexibility) can likewise be written as  $\Delta U[\text{FH}^{\text{op}}] = U[\Pi^{\text{int}}] - U[\Pi^{\text{op}}] = \lambda(\text{CVaR}_\beta^{\text{op}} - \text{CVaR}_\beta^{\text{int}})$ .  $\square$

**Proof of Theorem 3.2.** Comparing the value adjustment in the firm's utility via financial hedging in the absence versus the presence of operational flexibility, we can derive the interaction effects between these two strategies as follows:  $\Delta U[\text{fh}, \text{op}] = \Delta U[\text{FH}^{\text{op}}] - \Delta U[\text{FH}^{\text{bc}}] = \lambda(\text{CVaR}_\beta^{\text{op}} - \text{CVaR}_\beta^{\text{bc}} + \text{CVaR}_\beta^{\text{fh}} - \text{CVaR}_\beta^{\text{int}}) + (\mathbb{E}[\Pi^{\text{bc}}] - \mathbb{E}[\Pi^{\text{fh}}] + \mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}])$ . The interaction effects of operational flexibility and financial hedging are twofold. The first effect is a risk reduction interaction; that is,  $\lambda(\text{CVaR}_\beta^{\text{op}} - \text{CVaR}_\beta^{\text{bc}}) < 0$  and  $\lambda(\text{CVaR}_\beta^{\text{fh}} - \text{CVaR}_\beta^{\text{int}}) \leq 0$  iff  $\lambda(\text{CVaR}_\beta^{\text{op}} - \text{CVaR}_\beta^{\text{bc}} + \text{CVaR}_\beta^{\text{fh}} - \text{CVaR}_\beta^{\text{int}}) < 0$  (For financial hedging only, the loss function is continuous and linear w.r.t.  $\mathbf{h}$ ; in integrated risk management, the loss functions are discrete by virtue of real options. As a result,  $\text{CVaR}_\beta[\Pi^{\text{fh}}] \leq \text{CVaR}_\beta[\Pi^{\text{int}}]$ ; see Section 3.3.2). Thus operational flexibility and financial hedging are substitutes in risk reduction. The second effect is a value enhancement interaction:  $\mathbb{E}[\Pi^{\text{bc}}] - \mathbb{E}[\Pi^{\text{fh}}] + \mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}]$ . Since  $\mathbb{E}[\Pi^{\text{fh}}] \geq \mathbb{E}[\Pi^{\text{bc}}]$  and  $\mathbb{E}[\Pi^{\text{int}}] \geq \mathbb{E}[\Pi^{\text{op}}]$ , it follows that  $\mathbb{E}[\Pi^{\text{bc}}] - \mathbb{E}[\Pi^{\text{fh}}] + \mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}] > 0$  if and only if  $\mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}] > \mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]$ . Therefore, operational flexibility and financial hedging can be complements w.r.t. value enhancement. If  $\mathbb{E}[\Pi^{\text{int}}] - \mathbb{E}[\Pi^{\text{op}}] \leq \mathbb{E}[\Pi^{\text{fh}}] - \mathbb{E}[\Pi^{\text{bc}}]$ , then operational flexibility and financial hedging are strictly substitutes given that  $\Delta U[\text{fh}, \text{op}] < 0$ .  $\square$



### Appendix 3B: Input Parameters for Robustness Analysis

Table 3.7. List of Input Parameters

Domain	$P(\Omega_i)$	$D_1$	$D_2$	$s$
$\Omega_1$	0.0125	Uniform(110,125)	Uniform(35,75)	Uniform(0.8,0.875)
$\Omega_1$	0.0125	Uniform(60,107)	Uniform(50,75)	Uniform(0.8,0.875)
$\Omega_1$	0.0500	Uniform(60,70)	Uniform(50,60)	Uniform(0.9375,1.05)
$\Omega_1$	0.0125	Uniform(45,75)	Uniform(110,125)	Uniform(1.111,1.2)
$\Omega_1$	0.0125	Uniform(55,107)	Uniform(45,75)	Uniform(1.15,1.21)
$\Omega_2$	0.0333	Uniform(15,18)	Uniform(25,28)	Uniform(0.55,0.65)
$\Omega_2$	0.0333	Uniform(20,23)	Uniform(20,23)	Uniform(0.6,0.7)
$\Omega_2$	0.0333	Uniform(25,28)	Uniform(15,18)	Uniform(0.65,0.75)
$\Omega_3$	0.0333	Uniform(30,60)	Uniform(20,36)	Uniform(0.7,0.8)
$\Omega_3$	0.0333	Uniform(20,36)	Uniform(30,60)	Uniform(0.75,0.85)
$\Omega_3$	0.0333	Uniform(25,47)	Uniform(25,47)	Uniform(0.75,0.85)
$\Omega_4$	0.0500	Uniform(36,46)	Uniform(36,46)	Uniform(0.875,0.9375)
$\Omega_4$	0.0250	Uniform(30,36)	Uniform(50,60)	Uniform(0.89,0.9375)
$\Omega_4$	0.0250	Uniform(50,60)	Uniform(30,36)	Uniform(0.9,0.9375)
$\Omega_5$	0.0500	Uniform(40,56)	Uniform(30,36)	Uniform(0.9375,1.1)
$\Omega_5$	0.0250	Uniform(30,36)	Uniform(50,60)	Uniform(1,1.1)
$\Omega_5$	0.0250	Uniform(61,70)	Uniform(21, 26)	Uniform(1.05,1.15)
$\Omega_6$	0.0333	Uniform(15,18)	Uniform(25,28)	Uniform(1.17,1.21)
$\Omega_6$	0.0333	Uniform(20,23)	Uniform(20,23)	Uniform(1.18,1.21)
$\Omega_6$	0.0333	Uniform(25,28)	Uniform(15,18)	Uniform(1.18,1.21)
$\Omega_7$	0.0333	Uniform(20,36)	Uniform(30,60)	Uniform(1.15,1.21)
$\Omega_7$	0.0333	Uniform(25,47)	Uniform(25,47)	Uniform(1.16,1.21)
$\Omega_7$	0.0333	Uniform(30,60)	Uniform(20,36)	Uniform(1.17,1.21)
$\Omega_8$	0.0333	Uniform(18,21)	Uniform(32,35)	Uniform(1.3,1.4)
$\Omega_8$	0.0333	Uniform(25,28)	Uniform(25,28)	Uniform(1.35,1.45)
$\Omega_8$	0.0333	Uniform(32,35)	Uniform(18,21)	Uniform(1.35,1.45)
$\Omega_9$	0.0333	Uniform(28,38)	Uniform(32,68)	Uniform(1.21,1.35)
$\Omega_9$	0.0333	Uniform(30,53)	Uniform(30,53)	Uniform(1.21,1.35)
$\Omega_9$	0.0333	Uniform(32,68)	Uniform(28,38)	Uniform(1.3,1.4)
$\Omega_{10}$	0.0333	Uniform(59,63)	Uniform(39,43)	Uniform(0.75,0.85)
$\Omega_{10}$	0.0333	Uniform(50,53)	Uniform(50,53)	Uniform(1.05,1.15)
$\Omega_{10}$	0.0333	Uniform(40,44)	Uniform(60,63)	Uniform(1.111,1.2)

## Chapter 4

# Mitigating Supplier Distress: Purchase Order Finance, Advance Payment Discount, and Backup Production<sup>15</sup>

### 4.1 Introduction

Supply chain efficiency is strongly affected by the financial distress of suppliers, so the focal firm must be capable of appropriately managing these contingencies. For example, in February 2008 Chrysler closed four assembly plants and canceled one shift at a fifth plant citing a parts shortage after its supplier Plastech filed for Chapter 11 bankruptcy protection (Nussel and Sherefkin 2008). To mitigate supplier risks, a cross-functional approach is solicited to bring together procurement, finance, and operations (Carter and Giunipero 2010). In case a distressed supplier might not deliver the agreed order quantity, a buyer can arrange for dual sourcing from a backup supplier to mitigate any subsequent mismatches between supply and demand (Tomlin 2006, Yang et al. 2009, Wang et al. 2010, Sting and Huchzermeier 2014). On February 4th, 2009, 400 US auto suppliers, including the giant suppliers American Axle and Visteon, asked for \$25.5 billion in federal aid to relieve their cash flow problems (Sodhi and Tang 2012). One global original equipment manufacturer (OEM) in the automotive industry identified the early warning signs in the performance of a major parts supplier and had a contingency plan in place: “the OEM was able to start to dual source the products and build up an inventory buffer...with no disruption to its production lines” (KPMG 2011b).

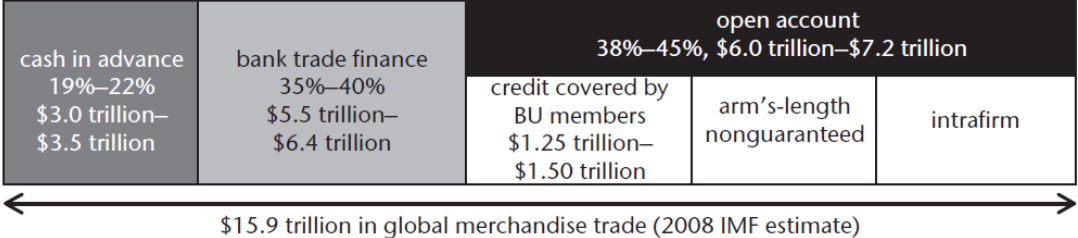
In addition to an operational hedging strategy, a buyer can support current supplier via trade finance instruments to alleviate financial distress (KPMG 2011b). In particular, buyer can finance supplier by advancing payment at a discount prior to product shipment, a procedure also known as “cash in advance”. According to 2008 International Monetary Fund (IMF) estimate, advance payment discount (APD) represents 19% – 22% of or 3 – 3.5 trillion US dollars in global trade finance (Chauffour and Malouche 2011); see Figure 4.1. Although bank finance and trade credit (i.e., open account) are often considered in the supply chain finance literature (Jing et al. 2012, Kouvelis and Zhao 2012, Cai et al. 2013), we are not aware

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<sup>15</sup> The content in this chapter is based on Zhao and Huchzermeier (2014b). Chapter 4 is scheduled for presentation at the 2014 POMS Conference in Atlanta, USA.

of any research that analyzes advance payment discounts—despite their prevalence in practice.

Figure 4.1. Trade Finance Arrangements by Market Share (BU = Berne Union). Source: Chauffour and Malouche (2011).



Furthermore, under purchase order finance (POF) a creditor provides a short-term loan, secured by the buyer’s purchase order, in order to finance the supplier before order delivery. A program of this type has been launched, for instance, by the Mexican state-owned development bank, Nacional Financiera (Nafin); POF is also known as “contract financing” (Klapper 2006). The United States Agency for International Development (USAID) reports that banks issued 4,600 POF loans with a total value of \$13.7 million from July 2007 to December 2008 (Landa 2009). Yet despite its emergence as a viable trade finance regime, purchase order finance has likewise been overlooked by the existing research on supply chain finance.

This chapter aims to fill these gaps by addressing the following questions. What are the relationships among purchase order finance, advance payment discount, and backup production in managing supplier risks? How do the retailer’s optimal joint sourcing and financing strategies affect supply chain efficiency? Which risk management tools most effectively mitigate supplier financial distress and supply–demand mismatches? How good are recommendations based on the models of supply chain finance and traditional procurement, which ignore the interaction between dual sourcing and financing strategies? To answer these questions, we consider a supply chain consisting of one retailer and two suppliers, where both the retailer and the offshore supplier may be subject to capital constraints. The retailer has three strategies to mitigate supplier financial distress and mismatch risk: purchase order finance, advance payment discount, and dual sourcing via a backup supplier.

In the single-financing mode where either POF or APD is viable, we show that the unique equilibrium is POF if the retailer's internal asset level is below a certain threshold but is APD otherwise. On the one hand, POF may serve as a financial buffer with finite capacity for the offshore supplier by outsourcing capital from a creditor based on retailer credit. On the other hand, APD can transfer financial flow from voluntary to binding positions within the operational supply chain and may thereby enhance supply chain efficiency. In the dual-financing mode, when both POF and APD are viable, there is a "pecking order" with respect to these two modes of pre-shipment finance. In particular, the retailer first uses internal capital to fund APD and then adopts POF to finance the offshore supplier—but only if the channel coordination benefits from APD are dominated by its effect on financial distress. We also find that capacity hedging via backup supplier and pre-shipment finance (i.e., POF and/or APD) are partial substitutes from the retailer's perspective, and their interaction (substitution) effect reflects the partial benefit of backup production only through hedging the supply underage due to budget constraints. Overall, the integration of these strategies can create significant value because the expected profit from this approach is strictly greater than that from either pre-shipment finance or backup supply alone.

## 4.2 Literature Review

Three streams of literature are relevant to our study: (i) supply chain finance, (ii) dual sourcing via a backup supplier, and (iii) empirical research on trade finance.

Closest to our work is research in supply chain finance that addresses the effect on financial constraints on contracting to achieve channel coordination.<sup>16</sup> Dada and Hu (2008) consider the inventory procurement of a capital-constrained newsvendor borrowing from a bank that sets its interest rate to coordinate the channel in Stackelberg equilibrium. Lai et al. (2009) consider short-term bank financing when there are bankruptcy costs in a capital-constrained supply chain. Caldentey and Haugh (2009) examine the performance of a supply chain consisting of a producer and a budget-constrained retailer. Caldentey and Chen (2012) propose a contract under which the supplier offers partial credit to the budget-constrained retailer. Jing et al. (2012) study the financing equilibrium in a model with both bank and trade credits. Cai et al. (2013) explore the relationship between bank and trade credits in a

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<sup>16</sup> For examples of non—capital-constrained supply chain coordinating contracts, see e.g. Cachon and Lariviere (2001), Lariviere and Porteus (2001), and Özer and Wei (2006). For an extensive overview of supply chain contracting, see Cachon (2003).

supply chain with a capital-constrained retailer facing demand uncertainty. Kouvelis and Zhao (2012) and Yang and Birge (2013) analyze the role of trade credit in inventory financing and/or channel coordination.

This supply chain finance literature focuses on single sourcing in decentralized supply chains and thus ignores the *interaction* between financing strategy and dual sourcing via a backup supplier. Our research contributes to this literature by exploring the relationships among purchase order finance, advance payment discount, and backup production in mitigating supplier distress. We remark that both POF and APD are examined analytically here for the first time in the context of a capital-constrained supply chain. Advance *payment* discount differs from advance *purchase* discount (Cachon 2004), which advances the order quantity decision rather than payment. Moreover, the distinction between *advance* payment discount and supplier *early* payment discount (Kouvelis and Zhao 2012) lies in whether payment is conducted, respectively, prior to or after product shipment.

Another related stream of literature concentrates on dual sourcing via a backup supplier under supply uncertainty. Tomlin (2006) investigates the value of dual sourcing, inventory mitigation, and contingent rerouting in a two-supplier supply chain under disruption risk. Babich (2006) shows how competing suppliers can be distinguished by the lead times they offer and the responsive supplier can be used as a backup. Along these lines, Babich et al. (2007) demonstrate how the interplay between correlated supplier disruption and price competition affects the buyer's profits under flexible sourcing. Yang et al. (2009) study the impact of a supplier's private information about supply disruption on the exercising of supplier backup production. Wang et al. (2010) explore the benefits of dual sourcing and supplier reliability improvement under random capacity or yield. Hou et al. (2010) design contracts with backup supplier to ensure responsive capacity and channel coordination under supply disruption. Sting and Huchzermeier (2014) set up responsive capacity via dual sourcing under correlated supply and demand uncertainty. None of this literature has addressed the effect of financial distress or bankruptcy risk on procurement and financing strategy. Our model complements this stream by examining the interaction between pre-shipment finance and dual sourcing via a backup supplier in a supply chain under financial distress and demand uncertainty.

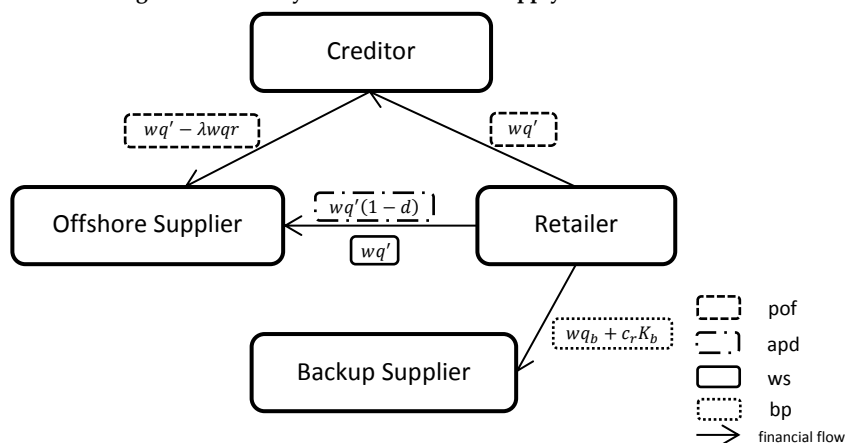
Finally, the literature on trade finance is largely dedicated to empirical investigation of various instruments in supply chain financing. Klapper (2006) finds that factoring allows a high-risk supplier to transfer its credit risk to a higher-quality buyer, and illustrates the benefits of reverse factoring and purchase order finance by the Nafin program in Mexico. Chauffour and Farole (2009) investigate trade finance instruments, which include working capital and pre-shipment finance, in times of crisis. Chauffour and Malouche (2011) provide an overview of supply chain and bank financing products and evidence of advance payment regimes. Navas-Alemán et al. (2012) categorize and survey trade finance regimes for small and medium-sized enterprise (SME), including purchase order finance and advance payment. Wuttke et al. (2013) use case studies to categorize and investigate tools of financial supply chain management. Our research is an important first step toward providing analytical treatments of purchase order finance and advance payment discount in a supply chain Stackelberg game.

The remainder of this chapter is organized as follows. In Section 4.3, we formulate our model and performance benchmarks and propose the optimal solutions for the base case and for backup production only. Section 4.4 performs an equilibrium analysis when only one financing type (i.e., either POF or APD) is viable. We derive the optimal solutions when both POF and APD are viable under the dual-financing mode in Section 4.5. The impact of demand variability and the retailer’s internal capital level on supply chain performance is examined in Section 4.6. We conclude in Section 4.7 with a summary of main insights and directions for future research.

### 4.3 A Supply Chain with Purchase Order Finance, Advance Payment Discount, and Backup Production

#### 4.3.1 Formulation and Assumptions

Figure 4.2. The Physical and Financial Supply Chain Network



We consider a supply chain of one retailer, two suppliers, and one creditor; see Figure 4.2,<sup>17</sup> where  $q' = \min(q, K)$  refers to the offshore supplier's delivered quantity. All parties are assumed to be risk neutral. The retailer (she) orders  $q$  units of a product from the offshore offshore supplier (he), a capital-constrained SME with internal asset  $A_s$  and short-term debt  $L_s$ . We assume that both the retailer and the offshore supplier have long-term capital structures financed solely by equity, yet have short-term debts due before the sales season. Hence both firms may face the distress cost of financial default, which depends on whether their liquid assets can cover their loan obligations. As the offshore supplier is subject to financial distress and, in the scenario we examine, therefore needs working capital to fulfill purchase order  $q$ . The capital market is assumed to be imperfect; thus  $1 - \alpha$  of firm value is lost as distress cost upon financial default (Leland 1994, Xu and Birge 2004, Gamba and Triantis 2013), where  $\alpha \in (0,1)$ . Bank financing is difficult to obtain or rather expensive for the SME supplier because of his low credit rating, so we assume that  $r_s = \infty$  is the commercial bank rate offered to offshore supplier. The risk-free interest rate  $r_f$  is normalized to zero without loss of generality (Brennan et al. 1988, Jing et al. 2012), which enables us to concentrate on the *effective* rate of APD and POF (i.e., the actual rate above the risk-free rate). The retailer may also source  $q_b$  from the "contingent" backup supplier with capacity  $K_b$  during the sales season. The financial institution and backup supplier are assumed to face no bankruptcy risk or related distress cost.

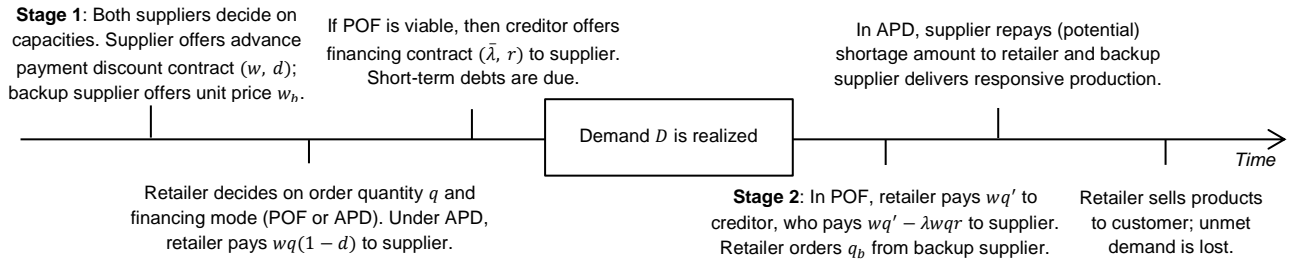
The offshore supplier and backup supplier install respective capacities  $K \in \mathbb{R}_+$  and  $K_b \in \mathbb{R}_+$ . One unit of capacity costs  $c_k$  and  $c_k^b$ , and one unit of production costs  $c_p$  and  $c_p^b$ , for (respectively) the offshore and backup suppliers. It is assumed that  $c_k^b > c_k$  and  $c_p^b > c_p$ , since backup (responsive) supply is more expensive than offshore supply. The stochastic capacity  $K$  and demand  $D$  are not realized until the sales season. The demand distribution function  $F(D)$  has the following properties:  $F(D)$  is absolutely continuous with density  $f(D) > 0$  and support  $[a, b)$  for  $0 \leq a < b \leq \infty$ ; it has a finite mean and an inverse  $F^{-1}(D)$ . The hazard rate  $h(D) \triangleq f(D)/\bar{F}(D)$  is increasing in  $D$ , where  $\bar{F}(D) = 1 - F(D)$ . Let  $H(D) \triangleq Dh(D)$  denote the generalized failure rate; then  $H(D)$  is monotonically increasing in  $D$ . We assume that there is no information asymmetry in supply chain operations – in other words, that all operational parameters (e.g., demand distribution, prices, and costs) are common

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<sup>17</sup> In Figure 4.2, we use "pof", "apd", "ws", and "bp" to denote (respectively) the cases of "purchase order finance", "advance payment discount", "wholesale price", and "backup production".

knowledge to all parties. However, financial information is private (e.g., the asset–liability structures of retailer and offshore supplier remain proprietary), though the retailer and creditor both know that the offshore supplier needs working capital in order to mitigate financial distress. The retailer can avail herself of three strategies to manage supplier financial distress and mismatch risk: purchase order finance, advance payment discount, and backup production.

Figure 4.3. Timeline of Events



The sequence of events is depicted in Figure 4.3.<sup>18</sup> In Stage 1, The offshore supplier and backup supplier decide on capacities  $K$  and  $K_b$ , respectively. Then the capital-constrained offshore supplier offers an advance payment discount contract  $(w, d)$  to the retailer, where  $w$  is the wholesale price due in Stage 2 and  $d$  is the offshore supplier's discount rate for advance payment in Stage 1. We assume that  $w > c_p + c_k$  (to ensure the profitability of the offshore supplier), and that the advance payment discount rate  $\underline{d} \leq d \leq \frac{w - c_p - c_k}{w}$ . Here  $\underline{d} \geq 0$  denotes the lower bound of discount rate, which may be subject to an upper limit in the equilibrium of single-financing mode (see Section 4.4.3) and thereby indirectly linked to the creditor's interest rate  $r$ ; here  $d \leq \frac{w - c_p - c_k}{w}$  ensures that  $w(1 - d) \geq c_p + c_k$  (i.e., that it is profitable for the offshore supplier to offer APD). Note that  $w$  and  $d$  merely specify how the retailer may make her payments; the contract does not restrict the retailer with regard to choice of financing. That is, accepting the contract does not obligate the retailer to finance the offshore supplier via APD, and the offshore supplier can affect the retailer's financing choice only by adjusting the values of the contract parameters  $(w, d)$ . If the retailer rejects the contract then the offshore supplier makes zero profit (positive reserved profits can be incorporated by modifying our model slightly). If the retailer accepts the contract, she decides on an order quantity  $q$  and a financing regime (POF/APD) to the offshore supplier. The backup (responsive) supplier offers an options contract (cf. Cachon and Lariviere 2001,

<sup>18</sup> To reduce the labeling in Figure 4.3, we denote the offshore offshore supplier more simply as "supplier".



Barnes-Schuster et al. 2002) with unit capacity reservation fee  $c_r$  in Stage 1 and unit execution price  $w_b$  in Stage 2. We assume that  $w_b + c_r > w$  (since the responsive backup supplier charges a higher unit price) and that  $w_b + c_r > c_p^b + c_k^b$  (to ensure the profitability of backup supplier).

A retailer who chooses the advance payment discount pays  $wq(1 - d)$  to the offshore supplier prior to shipment at the end of Stage 1. A retailer who chooses the purchase order finance asks a creditor to offer a POF contract  $(\bar{\lambda}, r)$  to the offshore supplier; here  $\bar{\lambda} \in (0,1)$  is the maximum percentage of the purchase order value that the creditor is willing to finance in Stage 1, and  $r$  is the interest rate of POF due in Stage 2. The POF interest rate is lower than the commercial bank rate  $r_s > r$  because POF is distinct from traditional forms of commercial lending, where the basis of credit is mainly the supplier's creditworthiness and not the value of his underlying assets, (here, the purchase order). If the offshore supplier accepts the POF contract, then he decides on a portion  $\lambda$  and receives a POF loan  $\lambda wq$  from the creditor in Stage 1. Short-term debts of the offshore supplier and of the retailer are both due at the end of Stage 1.

In Stage 2, after demand uncertainty is realized, the offshore supplier produces at unit production cost  $c_p$  and delivers  $q' = \min(q, K)$  units. If POF is viable then the retailer pays the full amount of purchase order  $wq'$  directly to the creditor, who deducts an amount equal to the used portion of the line of credit plus interest and pays the offshore supplier the difference:  $wq' - \lambda wq(1 + r)$ . Any additional fees charged by the creditor are normalized to zero without loss of generality. Under a wholesale price regime, the retailer pays  $wq'$  to the offshore supplier (see Figure 4.2). The retailer exercises her option to obtain  $q_b$  from the backup supplier at unit price  $w_b$ ; the backup supplier produces at unit production cost  $c_p^b$  and delivers responsive production. The retailer sells products to customers at unit price  $p > w_b + c_r > w$ ; we thus assume that every product sold is profitable for the retailer. Unmet demand is lost, salvage value of unsold product is assumed to be zero, and final payoffs are realized. An overview of our notation and assumptions is given in Table 4.1.<sup>19</sup>

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<sup>19</sup> Throughout this chapter, we use "s", "r", "b", and "c" to denote (respectively) the "offshore supplier", "retailer", "backup supplier", and "creditor".

**Table 4.1. Summary of Notation and Assumptions**

Symbol	Description	Assumptions
$\pi_i$	The (respective) expected cash flows of the offshore supplier, backup supplier, retailer, or creditor	$i = s, b, r, c$
$A_i$	Initial asset level of the offshore supplier/retailer at the beginning of Stage 1	Exogenous, $i = s, r$
$L_i$	Short-term debt of the offshore supplier/retailer due at the end of Stage 1	Exogenous, $i = s, r$
$D$	Product demand in Stage 2	Exogenous, stochastic
$f(\cdot)$	The probability density function (PDF) of demand distribution	Exogenous, known in Stage 1, $f(D) > 0$
$\bar{F}(\cdot)$	The complementary cumulative distribution function (CCDF) of the demand distribution, $\bar{F}(D) = 1 - F(D)$	Exogenous, known in Stage 1, $F(D)$ has support $[a, b]$ for $0 \leq a < b \leq \infty$
$h(\cdot)$	The failure rate of the demand distribution, $h(\cdot) = f(\cdot)/\bar{F}(\cdot)$	Endogenous, increasing in $D$
$K$	Capacity realized at the offshore supplier	Decision variable in Stage 1, $K \in \mathbb{R}_+$
$K_b$	Capacity installed at of the backup supplier	Decision variable in Stage 1, $K_b \in \mathbb{R}_+$
$q$	Order quantity of the retailer to the offshore supplier	Decision variable in Stage 1
$q_b$	Order quantity of the retailer to the backup supplier	Decision variable in Stage 2
$w$	Unit wholesale price of the offshore supplier due in Stage 2	Endogenous, deterministic, $p > w > c_p + c_k$
$d$	Discount rate of advance payment to the offshore supplier due in Stage 1	Endogenous, deterministic, $d \in \left[ d, \frac{w - c_p - c_k}{w} \right]$ , $d \geq 0$
$c_p$	Unit production cost at the offshore supplier	Exogenous, deterministic, $w > c_p + c_k$
$c_k$	Unit capacity cost at the offshore supplier	Exogenous, deterministic, $w > c_p + c_k$
$w_b$	Unit execution price of the backup supplier in Stage 2	Exogenous, deterministic, $p > w_b + c_r > w$
$c_p^b$	Unit production cost at the backup supplier	Exogenous, deterministic, $c_p^b > c_p$
$c_k^b$	Unit capacity cost at the backup supplier	Exogenous, deterministic, $c_k^b > c_k$
$p$	Market price of one product unit	Exogenous, deterministic, $p > w_b + c_r > w$
$c_r$	Unit capacity reservation cost of backup supplier in Stage 1	Incurs when the retailer reserves capacity from the backup supplier, $c_r < c_k^b$
$\alpha$	Proportional distress cost stated as a portion $(1 - \alpha)$ of realized payoff upon financial default	Exogenous, deterministic, $\alpha \in (0, 1)$
$\beta$	Portion of orders at wholesale price in dual-financing mode	Decision variable in Stage 1; $\beta \in [0, 1]$
$\lambda$	Proportion of purchase order value received by the offshore supplier from the creditor at Stage 1	$\lambda \in [0, \bar{\lambda}]$ , $\bar{\lambda} \in (0, 1)$
$r$	Interest rate of the POF loan offered by the creditor to the offshore supplier	$r \geq 0$ , interest due in Stage 2
$r_f$	Risk-free interest rate	$r_f = 0$
$r_s$	Commercial bank interest rate for the offshore supplier	$r_s = \infty$

**Definition 4.1.** The following strategies can be distinguished in terms of their respective choices of pre-shipment finance and backup production.<sup>20</sup>

(a) *Base case* refers to a supply chain consisting of one retailer and one offshore supplier under budget constraints *without* purchase order finance, advance payment discount, or backup supply option (i.e.,  $\bar{\lambda} = d = q_b = 0$ ); ceteris paribus.

(b) *Backup production only* denotes a supply chain with backup supplier but without purchase order finance or advance payment discount (i.e.,  $q_b > 0$  and  $\bar{\lambda} = d = 0$ ); ceteris paribus.

(c) *Purchase order finance only* means a supply chain with purchase order finance but without advance payment discount or backup supplier (i.e.,  $\bar{\lambda} > 0$  and  $d = q_b = 0$ ); ceteris paribus.

<sup>20</sup> Throughout this chapter, we use “bc”, “bp”, “pof”, “apd”, “df”, and “dfbp” to denote (respectively) “base case”, “backup production only”, “purchase order finance only”, “advance payment discount only”, “dual financing only”, and “dual financing with backup production”.

(d) *Advance payment discount only* denotes a supply chain with advance payment discount but without purchase order finance or backup supplier (i.e.,  $d > 0$  and  $\bar{\lambda} = q_b = 0$ ); ceteris paribus.

(e) *Dual financing only* refers to a supply chain with purchase order finance and advance payment discount but without backup supplier (i.e.,  $\bar{\lambda} > 0$  with  $d > 0$ , and  $q_b = 0$ ); ceteris paribus.

(f) *Dual financing with backup production* means a supply chain with advance payment discount, purchase order finance, and backup supplier (i.e.,  $d > 0$ ,  $q_b > 0$ , and  $\bar{\lambda} > 0$ ); ceteris paribus.

### 4.3.2 Centralized and Decentralized Benchmarks

To establish benchmarks for the capital-constrained supply chain, we analyze the cases of a centralized and a decentralized supply chain without financial constraints. First, in centralized single sourcing, an integrated firm with sufficient internal capital makes single capacity decision to achieve channel-wide optimal expected profit. The profit  $\pi^{\text{ces}}(D, K)$  of the integrated firm for capacity decision  $K$  is:<sup>21</sup>

$$\pi^{\text{ces}}(D, K) = (p - c_p) \min(K, D) - c_k K. \quad (4.1)$$

The profit function is concave, and the optimal solution is  $K^{\text{ces}} = F^{-1}\left(\frac{p - c_p - c_k}{p - c_p}\right)$ .

In a decentralized supply chain, we assume that both the retailer and the offshore supplier have sufficient internal capital. The retailer's problem is equivalent to that of the integrated firm under centralized single sourcing except that she orders inventory at wholesale price  $w$  instead of producing it at cost  $c_p$  and  $c_k$ . Hence her expected profit  $\pi_r^{\text{des}}$  is:

$$\pi_r^{\text{des}}(q, D, K) = p \min(D, \min(q^{\text{des}}, K)) - w \min(q^{\text{des}}, K). \quad (4.2)$$

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<sup>21</sup> Throughout this chapter, we use "ces" and "des" to denote (respectively) "centralized single sourcing" and "decentralized single sourcing". We use  $q$ ,  $w$ , and  $K$  to denote (respectively)  $q^i$ ,  $w^i$ , and  $K^i$  for  $i = \text{ces, des, bc, bp, pof, apd, df, dfbp}$  for brevity.

The profit function is concave and the optimal solution is  $q^{\text{des}} = F^{-1}\left(\frac{p-w}{p}\right)$ . In comparison to the centralized single sourcing,  $q^{\text{des}} = F^{-1}\left(\frac{p-w}{p}\right) < K^{\text{ces}} = F^{-1}\left(\frac{p-c_p-c_k}{p-c_p}\right)$ ; this expression reflects the result of “double marginalization” (Spengler 1950).

The offshore supplier has an initial asset  $A_s$  and a short-term liability  $L_s$  that is due at the end of Stage 1. As the leader in a Stackelberg game, the offshore supplier anticipates the retailer’s order for any wholesale price. He faces demand curve  $q^{\text{des}}(w)$  and chooses the optimal capacity and pricing  $(K^{\text{des}}, w)$  to maximize his profit:

$$\pi_s^{\text{des}}(D, K) = A_s - L_s + (w - c_p)\min(q^{\text{des}}, K) - c_k K^{\text{des}}. \quad (4.3)$$

We follow the approach of Lariviere and Porteus (2001, p. 295) and write the inverse demand curve of the offshore supplier as  $w(q) = p\bar{F}(q)$ . Suppose that  $F$  has a strictly increasing generalized failure rate (IGFR), let  $h(D) = Df(D)/(1 - F(D))$ , and define  $\hat{q}$  as the least upper bound on the set of points such that  $v(q) \geq 1$ . Then the price elasticity of the retailer’s order is  $v(q) = -w(q)/[qdw(q)/dq]$  if we assume that  $v'(q) \leq 0$  for  $q \in [a, b)$  and  $\hat{q} \in [a, \infty)$ .

**Lemma 4.1.** *In decentralized single sourcing with sufficient internal capital, the offshore supplier’s first-order condition is:*

$$p\bar{F}(q^{\text{des}})[1 - h(q^{\text{des}})] = c_k + c_p. \quad (4.4)$$

*The offshore supplier’s profit is unimodal on  $[0, \infty)$ , linear and strictly increasing on  $[0, a)$ , strictly concave on  $[a, \hat{q}]$ , and strictly decreasing on  $(\hat{q}, \infty)$ . The optimal solution  $q^{\text{des}}$  to equation (4.4) is unique and must be in the interval  $[a, \hat{q}]$ . The offshore supplier’s optimal capacity  $K^{\text{des}} = q^{\text{des}}$ , his optimal sales quantity is  $q^{\text{des}}$  or  $a$ , and the optimal wholesale price  $w^{\text{des}} = p\bar{F}(q^{\text{des}}) = \frac{c_k + c_p}{1 - h(q^{\text{des}})}$ .*

*Proof.* All proofs are given in Appendix 4.

### 4.3.3 Base Case and Backup Production Only

In the base case (see Definition 4.1), a retailer orders from a capital-constrained offshore supplier. We assume that the retailer has sufficient internal capital to cover not only short-

term debt but also the capacity reservation fee for a backup supplier (if viable) in Stage 1. Although we assume that the retailer is not at risk of bankruptcy, she may be subject to short-term financial distress when choosing advance payment discount only (see Section 4.4.2) in Stage 1 to finance the offshore supplier. Moreover, the offshore supplier is assumed to fulfill the retailer's order within a voluntary compliance regime (cf. Cachon and Lariviere 2001); that is, the offshore supplier cannot be forced to adhere to contractual obligations for his capacity investment. Because a forced compliance regime (as when the capacity installment is observable and enforceable by a court of law) will significantly increase the offshore supplier's bankruptcy risk, it is not a favorable regime for either channel member. The offshore supplier may enter into one of two modes of bankruptcy if his liquid assets cannot cover short-term debts.

The capital-constrained offshore supplier's profit following his capacity decision  $K^{\text{bc}} = q^{\text{bc}}$  is

$$\pi_s^{\text{bc}}(D, K) = A_s - L_s + (w - c_p)\min(q^{\text{bc}}, K^{\text{bc}}) - c_k K^{\text{bc}} - (1 - \alpha)[L_s - A_s + c_k K^{\text{bc}}]^+.$$

The optimal capacity and pricing decisions  $(K^{\text{bc}}, w^{\text{bc}})$  can be derived by satisfying the first-order condition (FOC)

$$p\bar{F}(q^{\text{bc}})[1 - h(q^{\text{bc}})] = c_p + c_k + (1 - \alpha)c_k P(L_s + c_k K^{\text{bc}} > A_s). \quad (4.5)$$

Hence  $w^{\text{bc}} = p\bar{F}(K^{\text{bc}}) = \frac{c_k + c_p + (1 - \alpha)c_k P(L_s + c_k K^{\text{bc}} > A_s)}{1 - h(K^{\text{bc}})}$ . Equation (4.5) suggests that the offshore supplier trades off the marginal benefit of capacity  $p\bar{F}(q^{\text{bc}})[1 - h(q^{\text{bc}})]$  against the marginal cost of additional capacity  $c_p + c_k + (1 - \alpha)c_k P(L_s + c_k K^{\text{bc}} > A_s)$ .

In the base case, the retailer's profit is

$$\pi_r^{\text{bc}}(q, D, K) = p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) - w \min(q^{\text{bc}}, K^{\text{bc}}).$$

In case of backup production only (see Definition 4.1), the retailer pays unit capacity reservation fee  $c_r$  to the backup supplier in Stage 1 and receives  $\min(q^{\text{bc}}, K^{\text{bc}})$  units from the offshore supplier (as in the base case) in Stage 2. Contingent on demand realization, the

retailer's optimal order quantity to the backup supplier can be derived as  $q_b = \min(K_b, [D - \min(q^{bc}, K^{bc})]^+)$ .

**Proposition 4.1.** *Under backup production only, the retailer's optimal sourcing strategy is  $\mathbf{q}^{bp} = (q^{bc}, \min(K_b, [D - \min(q^{bc}, K^{bc})]^+))^T$ , where  $K^{bp} = K^{bc}$  satisfies the FOC  $P(K^{bp} > \frac{A_s - L_s}{c_k}) = \frac{p\bar{F}(q^{bp})[1-h(q^{bp})] - c_p - c_k}{(1-\alpha)c_k}$ .*

In backup production only, the retailer's expected profit is

$$\begin{aligned} \pi_r^{bp}(\mathbf{q}, D, K) &= p \min(D, \min(q^{bc}, K^{bc}) + K_b) - w \min(q^{bc}, K^{bc}) \\ &\quad - w_b \min(K_b, [D - \min(q^{bc}, K^{bc})]^+) - c_r K_b \end{aligned}$$

and the backup supplier's terminal cash flow is

$$\pi_b^{bp}(K_b, D, K) = (w_b - c_p^b) \min(K_b, [D - \min(q^{bc}, K^{bc})]^+) + c_r K_b - c_k^b K_b.$$

Here backup production only is viable only if  $w_b \min(K_b, [D - \min(q^{bc}, K^{bc})]^+) + c_r K_b \in [c_p^b \min(K_b, [D - \min(q^{bc}, K^{bc})]^+) + c_k^b K_b, p \min(K_b, [D - \min(q^{bc}, K^{bc})]^+)]$ , given that backup production only is feasible only if the profit increments from backup supply (w.r.t. the base case) are nonnegative for the retailer and the backup supplier.

**Corollary 4.1.** *For backup production only, the retailer's service level resulting from strategy  $\mathbf{q}^{bp}$  is given by  $P(\min(q^{bp}, K^{bp}) + K_b \geq D)$ . Let  $\theta_b^{bp} = \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b}$  denote the critical fractile of responsive backup capacity in a decentralized supply chain. The supply chain's service level is determined solely by that critical fractile of the backup supplier:*

$$P(\min(q^{bc}, K^{bc}) + K_b \geq D) = \theta_b^{bp}. \quad (4.6)$$

Corollary 4.1 implies that, without unit capacity reservation fee, the service level of a decentralized supply chain may become even lower because of double marginalization—given that  $\frac{w_b - c_p^b - c_k^b}{w_b - c_p^b} < \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b} < \frac{p - c_p - c_k}{p - c_p}$ . The retailer may therefore increase the unit

capacity reservation fee  $c_r$  that incentivizes the backup supplier to choose a higher capacity level through its effect on the critical fractile  $\theta_b^{\text{bp}} = \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b}$ ; the fee  $c_r$  can thus serve as a risk-sharing mechanism that coordinates the decentralized supply chain.

Dual sourcing via a backup supplier can provide a capacity hedge for the retailer who faces supply underage due to financial constraints on the offshore supplier's capacity. This arrangement also enables the retailer to exploit any unanticipated demand by contingent sourcing from the backup supplier. Hence both the retailer and backup supplier are better-off even as the offshore supplier's profit (relative to the base case) remains unaffected.

#### 4.4 Financing with Purchase Order Finance or Advance Payment Discount

In this section, we first analyze the scenario in which only one financing option (i.e., either purchase order finance or advance payment discount) is available. In a single-financing mode where both options are available, we then study the interaction between POF and APD and derive their subgame perfect equilibrium.

##### 4.4.1 Purchase Order Finance

Suppose that neither a backup supplier and advance payment discount is available and that the retailer adopts purchase order finance only (see Definition 4.1); then the retailer and the offshore supplier sign contracts with a creditor to establish a line of credit based on the purchase order. In Stage 1, the creditor offers a POF contract  $(\bar{\lambda}, r)$  to the offshore supplier, where  $\bar{\lambda}$  is the maximum portion of the contract value  $wq$  that the creditor is willing to lend in Stage 1 and  $r$  is the interest rate of the POF loan. We assume that the POF loan is sufficient to fund the offshore supplier's working capital in Stage 1; that is,  $wq^* \bar{\lambda} \geq c_k K^* + L_s - A_s$  (this assumption is relaxed in Section 4.5). Recall that the POF interest rate is lower than the commercial bank rate  $r_s > r$ . The reason is that POF differs from traditional bank financing, where credit is primarily based on the supplier's creditworthiness and not on the purchase order's collateral value (i.e., the creditworthiness of the high-quality retailer). The POF program is also less expensive than ordinary commercial factoring because the creditor pays the costs associated with operating the electronic factoring platform and all legal work, such as preparing and transferring documents (e.g., the Nafin program; see Klapper 2006).

If the offshore supplier accepts the POF contract, he decides on the borrowing level  $\lambda \in [0, \bar{\lambda}]$  and receives a POF loan  $\lambda wq$  from the creditor. The offshore supplier repays his short-term debt  $L_s$  at the end of Stage 1. In Stage 2, after stochastic demand is realized, the offshore supplier delivers his production of  $\min(q^{\text{pof}}, K^{\text{pof}})$  units. The retailer pays  $w \min(q^{\text{pof}}, K^{\text{pof}})$  directly to the creditor, who deducts the POF loan principal (and interest) and pays the difference  $w \min(q^{\text{pof}}, K^{\text{pof}}) - \lambda wq^{\text{pof}}(1+r)$  to the offshore supplier. Any additional fees charged by the creditor are normalized to zero without loss of generality, since the effect of such (typically small) POF fees do not change our structural results. Hence the creditor's terminal payoff is

$$\pi_c = \lambda wqr - I \quad \text{s.t. } \lambda \in [0, \bar{\lambda}],$$

where  $I$  denotes the investment costs associated with initialization and operations of the POF program (e.g., electronic infrastructure, management and transaction costs).

We proceed backwards to derive the equilibrium in the supply chain. The retailer's profit is

$$\pi_r^{\text{pof}}(q, D, K) = p \min(D, \min(q^{\text{pof}}, K^{\text{pof}})) - w \min(q^{\text{pof}}, K^{\text{pof}}),$$

so her optimal order quantity  $q^{\text{pof}} = F^{-1}\left(\frac{p-w}{p}\right)$ .

In POF only, the offshore supplier chooses the borrowing level  $\lambda$  in addition to operational decisions  $(K, w)$  to maximize his profit:

$$\begin{aligned} \pi_s^{\text{pof}}(D, K) = & A_s - L_s + (w - c_p) \min(q^{\text{pof}}, K^{\text{pof}}) - c_k q^{\text{pof}} - (1 - \alpha)[L_s - A_s - \lambda wq + c_k K]^+ \\ & - \lambda wqr. \end{aligned}$$

A marginal analysis with respect to (w.r.t.)  $\lambda$  gives

$$\frac{\partial \pi_s(\lambda, D, K)}{\partial \lambda} = \begin{cases} (1 - \alpha - r)wq & \text{if } L_s + c_k K + c_p q > A_s + \lambda wq, \\ -rwq & \text{if } L_s + c_k K + c_p q \leq A_s + \lambda wq. \end{cases} \quad (4.7)$$



We assume that  $\alpha + r < 1$ , which rules out the trivial case where POF is not profitable and thus not used at all (i.e.,  $\lambda^* = 0$ ). The offshore supplier chooses his optimal borrowing level  $\lambda^*$  so that  $P(L_s + c_k K > A_s + \lambda wq) = 0$  iff  $\lambda^* = \frac{c_k K^{\text{pof}} + L_s - A_s}{wq^*}$ . That is, the offshore supplier first uses up his internal capital and then borrows up to the level that covers his working capital shortage  $c_k K^{\text{pof}} + L_s - A_s$ . This result is in line with the pecking-order theory of capital structure (Myers 1984), by which the firm should first use internal capital and should use external financing only when internal capital is insufficient.

**Proposition 4.2.** *In purchase order finance only, the offshore supplier sets his optimal borrowing level at*

$$\lambda^* = \frac{c_k K^{\text{pof}} + L_s - A_s}{wq^{\text{pof}}}, \quad (4.8)$$

where the optimal order quantity  $q^{\text{pof}}$  satisfies the FOC

$$p\bar{F}(q^{\text{pof}})[1 - h(q^{\text{pof}})] = c_k + c_p. \quad (4.9)$$

The offshore supplier's optimal capacity  $K^{\text{pof}} = q^{\text{pof}} = F^{-1}\left(\frac{p-w}{p}\right)$ , his optimal sales quantity is  $q^{\text{pof}}$  or  $a$ , and the optimal wholesale price  $w^{\text{pof}} = \frac{c_k + c_p}{1 - h(q^{\text{pof}})}$ .

Proposition 4.2 indicates that if capital constraints might lead the offshore supplier to underinvest in capacity (relative to the decentralized benchmark; see Section 4.3.2), then the risk of that scenario's transpiring can be mitigated by POF—albeit at the cost of an interest payment. Recall our assumption that POF is sufficient to fund the offshore supplier's working capital (i.e.,  $wq^* \bar{\lambda} \geq c_k K^* + L_s - A_s$ ); hence the offshore supplier can make capacity decision  $K^{\text{pof}} = q^{\text{pof}} = F^{-1}\left(\frac{p-w}{p}\right)$  as if he were capital unconstrained by borrowing the (minimum) needed amount  $c_k K^{\text{pof}} + L_s - A_s$  from the creditor. In other words, the offshore supplier can make his operational decisions independent of financial constraint if the POF is sufficient to fund his working capital. Thus POF may serve as a financial buffer (of finite capacity) for the offshore supplier, from which it follows that his optimal capacity quantity is the same as in the capital-unconstrained supply chain. This separation result is consistent with the Modigliani and Miller (1958) theorem that one can decouple operational and

financial decisions under certain strong assumptions (e.g., perfect capital markets and symmetric information); it is also in line with the supply chain finance literature (e.g., Babich 2010, Jing et al. 2012, Kouvelis and Zhao 2012) under strict assumptions that are specific to the cases examined.

**Definition 4.2.** The *value* of strategies (b)–(f) in Definition 4.1 refers to the profit increment they create—relative to the base case—via purchase order finance, advance payment discount, and/or backup production.

**Theorem 4.1.** *From the retailer’s perspective, the value of purchase order finance only is*

$$\Delta\pi_r[\text{pof}] = p \min(D, \min(q^{\text{pof}}, K^{\text{pof}})) - w \min(q^{\text{pof}}, K^{\text{pof}}) - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}}).$$

*From the offshore supplier’s perspective, the value of purchase order finance only is*

$$\Delta\pi_s[\text{pof}] = (w - c_p) \min(q^{\text{pof}}, K^{\text{pof}}) - c_k q^{\text{pof}} - \lambda^* w q^{\text{pof}} r - (w - c_p) \min(q^{\text{bc}}, K^{\text{bc}}) + c_k K^{\text{bc}} + (1 - \alpha)[L_s - A_s + c_k K^{\text{bc}}]^+.$$

*From the creditor’s perspective, the value of purchase order finance only is*

$$\Delta\pi_c[\text{pof}] = \lambda^* w q^{\text{pof}} r - I.$$

Here the POF program is viable only if  $\lambda^* w q^{\text{pof}} r \in [I, (w - c_p) \min(q^{\text{pof}}, K^{\text{pof}}) - c_k q^{\text{pof}} - (w - c_p) \min(q^{\text{bc}}, K^{\text{bc}}) + c_k K^{\text{bc}} + (1 - \alpha)[L_s - A_s + c_k K^{\text{bc}}]^+]$ , because POF can be feasible only if all three parties are willing to be involved, i.e., when  $\Delta\pi_i[\text{pof}] \geq 0$  for  $i = r, s, c$ . Theorem 4.1 implies that POF enables the offshore supplier to outsource working capital from a creditor based on the retailer’s creditworthiness and thus creates a “win–win–win” situation by coordinating the physical and financial channels. The benefits of this approach include (i) mitigating the retailer’s supply shortfall due to supplier financial distress, (ii) financing the offshore supplier’s working capital to ensure that orders are fulfilled (at the cost of POF interest), and (iii) providing the creditor with an interest payment from POF (at an investment cost).

This observation confirms the empirical evidence that a POF program offers triple benefits to suppliers, buyers, and creditors (Klapper 2006, Navas-Alemán et al. 2012). For suppliers, the POF program reduces borrowing and transaction costs. Purchase order finance offers working capital at favorable rates, which provides instant liquidity and allows businesses to grow with funds that were previously tied up in receivables. For buyers, the creditor manages their accounts payables; that management reduces buyers' administrative costs of processing different payment terms with many suppliers. By financing the suppliers with working capital, buyers can also improve their reputation and relationship with suppliers. For instance, buyers may then be able to negotiate better terms such as extended payments with suppliers. For creditors, POF is a way to develop relationships with suppliers. Creditors can use POF to assemble credit histories of suppliers, including information on their cash, accounts receivable, and inventory turnover. And because POF involves only high-quality receivables, creditors can expand their operations without increasing their credit risk.

#### 4.4.2 Advance Payment Discount

Suppose that neither a backup supplier nor purchase order finance is available, so the retailer adopts advance payment discount only (see Definition 4.1). In this section, we assume that the retailer purchases the *total* order quantity at discounted price in Stage 1 if she adopts advance payment discount only (this assumption is generalized in Section 4.5). First, the offshore supplier offers an advance payment discount contract  $(w, d)$  to the retailer. Because the retailer has chosen APD only, she pays  $wq^{\text{apd}}(1 - d)$  to the offshore supplier prior to delivery at the end of Stage 1. The offshore supplier delivers  $\min(q^{\text{apd}}, K^{\text{apd}})$  to the retailer in Stage 2.

Recall our assumption that all operational parameters—including demand distribution, prices, and costs—are common knowledge to both channel members (see Section 4.3.1). Hence the wholesale price in APD only is the same as that in the decentralized single-sourcing benchmark case:  $w = p\bar{F}(q^{\text{des}}) = \frac{c_k + c_p}{1 - h(q^{\text{des}})}$  (see Lemma 4.1). In other words, the offshore supplier cannot inflate his wholesale price because all information on operational parameters is symmetrical. Therefore, the retailer with initial asset  $A_r$  and short-term liability  $L_r$  (due at the end of Stage 1) has the following profit function:

$$\begin{aligned}\pi_r^{\text{apd}}(q, D, K) &= A_r - L_r + p \min(D, \min(q^{\text{apd}}, K^{\text{apd}})) - w(1-d)\min(q^{\text{apd}}, K^{\text{apd}}) \\ &\quad - (1-\alpha)[L_r + w(1-d)q^{\text{apd}} - A_r]^+.\end{aligned}$$

**Proposition 4.3.** *Under advance payment discount only, the retailer's optimal order quantity  $q^{\text{apd}}$  is uniquely given by*

$$p\bar{F}(q^{\text{apd}}) = w(1-d)[1 + (1-\alpha)P(L_r + w(1-d)q^{\text{apd}} > A_r)].$$

Moreover,  $q^{\text{apd}} \geq q^{\text{des}}$  if  $(1-d)[1 + (1-\alpha)P(L_r + w(1-d)q^{\text{apd}} > A_r)] \leq 1$ ; otherwise,  $q^{\text{apd}} < q^{\text{des}}$ .

This proposition demonstrates the retailer's trade-off between the marginal effect of advance payment discount  $1-d$  and the unit cost of financial distress  $1 + (1-\alpha)P(L_r + w(1-d)q^{\text{apd}} > A_r)$ . If the *effective* wholesale price (i.e., the actual unit price that matters for the retailer's order quantity decision)  $w_e \triangleq w(1-d)[1 + (1-\alpha)P(L_r + w(1-d)q > A_r)] \leq w$ , then the channel coordination benefit of APD dominates the financial distress effect and so  $q^{\text{apd}} \geq q^{\text{des}}$ . In one special case—where the retailer is a well-established firm endowed with large internal capital and thus is free from any financial distress (i.e.,  $P(L_r + w(1-d)q^{\text{apd}} > A_r) = 0$ )—we have  $w_e \leq w$ ; in this case the channel coordination effect of APD is guaranteed,  $q^{\text{apd}} \geq q^{\text{des}}$ . If the effective wholesale price  $w_e > w$ , then the channel coordination benefit of APD is dominated by the financial distress effect and so  $q^{\text{apd}} < q^{\text{des}}$ .

The offshore supplier's profit under APD only from his optimal capacity  $K^{\text{apd}} = q^{\text{apd}}$  is

$$\pi_s^{\text{apd}}(D, K) = A_s - L_s + [w(1-d) - c_p]\min(q^{\text{apd}}, K^{\text{apd}}) - c_k K^{\text{apd}}.$$

Recall that the offshore supplier's wholesale price is fixed to  $w = p\bar{F}(q^*) = \frac{c_k + c_p}{1-h(q^*)}$ , given the symmetry of information on operational parameters, yet he can still maximize his profit by choosing the minimum discount rate  $d = \underline{d}$  that incentivizes the retailer to adopt APD.

**Theorem 4.2.** *From the retailer's perspective, the value of advance payment discount only is*

$$\begin{aligned}\Delta\pi_r[\text{apd}] &= p \min(D, \min(q^{\text{apd}}, K^{\text{apd}})) - w(1-d)\min(q^{\text{apd}}, K^{\text{apd}}) \\ &\quad - (1-\alpha)[L_r + w(1-d)q^{\text{apd}} - A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) \\ &\quad + w \min(q^{\text{bc}}, K^{\text{bc}}).\end{aligned}$$

From the offshore supplier's perspective, the value of advance payment discount only is

$$\begin{aligned}\Delta\pi_s[\text{apd}] &= [w(1-d) - c_p]\min(q^{\text{apd}}, K^{\text{apd}}) - c_k K^{\text{apd}} - (w - c_p)\min(q^{\text{bc}}, K^{\text{bc}}) + c_k K^{\text{bc}} \\ &\quad + (1-\alpha)[L_s - A_s + c_k K^{\text{bc}}]^+.\end{aligned}$$

Here APD is viable only if  $w(1-d)\min(q^{\text{apd}}, K^{\text{apd}}) \in [c_p\min(q^{\text{apd}}, K^{\text{apd}}) + c_k K^{\text{apd}} + (w - c_p)\min(q^{\text{bc}}, K^{\text{bc}}) - c_k K^{\text{bc}} - (1-\alpha)[L_s - A_s + c_k K^{\text{bc}}]^+, p \min(D, \min(q^{\text{apd}}, K^{\text{apd}})) - (1-\alpha)[L_r + w(1-d)q^{\text{apd}} - A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}})]$ , given that APD is feasible only if the profit increments from APD (w.r.t. the base case) are nonnegative for the retailer and the offshore supplier. Theorem 4.2 implies that the retailer benefits from the channel coordination effect of APD, at the cost of potential financial distress, whereas the offshore supplier benefits from channel coordination effect and the avoidance of financial distress cost. Although both POF and APD can relieve the capital constraint on the offshore supplier, POF outsources capital from a creditor (based on retailer credit) to finance the offshore supplier (see Theorem 4.1) whereas APD transfers financial flow from voluntary to binding positions within the operational supply chain. APD results in a lower wholesale price and can thereby coordinate the channel, enhancing supply chain efficiency (at the cost of potential retailer financial distress).

#### 4.4.3 Financing Equilibrium between POF and APD

So far we have separately derived the supply chain equilibria under POF only and APD only. However, when the retailer chooses either POF or APD in the single-financing mode, a natural question is: which financing scheme is optimal for the retailer and so it will be chosen in equilibrium? Without loss of generality, we assume that the retailer chooses APD over POF if she is indifferent between the two.

##### *Retailer's Perspective: POF versus APD*

When either POF or APD is viable in single-financing mode, we use backward induction to derive the respective optimal strategies of both channel members.

**Proposition 4.4.** *In single-financing mode: if the retailer's internal asset level is below a certain threshold,*

$$A_r < \omega_r = L_r + w(1 - d)q^{\text{apd}} - \frac{p\min(q^{\text{apd}}, D) - w(1 - d)q^{\text{apd}} - p\min(q^{\text{pof}}, D) + wq^{\text{pof}}}{1 - \alpha},$$

*the retailer prefers financing the offshore supplier via POF because  $\pi_r^{\text{pof}}(q, D, K) > \pi_r^{\text{apd}}(q, D, K)$ . Otherwise, the retailer chooses APD to finance the offshore supplier because  $A_r \geq \omega_r$  iff  $\pi_r^{\text{pof}}(q, D, K) \leq \pi_r^{\text{apd}}(q, D, K)$ .*

This proposition indicates that the retailer's optimal financing choice depends on whether the channel coordination benefit of APD dominates its financial distress cost (see Proposition 4.3), which in turn is determined by whether the retailer's internal asset level is above a certain threshold. In other words, even though the retailer pays a lower price in APD than in POF, she must then also accept the risk of potential financial distress in Stage 1 as well as increased inventory risk (because the order quantity is greater) in Stage 2. In the special case where the retailer's internal asset level is extremely high and so free from any financial distress (i.e.,  $P(L_r + w(1 - d)q^{\text{apd}} > A_r) = 0$ ), she always prefers APD over POF.

The intuition behind Proposition 4.4 is as follows. First, APD is most applicable in a supply chain consisting of a capital-constrained supplier and an established retailer whose high internal asset level precludes financial distress; this follows because the retailer prefers APD to POF as long as the former's channel coordination benefits dominate her concerns about financial distress. Second, POF is more suitable in a supply chain with a capital-constrained supplier and a medium-sized retailer who has a good credit rating yet may be subject to short-term financial distress. This result explains the empirical finding that APD accounts for 19%–22% of or 3–3.5 trillion US dollars in global trade finance (Chauffour and Malouche 2011) because established wealthier retailers with larger trade volumes are more likely to adopt APD. Proposition 4.4 is consistent also with the case-study finding that a POF transfers the loan's credit risk from a risky supplier to a higher-quality buyer (Klapper 2006); this explains its frequent use in transactions between medium-sized buyers and start-up suppliers from developing countries (Gold and Jacobs 2007, USAID 2011a, b).

### *Supplier's Perspective: Equilibrium Conditions*

The retailer's single-financing choice is ex ante ambiguous to the offshore supplier because we have assumed (see Section 4.3.1) that *financial* information is asymmetric; ambiguity here characterizes the situation of an offshore supplier who is unable to assign exact probabilities to the retailer's single-financing choice (POF or APD) because he has no financial information on her capital structure (cf. Natarajan et al. 2012). Given that the POF's payoff is determined by the financing contract  $(\bar{\lambda}, r)$  offered by the creditor, the offshore supplier can optimize his profit only by maximizing the expected payoffs in the APD-only regime. Hence the offshore supplier chooses the minimum discount rate  $d = \underline{d} \geq 0$  to make APD more profitable than POF for him (see Section 4.4.2). In single-financing mode we have  $\underline{d} \in [0, \frac{(w-c_p-c_k)(q^{\text{adp}}-q^{\text{pof}})+w\lambda r q^{\text{pof}}}{wq^{\text{adp}}}]$ , where the upper limit ensures that  $\pi_s^{\text{adp}}(D, K) \geq \pi_s^{\text{pof}}(D, K)$ . If  $\underline{d} = 0$ , the retailer is willing to finance the offshore supplier via cash in advance without discount. If  $\underline{d} > \frac{(w-c_p-c_k)(q^{\text{adp}}-q^{\text{pof}})+w\lambda r q^{\text{pof}}}{wq^{\text{adp}}}$  then the offshore supplier has incentives to cancel APD in the presence of POF, given that  $wq^*\bar{\lambda} \geq c_k K^* + L_s - A_s$  (see Section 4.4.1).

**Proposition 4.5.** *In single-financing mode, the offshore supplier will offer an advance payment discount contract  $(w, \underline{d})$  in equilibrium, where  $\underline{d} \in [0, \frac{(w-c_p-c_k)(q^{\text{adp}}-q^{\text{pof}})+w\lambda r q^{\text{pof}}}{wq^{\text{adp}}}]$ . Hence the offshore supplier prefers APD over POF:*

$$\pi_s^{\text{adp}}(D, K) \geq \pi_s^{\text{pof}}(D, K) \Leftrightarrow 0 \leq d^* \leq \frac{(w - c_p - c_k)(q^{\text{adp}} - q^{\text{pof}}) + w\lambda r q^{\text{pof}}}{wq^{\text{adp}}}.$$

Proposition 4.5 implies that the offshore supplier maximizes his profit by choosing a minimum discount rate that also ensures APD only is more profitable for him than is POF only—because otherwise the offshore supplier may opt to cancel APD. Propositions 4.4 and 4.5 characterize the unique Stackelberg equilibrium in single-financing mode.

## **4.5 Interaction of Pre-shipment Finance and Backup Production**

### **4.5.1 Dual Financing: Pecking Order of POF and APD**

Next we examine the supply chain equilibrium when both POF and APD are viable in the dual-financing mode. In this case, the retailer orders  $q^{\text{df}} = q_1 + q_2$  from the offshore supplier; here  $q_1 = (1 - \beta)q^{\text{df}}$  and  $q_2 = \beta q^{\text{df}}$  ( $\beta \in [0,1]$ ) denote, respectively, the order quantities paid

at advance discount in Stage 1 and the wholesale price in Stage 2. The retailer maximizes her profit by jointly choosing the total order quantity  $q^{\text{df}}$  and the portion of orders paid at wholesale price  $\beta$ . That is, dual financing allows the retailer to divide the purchase order into two parts: the first part is paid in advance at discount, and the second part can be used as POF collateral for the creditor. Dual financing is applicable in two situations: (i) when the POF loan is insufficient to cover the offshore supplier's working capital because of the credit limit (i.e.,  $\bar{\lambda} < \frac{c_k K^* + L_s - A_s}{wq^*}$ ), which relaxes the assumption in Section 4.4.1; and (ii) when the retailer purchases partially via APD owing to her limited internal capital (i.e.,  $q_1 < q^{\text{df}}$ ), which generalizes the assumption in Section 4.4.2. Hence dual financing represents the general case of pre-shipment finance for two reasons. First,  $\beta = 1$  and  $\beta = 0$  denote respectively the two special cases of POF only (see Section 4.4.1) and APD only (see Section 4.4.2). Second, the subcase where the retailer pays partially via APD (i.e.,  $0 < \beta < 1$ ) and the supplier chooses not to use POF (i.e.,  $\lambda^* = 0$ ) extends the APD-only scenario by allowing the retailer to purchase the order *partially* via APD (as opposed to purchasing total order quantity at APD; see Section 4.4.2).

In dual-financing mode, the offshore supplier's profits are

$$\begin{aligned}\pi_s^{\text{df}}(D, K) &= A_s - L_s + w(1-d)q_1 + w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ - w(1-d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ \\ &\quad - c_p \min(q^{\text{df}}, K^{\text{df}}) - c_k K^{\text{df}} - \lambda w q_2 r \\ &\quad - (1-\alpha)[L_s + c_k K + c_p q - A_s - w q_1(1-d) - \lambda w q_2]^+\end{aligned}$$

and the retailer's profits are

$$\begin{aligned}\pi_r^{\text{df}}(q^{\text{df}}, D, K) &= A_r - L_r + p \min(D, \min(q^{\text{df}}, K^{\text{df}})) - w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ \\ &\quad + w(1-d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ - w(1-d)q_1 \\ &\quad - (1-\alpha)[L_r + w(1-d)q_1 - A_r]^+.\end{aligned}$$

Here the effective wholesale price that matters for the retailer's order quantity decision is  $w^{\text{df}} \triangleq (1-\beta)w(1-d) + \beta w$ . Hence  $K^{\text{df}} = q^{\text{df}} = F^{-1}\left(\frac{p-w^{\text{df}}}{p}\right) \in \left[F^{-1}\left(\frac{p-w}{p}\right), F^{-1}\left(\frac{p-w(1-d)}{p}\right)\right]$  provided that  $w^{\text{df}} \in [w(1-d), w]$ . In other words, the order quantity under dual financing lies between the respective quantities in POF only and APD only.



The retailer decides on  $(q^{\text{df}}, \beta)$  to maximize her expected profit, the FOC of which w.r.t.  $q_1 = (1 - \beta)q^{\text{df}}$  is

$$\frac{\partial \mathbb{E}[\pi_r^{\text{df}}(q^{\text{df}}, D, K)]}{\partial q_1} = \frac{\partial [p \min(D, q^{\text{df}}) - w^{\text{df}} q^{\text{df}}]}{\partial q_1} + wd - (1 - \alpha)w(1 - d). \quad (4.10)$$

In equation (4.10):  $\frac{\partial p \min(D, q^{\text{df}}) - w^{\text{df}} q^{\text{df}}}{\partial q_1} > 0$  represents the marginal channel coordination benefit, given that  $q_1 = (1 - \beta)q^{\text{df}} \rightarrow q^{\text{df}}$  only if  $w^{\text{df}} \rightarrow w(1 - d)$  only if  $q^{\text{df}} \rightarrow F^{-1}\left(\frac{p - w(1 - d)}{p}\right)$  and that  $q^{\text{des}} = F^{-1}\left(\frac{p - w}{p}\right) \leq q^{\text{df}} \leq F^{-1}\left(\frac{p - w(1 - d)}{p}\right) < F^{-1}\left(\frac{p - c_p - c_k}{p - c_p}\right) = K^{\text{ces}}$  (see Section 4.3.2);  $wd > 0$  shows the unit benefit of discounted wholesale price; and  $-(1 - \alpha)w(1 - d) < 0$  reflects the marginal cost of financial distress. That is, the retailer trades off the marginal benefits of channel coordination against the marginal cost of financial distress.

**Proposition 4.6.** *In dual financing only, if  $\frac{\partial \mathbb{E}[\pi_r^{\text{df}}(q^{\text{df}}, D, K)]}{\partial q_1} \leq 0$  then the pecking order of pre-shipment finance is as follows. The retailer first uses her internal capital to fund APD:  $q_1^* = \frac{A_r - L_r}{w(1 - d)}$ . If  $1 - d < \frac{c_k K^* + L_s - A_s}{w q_1^*}$  then the offshore supplier outsources via POF to cover his working capital,  $\lambda^* = \min(\bar{\lambda}, \frac{c_k K^* + L_s - A_s - w q_1^* (1 - d)}{w q_2^*})$ , but otherwise adopts APD only. If  $\frac{\partial \mathbb{E}[\pi_r^{\text{df}}(q^{\text{df}}, D, K)]}{\partial q_1} > 0$ , it is optimal for the retailer to purchase total order quantity via APD; that is,  $q_1^* = q^{\text{df}}$  in equilibrium.*

Note that if  $A_r - L_r = 0$  then  $q_1^* = 0$ ; this captures the special case where the retailer adopts POF only if her internal capital level is zero. Proposition 4.6 is consistent the pecking order of capital structure (Myers 1984) in that the retailer first uses internal capital to fund the offshore supplier (via APD) and does not use external financing (via POF) unless her internal capital is insufficient.

#### 4.5.2 Relationship between Pre-shipment Finance and Backup Production

The dual-financing mode is the general case of pre-shipment finance that incorporates, under certain conditions, the two special cases of POF only and APD only (see Section 4.5.1). Therefore, when assessing the relationship between pre-shipment finance and backup production, it is sufficient to examine the joint and respective value of dual financing (POF and APD) and backup production.

**Corollary 4.2.** In dual financing (POF and APD) with backup production, the retailer's service level resulting from her optimal sourcing strategy strategy  $\mathbf{q}^{\text{dfbp}} = (q^{\text{df}}, \min(K_b, [D - \min(K, q^{\text{df}})]^+)$  is given by  $P(\min(K^{\text{dfbp}}, q^{\text{dfbp}}) + K_b \geq D)$ . Let  $\theta_b^{\text{dfbp}} = \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b}$  denote the critical fractile of responsive backup capacity in a decentralized supply chain. Then the supply chain's service level is determined solely by the critical fractile of the backup supplier:

$$P(\min(K^{\text{dfbp}}, q^{\text{dfbp}}) + K_b \geq D) = \theta_b^{\text{dfbp}}. \quad (4.11)$$

Corollary 4.2 also shows that the retailer may adjust her unit capacity reservation fee  $c_r$ , which incentivizes the backup supplier to choose an optimal capacity level based on the critical fractile  $\theta_b^{\text{dfbp}} = \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b}$ , and thereby ensures any particular service level of the decentralized supply chain.

**Definition 4.3.** From the retailer's viewpoint, backup production and dual financing (POF and APD) are complements, separate, or substitutes according as whether (respectively)  $\Delta\pi_r[\text{dfbp}] > \Delta\pi_r[\text{bp}] + \Delta\pi_r[\text{df}]$ ,  $\Delta\pi_r[\text{dfbp}] = \Delta\pi_r[\text{bp}] + \Delta\pi_r[\text{df}]$ , or  $\Delta\pi_r[\text{dfbp}] < \Delta\pi_r[\text{bp}] + \Delta\pi_r[\text{df}]$ . If backup production and dual financing (POF and APD) are substitutes, then we define that they are *partial* or *perfect* substitutes according as whether (respectively)  $\Delta\pi_r[\text{dfbp}] > \max(\Delta\pi_r[\text{bp}], \Delta\pi_r[\text{df}])$  or  $\Delta\pi_r[\text{dfbp}] \leq \max(\Delta\pi_r[\text{bp}], \Delta\pi_r[\text{df}])$ .

**Theorem 4.3.** From the retailer's perspective, the value of backup production only is

$$\begin{aligned} \Delta\pi_r[\text{bp}] &= p \min(D, \min(q^{\text{bc}}, K^{\text{bc}}) + K_b) - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) \\ &\quad - w_b \min(K_b, [D - \min(q^{\text{bc}}, K^{\text{bc}})]^+) - c_r K_b \end{aligned}$$

and the value of dual financing only is

$$\begin{aligned} \Delta\pi_r[\text{df}] &= p \min(D, \min(q^{\text{df}}, K^{\text{df}})) - w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ + w(1-d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ \\ &\quad - w(1-d)q_1 - (1-\alpha)[L_r + w(1-d)q_1 - A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) \\ &\quad + w \min(q^{\text{bc}}, K^{\text{bc}}). \end{aligned}$$

Here backup production only and dual financing only are viable only if (respectively)  $(p - w_b) \min(K_b, [D - \min(q^{bc}, K^{bc})]^+) \geq c_r K_b$  (see Section 4.3.3) and  $p \min(D, \min(q^{df}, K^{df})) - w[\min(q^{df}, K^{df}) - q_1]^+ + w(1 - d)[q_1 - \min(q^{df}, K^{df})]^+ - w(1 - d)q_1 - (1 - \alpha)[L_r + w(1 - d)q_1 - A_r]^+ \geq p \min(D, \min(q^{bc}, K^{bc})) - w \min(q^{bc}, K^{bc})$ , so that the profit increments from backup production only and dual financing only w.r.t. the base case are (respectively) nonnegative for the retailer. Theorem 4.3 indicates that backup production only can hedge (i) the retailer's supply shortage caused by the offshore supplier's capital constraint as well as (ii) demand upside potential. In contrast, dual financing enables the retailer to (i) exploit the channel coordination benefits of APD and (ii) reduce financial distress costs by outsourcing capital from the POF creditor.

**Theorem 4.4.** *From the retailer's perspective, the value of dual financing with backup production is*

$$\begin{aligned} \Delta\pi_r[\text{dfbp}] = & p \min(D, \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + K_b) - w[\min(q^{\text{dfbp}}, K^{\text{dfbp}}) - q_1]^+ + w(1 - d) \\ & [q_1 - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+ - w(1 - d)q_1 - w_b \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + K_b]^+) - c_r K_b - \\ & (1 - \alpha)[L_r + c_r K_b + w(1 - d)q_1 - A_r]^+ - p \min(D, \min(q^{bc}, K^{bc})) + w \min(q^{bc}, K^{bc}). \end{aligned}$$

*From the offshore supplier's perspective, the value of dual financing with backup production is*

$$\begin{aligned} \Delta\pi_s[\text{dfbp}] = & w(1 - d)q_1 + w[\min(q^{\text{dfbp}}, K^{\text{dfbp}}) - q_1]^+ - w(1 - d)[q_1 - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+ \\ & - c_p \min(q^{\text{dfbp}}, K^{\text{dfbp}}) - c_k K^{\text{dfbp}} - \lambda w q_2 r - (w - c_p) \min(q^{bc}, K^{bc}) + c_k K^{bc} \\ & + (1 - \alpha)[L_s - A_s + c_k K^{bc}]^+. \end{aligned}$$

*From the backup supplier's perspective, the value of dual financing with backup production is*

$$\Delta\pi_b[\text{dfbp}] = (w_b - c_p^b) \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+) + c_r K_b - c_k^b K_b.$$

*From the creditor's perspective, the value of dual financing with backup production is*

$$\Delta\pi_c[\text{dfbp}] = \lambda\beta w q^{\text{dfbp}} r - I.$$

Here dual financing with backup production is viable only if the following conditions are satisfied. First,  $\Delta\pi_i[\text{dfbp}] \geq 0$  for  $i = r, s, b, c$ ; i.e., dual financing with backup production is profitable (w.r.t. the base case) for all involved parties. Second, since the effective wholesale price is  $w^{\text{dfbp}} = (1 - \beta)w(1 - d) + \beta w \in [w(1 - d), w]$ , this leads to  $K^{\text{dfbp}} = q^{\text{dfbp}} = F^{-1}\left(\frac{p-w^{\text{df}}}{p}\right) \in \left[F^{-1}\left(\frac{p-w}{p}\right), F^{-1}\left(\frac{p-w(1-d)}{p}\right)\right]$ . This channel coordination effect ensures that it is profitable for the retailer and the offshore supplier to employ dual financing in addition to backup production. Third,  $w_b \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) + c_r K_b \in \left[c_p^b \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) + c_k^b K_b, p \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right)\right]$  ensures that the profit increments by adding backup production to dual financing are nonnegative for the retailer and the backup supplier.

Theorem 4.4 shows that dual financing with backup production inherits all the advantages of APD, POF, and backup production. The retailer optimally exploits the channel coordination benefits of APD depending on her internal capital level, outsources capital via POF to avoid financial distress, and uses backup production to hedge both demand surge. The offshore supplier's liquidity constraint is relaxed by dual financing (POF and APD), and additional benefits are provided to the backup supplier and creditor via backup production and POF, respectively.

**Theorem 4.5.** *From the retailer's perspective, backup production and dual financing (POF and APD) can be complements or partial substitutes, depending on demand variability (upside potential). Their interaction effect (i.e., the value increment in the retailer's profit) is*

$$\Delta\pi_r[\text{df, bp}] = (p - w_b) \left[ \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) - \min\left(K_b, [D - K^{\text{bc}}]^+\right) \right] - (1 - \alpha) ([L_r + c_r K_b + w(1 - d)q_1 - A_r]^+ - [L_r + w(1 - d)q_1 - A_r]^+). \quad (4.12)$$

Both backup production and dual financing can hedge mismatch risk caused by financial distress, one might well expect them to be substitutes. However, Theorem 1 shows that they can also be complements if demand volatility (upside potential) is high. Recall that backup production alone can provide two benefits for the retailer (see Section 4.3.3): (i) hedging supply underage owing to the offshore supplier's financial constraint and (ii) hedging demand upside potential. Yet the first of these benefits is optimally provided by pre-shipment finance because dual financing releases the offshore supplier's capital constraint

and thereby fully mitigates the effect of financial distress at a *lower* cost for the retailer. Hence the interaction effect (i.e., the value increment in the retailer's profit) between backup production and dual financing includes the profit increment from backup supply (in the presence of pre-shipment finance than in its absence) and the potential increase in distress cost, as denoted (respectively) by the two terms on the right hand-side of (4.12). The first term can be positive if demand variability (especially upside surge) is high whereas the second term is nonpositive. Therefore, the relationship of dual financing and backup production depends on the trade-off between profit increment from backup supply and the potential increase in distress cost: dual financing and backup production are complements when demand variability (upside potential) is high and are partial substitutes otherwise. Although dual financing is more effective than backup production in mitigating financial distress risk, it cannot hedge mismatch risk caused by capacity underage and demand surge; this result is in line with the argument that demand uncertainty is a *private* risk that cannot be hedged in the financial market (Chen et al. 2007). Overall, the integration of backup production and dual financing can create significant value because its expected profit is strictly greater than that of any single risk management strategy.

In practice, the optimality of a joint dual sourcing and pre-shipment finance (POF and APD) strategy is justified by the two sources of uncertainty: financial distress and mismatch risk. The former can be fully mitigated via financing strategy, and the latter is optimally hedged by backup production. The OM literature on dual sourcing under supply uncertainty has overlooked that one root cause of the operational risk can be supplier financial distress, which is better hedged by pre-shipment finance than by dual sourcing because financing eliminates the source of uncertainty. At the same time, the supply chain finance literature has failed to address one natural response to supplier default risk – dual sourcing via a backup supplier – and its interaction with financing strategy. Although supplier financial risk is eliminated by pre-shipment finance, operational risk (i.e., unexpected demand surge) can be hedged only by backup production. In sum, dual sourcing and pre-shipment finance can be complements or partial substitutes depending on the magnitude of demand uncertainty. In both cases, optimality can be achieved from the integration of backup supply and financing.

## 4.6 Robustness Analysis

In this section, we examine robustness of our main results (Proposition 4.4 and Theorem 4.5) via an extensive numerical study. Examples are provided to demonstrate how demand variability and the retailer's internal capital level each affect not only supply chain performance but also the equilibrium regions of POF and APD. Unless stated otherwise, the figures illustrating our numerical results are representative of all parameter combinations that we considered. Our numerical study relies on optimization via simulation using Palisade @RISK software with 1,000,000 uncertainty scenarios (supply–demand matching states and price–quantity decisions) and the following benchmark parameter values:  $p = 60, c_k = c_p = 10, c_k^b = c_p^b = 15, A_s = 5,000, L_s = 3,000, A_r = 60,000, L_r = 30,000, \bar{\lambda} = 0.5, r = 0.07$  (see Klapper 2006),  $\alpha = 0.85$  (see Gamba and Triantis 2013), and  $R \sim \text{Unif}(0.95, 1.05)$ . Demand  $D$  follows a normal distribution,  $D \sim N(1000, 100)$ , whose standard deviation may vary with its coefficient of variation (see Section 4.6.1).

Table 4.2. Relative Effectiveness of Pre-shipment Finance and Backup Production

Base Case			Dual financing Only			$(\mathbf{T}^{\text{df}} - \mathbf{T}^{\text{bc}})/\mathbf{T}^{\text{bc}}$ ( $\mathbf{T} = \min(q^*, K), \mathbb{E}^*[\pi_x], x = r, s$ )		
$\min(q^*, K)$	$\mathbb{E}^*[\pi_r]$	$\mathbb{E}^*[\pi_s]$	$\min(q^*, K)$	$\mathbb{E}^*[\pi_r]$	$\mathbb{E}^*[\pi_s]$	$\min(q^*, K)$	$\mathbb{E}^*[\pi_r]$	$\mathbb{E}^*[\pi_s]$
503.39	875.89	18715.16	807.78	1914.83	30031.00	60.47%	118.62%	60.46%
Backup Production Only			Dual financing & Backup Production			$(\mathbf{T}^{\text{dfds}} - \mathbf{T}^{\text{ds}})/\mathbf{T}^{\text{ds}}$		
503.39	1125.72	18715.16	807.78	2034.30	30031.00	60.47%	80.71%	60.46%
$(\mathbf{T}^{\text{ds}} - \mathbf{T}^{\text{bc}})/\mathbf{T}^{\text{bc}}$			$(\mathbf{T}^{\text{dfds}} - \mathbf{T}^{\text{df}})/\mathbf{T}^{\text{df}}$			$(\mathbf{T}^{\text{dfds}} - \mathbf{T}^{\text{bc}})/\mathbf{T}^{\text{bc}}$		
0.00%	28.52%	0.00%	0.00%	6.24%	0.00%	60.47%	132.25%	60.46%

Table 4.2 verifies Theorem 4.5 by showing that pre-shipment finance (POF and APD) and backup production can be partial substitutes from the retailer's perspective. In this benchmark example, dual financing and backup production increase the retailer's expected profit by 118.62% and 28.52%, respectively. As discussed in Section 4.5.2, pre-shipment finance is more effective than backup production in mitigating the offshore supplier's capital constraint, yet backup production can create value for the retailer in addition to that from dual financing by providing an operational hedge of demand upside uncertainty. When only one of the two risk management strategies is adopted by the retailer, their relative effectiveness depends on the profit increments determined by the magnitude of the coordination benefit and the extent of financial distress. The value of dual financing with backup production is smaller than the sum of dual financing only and backup production only (i.e.,  $132.25\% < 118.62\% + 28.52\% = 147.14\%$ ; see Table 4.2) owing to their interaction (substitution) effect in mitigating offshore supplier financial distress. However, integrating

pre-shipment finance and backup production significantly improves supply chain efficiency as compared with any single strategy.

#### 4.6.1 Impact of Demand Variability

We next examine how demand volatility affects the supply chain<sup>22</sup> performance and the equilibrium regions of POF and APD for the six strategies (see Definition 4.1). When adjusting demand volatility, we allow its coefficient of variation  $\delta(D)$  to vary between 0.1 and 0.5; at the same time, we retain an expected demand  $\mathbb{E}[D] = 1,000$ . The effect of increasing demand volatility is illustrated in Figures 4.4(a) – (d).

Figure 4.4. Effect of Demand Volatility on (a) Offshore Supplier Delivered Quantity; (b) Retailer Expected Profit; (c) Offshore Supplier Expected Profit; and (d) Supply Chain Expected Profit

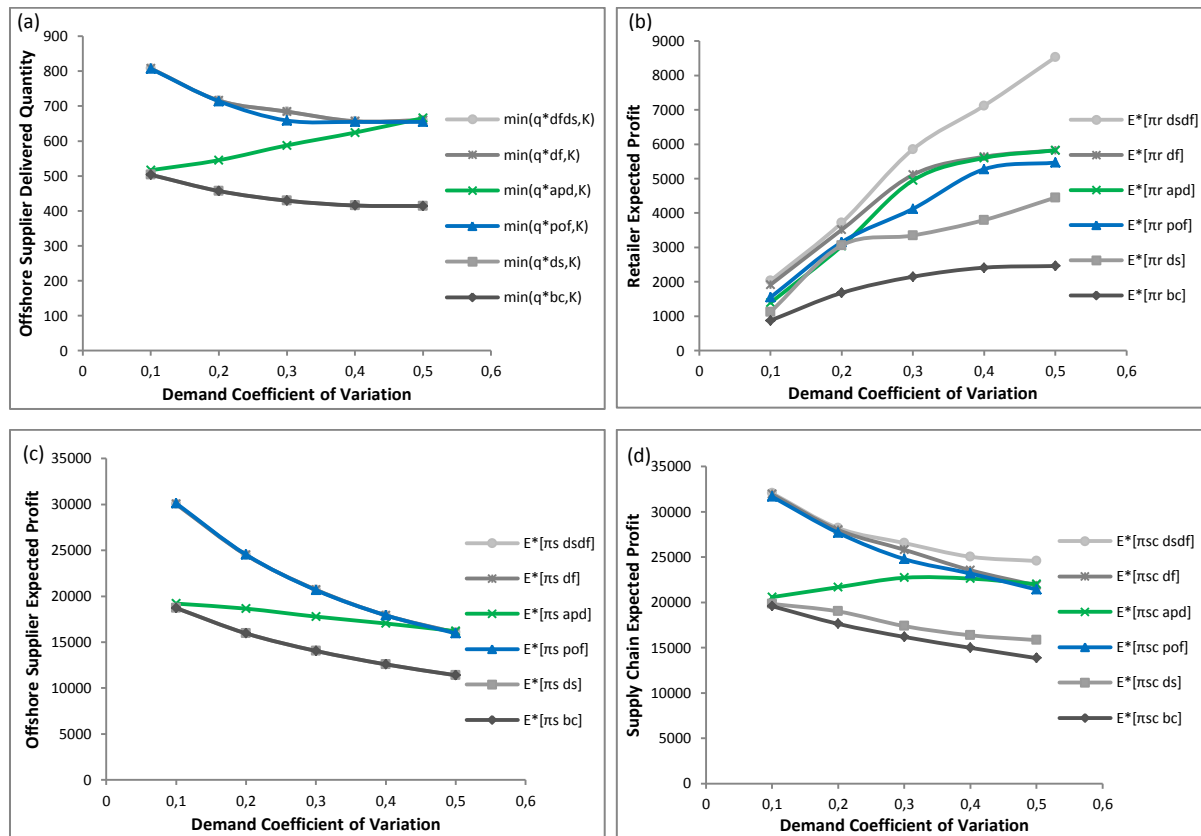


Figure 4.4(a) shows that the offshore supplier’s delivered quantity is decreasing in demand volatility without pre-shipment finance (APD and POF). Whereas offshore supplier delivered quantity is strictly increasing in advance payment discount only (see Figure 4.4), it is convex in purchase order finance only, dual financing only, and dual financing with backup production. Absent pre-shipment finance, operational hedge via backup production is the only risk management instrument that increases the retailer’s expected profit without

<sup>22</sup> In Section 4.6, we use “supply chain” to denote the retailer-offshore supplier channel.

affecting the offshore supplier's delivered quantity and expected profit (see Figures 4.4(a) and 4.4(c)); hence the offshore supplier's order fulfillment decreases as demand volatility increases. When pre-shipment finance (APD and/or POF) is employed, the offshore supplier's delivered quantity is less sensitive to demand volatility because his financial distress is mitigated by pre-shipment finance; hence that supplier may lower his wholesale price to induce a larger order quantity, thereby sharing demand risk with the retailer. Figure 4.4(b) shows that the retailer's expected profit is increasing in demand volatility, which results from the offshore supplier's lower wholesale price in response to increasing demand volatility. The contrast in retailer's expected profit under APD only versus POF only indicates that the equilibrium region of purchase order finance is decreasing in demand variability: the retailer prefers POF when the demand coefficient of variation is relatively low, but otherwise she chooses APD to finance the offshore supplier (i.e.,  $\delta(D) > 0.21$ ).

Figure 4.4(c) illustrates that the offshore supplier's expected profit declines in response to increasing demand volatility. The offshore supplier's expected profit is decreasing at a constant rate in demand volatility when there is no pre-shipment finance (i.e., in the base case and under backup production only). However, the decrease is much less under advance payment discount only because APD serves as a risk-sharing mechanism between channel members; the offshore supplier's expected profit is reduced (albeit at a decreasing rate) under purchase order finance only, dual financing only, and dual financing with backup production – given that POF and dual financing can mitigate financial distress and so enable the offshore supplier to offer a lower wholesale price for a larger order quantity. Contrary to Figure 4.4(b), the supplier prefers APD over POF only if demand coefficient of variation is relatively high (i.e.,  $\delta(D) \rightarrow 0.5$ ). Yet the supply chain's expected profit is concave under advance payment discount only owing to the APD's channel coordination effect, but otherwise declines in demand volatility; see Figure 4.4(d). Much as in Figure 4.4(c), POF dominates APD unless the demand coefficient of variation is fairly high (i.e.,  $\delta(D) > 0.44$ ) from the supply chain's viewpoint, a dynamic that reflects the competition penalty (i.e., the profit inefficiency due to the competition between channel members; see Jing et al. 2012). This may arise when demand variability falls into a specific domain:  $\delta(D) \in (0.21, 0.44)$ , because the retailer chooses APD if  $\delta(D) > 0.21$  (see Figure 4.4(b) and Section 4.4.3).



### 4.6.2 Impact of the Retailer's Internal Capital Level

To study the role played by a retailer's internal capital level (i.e.,  $A_r - L_r$ ), we vary her asset level  $A_r$  from 40,000 to 80,000 while keeping the short-term liability  $L_r$  at a constant level of 30,000. Figure 4.5(a) reveals that the offshore supplier's delivered quantity is increasing under APD only but is insensible to the retailer's internal wealth level in the other five strategies. The reason is that the retailer's growing internal capital relieves financial distress and thus allows the APD-based exploitation of channel coordination, whereas the retailer may suffer financial distress if she employs advance payment discount only. Similarly, Figure 4.5(b) illustrates that the retailer's expected profit is increasing in her internal capital level under advance payment discount only; because the increase is less significant as the retailer's internal capital grows up to a certain level (i.e.,  $A_r - L_r > 30000$ ), financial distress cost is unlikely to be incurred when using advance payment discount only. A comparison of APD only and POF only with respect to the retailer's expected profit confirms that the financing equilibrium is POF if retailer internal capital is below a certain threshold level,  $A_r - L_r < \omega_r - L_r \in (20000, 25000)$ , but is APD otherwise. This finding confirms Proposition 4.4: the equilibrium region of purchase order finance is decreasing in the retailer's internal capital level.

Figure 4.5. Effect of Retailer's Internal Capital Level on (a) Offshore Supplier Delivered Quantity; (b) Retailer Expected Profit; (c) Offshore Supplier Expected Profit; and (d) Supply Chain Expected Profit

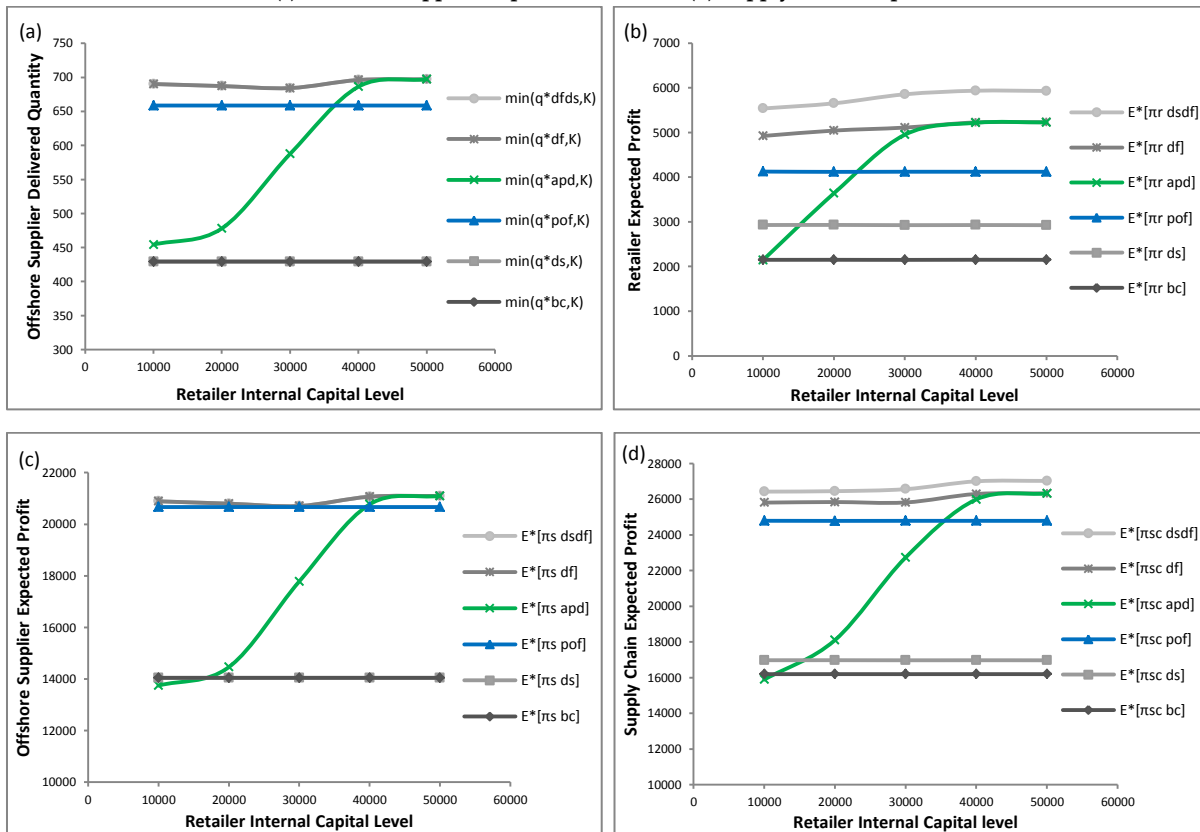


Figure 4.5(c) demonstrates that the offshore supplier's expected profit is increasing in the retailer's internal capital level under advance payment discount only, a result of the effect plotted in Figure 4.5(a). APD is viable for the offshore supplier only if the retailer internal capital level is higher than a certain level (i.e., only if  $A_r - L_r > 17500$ ). The offshore supplier prefers APD over POF only if the retailer internal capital level is rather high (i.e., only if  $A_r - L_r > 39500$ ), which is contour to the result in Figure 4.5(b). Figure 4.5(d) illustrates the net effect of the retailer's internal capital level on supply chain expected profit: the channel coordination effect of APD is increasing in the retailer's internal wealth. Analogously to Figure 4.5(c), here APD is viable for the supply chain only if the retailer internal capital level is higher than a certain level (i.e., only if  $A_r - L_r > 11000$ ). APD dominates POF when the retailer's internal capital level is relatively high (i.e., when  $A_r - L_r > 35000$ ) from the supply chain's perspective. So under the optimal financing choice there is a competition penalty between channel members if the retailer's internal capital level falls into a specific domain:  $A_r - L_r \in (25000, 35000)$ . In sum, the integration of dual financing and backup production creates significant value across the supply chain, as shown in Figures 4.4 and 4.5.

## 4.7 Conclusions

This chapter contributes to supply chain finance literature by exploring the relationships among purchase order finance, advance payment discount, and backup production in managing supplier financial distress and mismatch risk. We provide the first analytical treatment of POF and APD in a supply chain Stackelberg game. Our main findings are as follows. First, the unique equilibrium in single-financing mode is POF if the retailer's internal asset level is below a certain threshold but is APD otherwise; in this case, the equilibrium region of purchase order finance is decreasing in demand variability and also in the retailer's internal capital level. Second, the pecking order of pre-shipment finance under dual financing is that the retailer first uses internal capital for APD and then adopts POF to finance the offshore supplier—provided the channel coordination benefits of APD are dominated by the costs of financial distress; otherwise, she uses APD only. Third, pre-shipment finance (POF and/or APD) and backup production can be complements or partial substitutes, depending on the magnitude of demand variability. Overall, the integration of these strategies can create significant value because the expected profit from that approach is strictly greater than that from either pre-shipment finance or backup production alone.

The supply chain finance model proposed here could motivate a number of research directions. First, new combinations of operational hedging and financial flexibility (see Kouvelis et al. 2012a) can be explored. Second, the pre-shipment finance and backup production can be examined in a global supply chain setting by incorporating exchange rate uncertainty. Because the research reported here focuses on a risk-neutral supply chain, it could be extended by considering risk-averse channel members. Fourth, the role of pre-shipment finance can be examined in various supply chain structures. Finally, empirical research could be conducted to test the relative effectiveness of pre-shipment finance and backup production and to investigate the financing venues (e.g., POF and APD) of capital-constrained supply chains in practice.

## 4.8 Appendix to Chapter 4

### Appendix 4: Proofs

**Proof of Lemma 4.1.** In decentralized single sourcing, the offshore supplier's revenue function is defined as  $R(q) \triangleq (w(q) - c_p)q$  (cf. Lariviere and Porteus 2001); the supplier therefore sets  $q$  to maximize his expected profit  $\mathbb{E}[\pi_s^{\text{des}}(D, K)] = (w(q) - c_p)q - c_k q = R(q) - c_k q$ . The first- and second-order differentiations of the revenue function yield  $R'(q) = w(q)[1 - 1/v(q)]$  and  $R''(q) = w'(q)[1 - 1/v(q)] + v'(q)w(q)/v(q)^2$ , respectively. The offshore supplier's first-order condition (4.4) can be derived by setting marginal revenue  $R'(q)$  equal to marginal cost  $c_k$ . Since  $F(D)$  has support  $[a, b]$  for  $0 \leq a < b \leq \infty$  and since  $w(q) = p\bar{F}(q)$ , it follows that  $w(q)$  is strictly decreasing for  $q \in [a, b]$ . In addition,  $v'(q) \leq 0$  for  $q \in [a, b]$  and so the revenue function is strictly concave for  $q \in [a, \hat{q}]$ ; this is derived as follows. Since  $R'(q) = p - c_p$  for  $q \in [0, a)$ , profit is linear and strictly increasing. For  $q \in [a, \hat{q})$ ,  $\bar{F}(q)$  is strictly decreasing and  $(1 - h(q))$  is positive (by construction) and weakly decreasing (by the IGFR assumption).  $R(q)$  is thus strictly decreasing making revenues and profit strictly concave. For  $q > \hat{q}$ , marginal revenue  $R'(q)$  is negative while costs are increasing. Profit must fall. The uniqueness of  $q^{\text{des}}$  follows from the strict concavity over  $[a, \hat{q}]$ . Solving  $R'(q) = 0$  establishes that  $\hat{q}$  must maximize the offshore supplier's revenue. Hence the optimal order quantity  $q^{\text{des}} \in [a, \hat{q}]$ , and the offshore supplier will choose to sell  $a$  only if  $a > 0$  and  $\lim_{q \rightarrow a^+} p\bar{F}(q)[1 - h(q)] < c_k + c_p$ . Because  $v(q) = 1/h(q)$  and  $F$  is IGFR,  $v(D)$  must be decreasing. The optimal wholesale price is then  $w^{\text{des}} = p\bar{F}(q^{\text{des}}) = \frac{c_k + c_p}{1 - h(q^{\text{des}})} = \frac{v(q^{\text{des}})(c_k + c_p)}{v(q^{\text{des}}) - 1}$ .  $\square$

**Proof of Proposition 4.1.** Under backup production only, the retailer's optimal sourcing strategy is  $\mathbf{q} = (q^{\text{bp}}, q_b)^T = (q^{\text{bc}}, \min(K_b, [D - \min(q^{\text{bc}}, K^{\text{bc}})]^+))^T$ ; here  $q^{\text{bp}} = q^{\text{bc}} = F^{-1}\left(\frac{p - w^{\text{bc}}}{p}\right)$  follows from the reasoning applied in base case, and  $q_b = \min(K_b, [D - \min(q^{\text{bc}}, K^{\text{bc}})]^+)$  is the "greedy" solution that maximizes the retailer's profit contingent on demand in Stage 2. The offshore supplier's capacity  $K^{\text{bp}} = K^{\text{bc}}$ , where  $K^{\text{bc}} = F^{-1}\left(\frac{p - w^{\text{bc}}}{p}\right)$ . The FOC yields  $P\left(K^{\text{bp}} > \frac{A_s - L_s}{c_k}\right) = \frac{p\bar{F}(q^{\text{bp}})[1 - h(q^{\text{bp}})] - c_p - c_k}{(1 - \alpha)c_k}$ .  $\square$

**Proof of Corollary 4.1.** Under backup production only, the backup supplier makes a responsive capacity decision by matching the capacity shadow price (Van Miegham 1998) – that is, the marginal value obtained by adding one unit of capacity – with unit capacity cost; thus,  $(w_b - c_p^b)P(\min(q^{bc}, K^{bc}) + K_b < D) = c_k^b - c_r$ . Hence  $P(\min(q^{bc}, K^{bc}) + K_b < D) = \frac{c_k^b - c_r}{w_b - c_p^b}$  iff  $1 - P(\min(q^{bc}, K^{bc}) + K_b < D) = 1 - \frac{c_k^b - c_r}{w_b - c_p^b}$  iff  $P(\min(q^{bc}, K^{bc}) + K_b \geq D) = \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b} = \theta_b^{\text{bp}}$ .  $\square$

**Proof of Proposition 4.2.** The offshore supplier's optimal borrowing level in POF only is derived from the marginal analysis w.r.t.  $\lambda$ :

$$\frac{\partial \pi_s(\lambda, D, K)}{\partial \lambda} = \begin{cases} (1 - \alpha - r)wq & \text{if } L_s + c_k K + c_p q > A_s + \lambda wq, \\ -rwq & \text{if } L_s + c_k K + c_p q \leq A_s + \lambda wq. \end{cases}$$

Given that  $\alpha + r < 1$ , we obtain  $\lambda^* = \frac{c_k K^{\text{pof}} + L_s - A_s}{wq^{\text{pof}}}$ . Analogously to Lemma 4.1, here the FOC of the offshore supplier's expected profit demonstrates that the optimal capacity  $K^{\text{pof}} = q^{\text{pof}} = F^{-1}\left(\frac{p-w}{p}\right)$ , the optimal sales quantity is  $q^{\text{pof}}$  or  $a$ , and the optimal wholesale price  $w^{\text{pof}} = \frac{c_k + c_p}{1 - h(q^{\text{pof}})}$ .  $\square$

**Proof of Theorem 4.1.** The profit created by purchase order finance only w.r.t. the base case is derived as follows:  $\Delta \pi_r[\text{pof}] = \pi_r^{\text{pof}}(q, D, K) - \pi_r^{\text{bc}}(q, D, K) = p \min(D, \min(q^{\text{pof}}, K^{\text{pof}})) - w \min(q^{\text{pof}}, K^{\text{pof}}) - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}})$ . Similarly,  $\Delta \pi_s[\text{pof}] = (w - c_p) \min(q^{\text{pof}}, K^{\text{pof}}) - c_k q^{\text{pof}} - \lambda^* w q^{\text{pof}} r - (w - c_p) \min(q^{\text{bc}}, K^{\text{bc}}) + c_k K^{\text{bc}} + (1 - \alpha)[L_s - A_s + c_k K^{\text{bc}}]^+$  and  $\Delta \pi_c[\text{pof}] = \lambda^* w q r - I$ . Here the condition  $\lambda^* w q^{\text{pof}} r \in [I, (w - c_p) \min(q^{\text{pof}}, K^{\text{pof}}) - c_k q^{\text{pof}} - (w - c_p) \min(q^{\text{bc}}, K^{\text{bc}}) + c_k K^{\text{bc}} + (1 - \alpha)[L_s - A_s + c_k K^{\text{bc}}]^+]$  ensures that the profit increments from POF are nonnegative for the offshore supplier and creditor.  $\square$

**Proof of Proposition 4.3.** The retailer's optimal order quantity in APD only satisfies the condition  $\frac{\partial \pi_r^{\text{apd}}(q, D, K)}{\partial q} = 0$  iff  $p\bar{F}(q^{\text{apd}}) = w(1 - d)[1 + (1 - \alpha)P(L_r + w(1 - d)q^{\text{apd}} > A_r)]$ . Since  $q^{\text{apd}} = F^{-1}\left(\frac{p - w_e}{p}\right)$ , where the effective wholesale price  $w_e = w(1 - d)[1 + (1 -$

$\alpha)P(L_r + w(1-d)q^{\text{apd}} > A_r)]$ , it follows that  $q^{\text{apd}} \geq q^{\text{des}}$ , if  $(1-d)[1 + (1-\alpha)P(L_r + w(1-d)q^{\text{apd}} > A_r)] \leq 1$  and that  $q^{\text{apd}} < q^{\text{des}}$  otherwise.  $\square$

**Proof of Theorem 4.2.** The value of advance payment discount only w.r.t. the base case is

$$\begin{aligned}\Delta\pi_r[\text{apd}] &= \pi_r^{\text{apd}}(q, D, K) - \pi_r^{\text{bc}}(q, D, K) \\ &= p \min(D, \min(q^{\text{apd}}, K^{\text{apd}})) - w(1-d)\min(q^{\text{apd}}, K^{\text{apd}}) \\ &\quad - (1-\alpha)[L_r + w(1-d)q^{\text{apd}} - A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) \\ &\quad + w \min(q^{\text{bc}}, K^{\text{bc}})\end{aligned}$$

for the retailer and

$$\begin{aligned}\Delta\pi_s[\text{apd}] &= \pi_s^{\text{apd}}(D, K) - \pi_s^{\text{bc}}(D, K) \\ &= [w(1-d) - c_p]\min(q^{\text{apd}}, K^{\text{apd}}) - c_k K^{\text{apd}} - (w - c_p)\min(q^{\text{bc}}, K^{\text{bc}}) + c_k K^{\text{bc}} \\ &\quad + (1-\alpha)[L_s - A_s + c_k K^{\text{bc}}]^+\end{aligned}$$

for the offshore supplier. Here the condition  $w(1-d)\min(q^{\text{apd}}, K^{\text{apd}}) \in [c_p \min(q^{\text{apd}}, K^{\text{apd}}) + c_k K^{\text{apd}} + (w - c_p)\min(q^{\text{bc}}, K^{\text{bc}}) - c_k K^{\text{bc}} - (1-\alpha)[L_s - A_s + c_k K^{\text{bc}}]^+, p \min(D, \min(q^{\text{apd}}, K^{\text{apd}})) - (1-\alpha)[L_r + w(1-d)q^{\text{apd}} - A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}})]$  ensures the profitability of APD for the retailer and the offshore supplier.  $\square$

**Proof of Proposition 4.4.** The retailer chooses the financing regime that leads to a higher expected profit:  $\pi_r^{\text{pof}}(q, D, K) > \pi_r^{\text{apd}}(q, D, K)$  iff  $p \min(q^{\text{pof}}, D) - wq^{\text{pof}} > p \min(q^{\text{apd}}, D) - w(1-d)q^{\text{apd}} - (1-\alpha)[L_r + w(1-d)q^{\text{apd}} - A_r]^+$  iff  $(1-\alpha)(L_r + w(1-d)q^{\text{apd}} - A_r) > p \min(q^{\text{apd}}, D) - w(1-d)q^{\text{apd}} - p \min(q^{\text{pof}}, D) + wq^{\text{pof}}$  iff  $L_r + w(1-d)q^{\text{apd}} - A_r > \frac{p \min(q^{\text{apd}}, D) - w(1-d)q^{\text{apd}} - p \min(q^{\text{pof}}, D) + wq^{\text{pof}}}{1-\alpha}$  iff  $A_r < L_r + w(1-d)q^{\text{apd}} - \frac{p \min(q^{\text{apd}}, D) - w(1-d)q^{\text{apd}} - p \min(q^{\text{pof}}, D) + wq^{\text{pof}}}{1-\alpha} = \omega_r$ . And  $\pi_r^{\text{pof}}(q, D, K) \leq \pi_r^{\text{apd}}(q, D, K)$  if and only if  $A_r \geq \omega_r$ .  $\square$

**Proof of Proposition 4.5.** Since the offshore supplier maximizes his expected payoffs by making APD to be more profitable than POF:  $\pi_s^{\text{apd}}(D, K) \geq \pi_s^{\text{pof}}(D, K)$  iff  $[w(1-d) -$

$$c_p] \min(q^{\text{apd}}, K) - c_k q^{\text{apd}} \geq (w - c_p) \min(q^{\text{pof}}, K) - c_k q^{\text{pof}} - \lambda w q^{\text{pof}} r \quad \text{iff} \quad [w(1-d) - c_p - c_k] q^{\text{apd}} \geq (w - c_p - c_k) q^{\text{pof}} - \lambda w q^{\text{pof}} r \quad \text{iff} \quad (w - c_p - c_k) q^{\text{apd}} - w d q^{\text{apd}} \geq (w - c_p - c_k) q^{\text{pof}} - \lambda w q^{\text{pof}} r \quad \text{iff} \quad (w - c_p - c_k)(q^{\text{apd}} - q^{\text{pof}}) \geq w(d q^{\text{apd}} - \lambda r q^{\text{pof}}) \quad \text{iff} \quad d \leq \frac{(w - c_p - c_k)(q^{\text{apd}} - q^{\text{pof}}) + w \lambda r q^{\text{pof}}}{w q^{\text{apd}}}.$$

Therefore,  $\pi_s^{\text{apd}}(D, K) \geq \pi_s^{\text{pof}}(D, K)$  iff  $0 \leq d^* \leq \frac{(w - c_p - c_k)(q^{\text{apd}} - q^{\text{pof}}) + w \lambda r q^{\text{pof}}}{w q^{\text{apd}}}$ .  $\square$

**Proof of Proposition 4.6.** If  $\frac{\partial \mathbb{E}[\pi_r^{\text{df}}(q^{\text{df}}, D, K)]}{\partial q_1} \leq 0$ , then it is optimal for the retailer to use up her internal capital to fund APD, because  $\frac{\partial [p \min(D, q^{\text{df}}) - w q^{\text{df}}]}{\partial q_1} + w d > 0$ . When  $q_1$  exceeds a certain threshold  $q_1^* = \frac{A_r - L_r}{w(1-d)}$ , the marginal cost of financial distress  $-(1-\alpha)w(1-d) < 0$  incurs so that  $\frac{\partial \mathbb{E}[\pi_r^{\text{df}}(q^{\text{df}}, D, K)]}{\partial q_1} = \frac{\partial [p \min(D, q^{\text{df}}) - w q^{\text{df}}]}{\partial q_1} + w d - (1-\alpha)w(1-d) \leq 0$ ; hence it is no longer beneficial to increase  $q_1$  further. In this case, if  $1-d \geq \frac{c_k K^* + L_s - A_s}{w q_1^*}$ , then the offshore supplier's working capital can be fully covered by the retailer's partial purchase via APD (cf. Section 4.4.2) and so uses APD alone by setting  $\lambda^* = 0$ . But if  $1-d < \frac{c_k K^* + L_s - A_s}{w q_1^*}$  and so the retailer's partial purchase via APD can *not* cover the offshore supplier's shortage of working capital, then that supplier employs POF in addition to APD; he sets the optimal borrowing level  $\lambda^* = \min(\bar{\lambda}, \frac{c_k K^* + L_s - A_s - w q_1^*(1-d)}{w q_2^*})$ , because the marginal analysis w.r.t.  $\lambda$  shows that

$$\frac{\partial \pi_s(\lambda, D, K)}{\partial \lambda} = \begin{cases} (1-\alpha-r)w q_2^* & \text{if } L_s + c_k K + c_p q > A_s + w q_1^*(1-d) + \lambda w q_2^*, \\ -r w q_2^* & \text{if } L_s + c_k K + c_p q \leq A_s + w q_1^*(1-d) + \lambda w q_2^*. \end{cases}$$

Recall our assumption  $1 > \alpha + r$ , which rules out the trivial case where POF will not be adopted by the offshore supplier (i.e.,  $\lambda^* = 0$ ; see Section 4.4.1). If  $\frac{\partial \mathbb{E}[\pi_r^{\text{df}}(q^{\text{df}}, D, K)]}{\partial q_1} > 0$  then it is straightforward to derive that  $q_1^* = q^{\text{df}}$  in equilibrium, so that the retailer fully exploits the benefits of APD.  $\square$

**Proof of Corollary 4.2.** For dual financing (POF and APD) with backup production, the backup supplier makes his capacity decision by matching unit shadow price with capacity cost; hence  $(w_b - c_p^b)P(\min(K^{\text{dfbp}}, q^{\text{dfbp}}) + K_b < D) = c_k^b - c_r$  for  $x = \text{pof, apd}$ . Therefore,

$$P(\min(K^{\text{dfbp}}, q^{\text{dfbp}}) + K_b < D) = \frac{c_k^b - c_r}{w_b - c_p^b} \quad \text{iff} \quad 1 - P(\min(K^{\text{dfbp}}, q^{\text{dfbp}}) + K_b < D) = 1 - \frac{c_k^b - c_r}{w_b - c_p^b} \text{ iff } P(\min(K^{\text{dfbp}}, q^{\text{dfbp}}) + K_b \geq D) = \frac{w_b - c_p^b - c_k^b + c_r}{w_b - c_p^b} = \theta_b^{\text{dfbp}}. \quad \square$$

**Proof of Theorem 4.3.** For the retailer, the value of backup production only relative to the base case is

$$\begin{aligned} \Delta\pi_r[\text{bp}] &= \pi_r^{\text{bp}}(\mathbf{q}, D, K) - \pi_r^{\text{bc}}(\mathbf{q}, D, K) \\ &= p \min(D, \min(q^{\text{bc}}, K^{\text{bc}}) + K_b) - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) \\ &\quad - w_b \min(K_b, [D - \min(q^{\text{bc}}, K^{\text{bc}})]^+) - c_r K_b \end{aligned}$$

and the value of dual financing only for the retailer is

$$\begin{aligned} \Delta\pi_r[\text{df}] &= \pi_r^{\text{df}}(\mathbf{q}, D, K) - \pi_r^{\text{bc}}(\mathbf{q}, D, K) = p \min(D, \min(q^{\text{df}}, K^{\text{df}})) - w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ + \\ &\quad w(1-d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ - w(1-d)q_1 - (1-\alpha)[L_r + w(1-d)q_1 - A_r]^+ - \\ &\quad p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}}). \end{aligned}$$

The conditions  $(p - w_b) \min(K_b, [D - \min(q^{\text{bc}}, K^{\text{bc}})]^+) \geq c_r K_b$  and  $p \min(D, \min(q^{\text{df}}, K^{\text{df}})) - w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ + w(1-d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ - w(1-d)q_1 - (1-\alpha)[L_r + w(1-d)q_1 - A_r]^+ \geq p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) - w \min(q^{\text{bc}}, K^{\text{bc}})$  ensure (respectively) the profitability of backup production only and dual financing only w.r.t. the base case for the retailer.  $\square$

**Proof of Theorem 4.4.** The value creation of dual financing (POF and APD) with backup production relative to the base case can be derived from the equality  $\Delta\pi_r[\text{dfbp}] = \pi_r^{\text{dfbp}}(\mathbf{q}, D, K) - \pi_r^{\text{bc}}(\mathbf{q}, D, K)$  for  $x = \text{pof}, \text{apd}$ . Similarly, we have

$$\begin{aligned} \Delta\pi_s[\text{dfbp}] &= \pi_s^{\text{dfbp}}(\mathbf{q}, D, K) - \pi_s^{\text{bc}}(\mathbf{q}, D, K) = \\ &\quad p \min(D, \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + K_b) - w[\min(q^{\text{dfbp}}, K^{\text{dfbp}}) - q_1]^+ + \\ &\quad w(1-d)[q_1 - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+ - w(1-d)q_1 - w_b \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + \\ &\quad K_b]^+) - c_r K_b - (1-\alpha)[L_r + c_r K_b + w(1-d)q_1 - A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + \\ &\quad w \min(q^{\text{bc}}, K^{\text{bc}}), \end{aligned}$$



$$\begin{aligned}\Delta\pi_b[\text{xbp}] &= \pi_b^{\text{dfbp}}(\mathbf{q}, D, K) - \pi_b^{\text{bc}}(q, D, K) \\ &= (w_b - c_p^b) \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) + c_r K_b - c_k^b K_b,\end{aligned}$$

$$\text{and } \Delta\pi_c[\text{dfbp}] = \lambda\beta w q^{\text{dfbp}} r - I.$$

Here the conditions  $\Delta\pi_i[\text{dfbp}] \geq 0$  for  $i = r, s, b, c$  and  $w_b \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) + c_r K_b \in \left[c_p^b \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) + c_k^b K_b, p \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right)\right]$  ensure the profit increments by combining dual financing with backup production are nonnegative for the four parties involved.  $\square$

**Proof of Theorem 4.5.** The interaction effect between backup production and dual financing is

$$\begin{aligned}\Delta\pi_r[\text{df, bsp}] &= \Delta\pi_r[\text{dfbp}] - \Delta\pi_r[\text{bsp}] - \Delta\pi_r[\text{df}] = p \min(D, \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + K_b) - \\ &w \left[\min(q^{\text{dfbp}}, K^{\text{dfbp}}) - q_1\right]^+ + w(1-d)[q_1 - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+ - w(1-d)q_1 - \\ &w_b \min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) - c_r K_b - (1-\alpha)[L_r + c_r K_b + w(1-d)q_1 - A_r]^+ - \\ &p \min\left(D, \min(q^{\text{bc}}, K^{\text{bc}})\right) + w \min(q^{\text{bc}}, K^{\text{bc}}) - \left[p \min(K^{\text{bc}} + K_b, D) - p \min(K^{\text{bc}}, D) - \right. \\ &w_b \min\left(K_b, [D - K^{\text{bc}}]^+\right) - c_r K_b] - \left[p \min\left(D, \min(q^{\text{df}}, K^{\text{df}})\right) - w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ + \right. \\ &w(1-d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ - w(1-d)q_1 - (1-\alpha)[L_r + w(1-d)q_1 - A_r]^+ - \\ &p \min\left(D, \min(q^{\text{bc}}, K^{\text{bc}})\right) + w \min(q^{\text{bc}}, K^{\text{bc}})] = (p - w_b) \left[\min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) - \right. \\ &\left. \min\left(K_b, [D - K^{\text{bc}}]^+\right)\right] - (1-\alpha) \left([L_r + c_r K_b + w(1-d)q_1 - A_r]^+ - [L_r + w(1-d)q_1 - A_r]^+\right).\end{aligned}$$

The term  $(p - w_b) \left[\min\left(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+\right) - \min\left(K_b, [D - K^{\text{bc}}]^+\right)\right]$  can be positive if demand variability (especially upside surge) is high. Whereas  $-(1-\alpha) \left([L_r + c_r K_b + w(1-d)q_1 - A_r]^+ - [L_r + w(1-d)q_1 - A_r]^+\right) \leq 0$ . Therefore, by Definition 3, dual financing and backup production are complements when demand variability (upside potential) is high and are partial substitutes otherwise.

In this case, the effective wholesale price is  $w^{\text{dfbp}} = (1 - \beta)w(1 - d) + \beta w \in [w(1 - d), w]$ . This implies that  $K^{\text{dfbp}} = q^{\text{dfbp}} = F^{-1}\left(\frac{p-w^{\text{df}}}{p}\right) \in \left[F^{-1}\left(\frac{p-w}{p}\right), F^{-1}\left(\frac{p-w(1-d)}{p}\right)\right]$ . This channel coordination effect ensures that the profit increment by adding dual financing to backup production only is nonnegative for the retailer. That is,

$$\begin{aligned} \Delta\pi_r[\text{dfbp}] &= p \min(D, \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + K_b) - w[\min(q^{\text{dfbp}}, K^{\text{dfbp}}) - q_1]^+ + \\ &w(1 - d)[q_1 - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+ - w(1 - d)q_1 - \\ &w_b \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}}) + K_b]^+) - c_r K_b - (1 - \alpha)[L_r + c_r K_b + w(1 - d)q_1 - \\ &A_r]^+ - p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}}) \geq \Delta\pi_r[\text{bp}] = p \min(K^{\text{bc}} + K_b, D) - \\ &p \min(K^{\text{bc}}, D) - w_b \min(K_b, [D - K^{\text{bc}}]^+) - c_r K_b. \end{aligned}$$

Since dual financing with backup production is viable only if  $w_b \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+) + c_r K_b \in [c_p^b \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+) + c_k^b K_b, p \min(K_b, [D - \min(q^{\text{dfbp}}, K^{\text{dfbp}})]^+)]$  (see Theorem 4.4), the profit increment by adding backup supply to dual financing is nonnegative for the retailer. Hence

$$\begin{aligned} \Delta\pi_r[\text{dfbp}] &\geq \Delta\pi_r[\text{df}] = p \min(D, \min(q^{\text{df}}, K^{\text{df}})) - w[\min(q^{\text{df}}, K^{\text{df}}) - q_1]^+ + \\ &w(1 - d)[q_1 - \min(q^{\text{df}}, K^{\text{df}})]^+ - w(1 - d)q_1 - (1 - \alpha)[L_r + w(1 - d)q_1 - A_r]^+ - \\ &p \min(D, \min(q^{\text{bc}}, K^{\text{bc}})) + w \min(q^{\text{bc}}, K^{\text{bc}}), \end{aligned}$$

it follows that  $\Delta\pi_r[\text{bp}] + \Delta\pi_r[\text{df}] > \Delta\pi_r[\text{pofbp}] \geq \max(\Delta\pi_r[\text{bp}], \Delta\pi_r[\text{df}])$ . So by Definition 4.3, backup production and dual financing are either complements or partial substitutes for the retailer.  $\square$

## Chapter 5

### Managerial Insights

As an emerging research area, the interface of operations and finance in global supply chains proposes ways to either mitigate risk or enhance competitiveness with both operational and financial tools. Our work contributes to this research stream by reviewing the literature, modelling intertwined operational and financial hedging as well as supply chain finance, and providing managerial insights to industrial practice.

Based on the closed-loop view of operations and finance in Chapter 2, the goal of integrated risk management is to match supply with demand of material, financial, and information flows in an enterprise and across a supply chain. A roadmap to integrated risk management is proposed via a four-step process: (i) identify operational and financial risks, (ii) specify (generic) integration conditions, (iii) select operational hedging and financial flexibility, and (iv) optimize integrated operations and finance. Linking the relationship analysis (complements/substitutes) and approach choice (centralization/decentralization), the following two results are derived. First, zero interaction effects (separation) of operations and finance lead to decentralization. Second, operational hedging and financial flexibility should be centralized even if they are partial substitutes.

Chapter 3 models a MNC that makes ex ante capacity investment and financial hedging decisions and executes ex post backup production and switching options to manage both exchange rate uncertainty and mismatch risk. The intuition behind our mean-CVaR analysis is as follows. First, backup production and switching options are complements when both are used to fulfill foreign demand but are substitutes when used to fulfill domestic demand. Operational flexibility and financial hedging are substitutes in risk reduction, yet they can be complements in profit enhancement if financial hedging alters the feasible set of capacity portfolios by relaxing the CVaR constraint. On the one hand, operational flexibility enhances profitability and reduces downside risk; financial hedging reduces downside risk to a minimum and can affect profitability only if it enlarges the feasible set of capacity portfolios by relaxing the CVaR constraint. On the other hand, operational flexibility can be viewed as a portfolio of “knock-out” call/put real options written on costs in foreign/home currency.

In contrast, a financial hedging portfolio of “knock-in” put options on foreign currency mitigates the impact of rare and extreme low exchange rates on the MNC’s cash flow. Second, given operational flexibility, financial hedging is viable only in the event of rare and extreme exchange rates; the reason is that real options are expected to generate greater profits otherwise. In contrast, under financial hedging only, the result is larger risk reduction effects; that outcome reflects the substitution effects between operational flexibility and financial hedging in reducing risk. Third, even though a mean-CVaR optimization problem can be decomposed into CVaR minimization via financial hedging with a minimum expected profit and expected profit maximization by operational flexibility subject to a CVaR constraint, collaboration and coordination between operations and finance is needed to minimize substitution effects in the mean-CVaR utility—especially with respect to risk reduction. Hence information exchange between operations and finance is crucial: efficient financial hedging relies on a rigorous estimation of the probability distribution of cash flow as shaped by operational flexibility, while the feasible set of capacity portfolios depends on financial hedging by virtue of the CVaR constraint.

Table 5.1. Summary of Supply Chain Models in Chapters 3 and 4

	Source of Uncertainty				Operational Strategy	Financial Instrument	Relationship
	Supply	Demand	Exchange Rate	Financial Distress			
Chapter 3	√	√	√		Backup production, switching options	Currency forwards, options	Operational flexibility and financial hedging are substitutes in risk reduction, yet they can be complements in profit enhancement. Backup production and switching options are complements (substitutes) if used to fulfill foreign (domestic) demand.
Chapter 4	√	√		√	Backup supply	Purchase order finance, advance payment discount	Pre-shipment finance (POF and/or APD) and backup supply can be complements or partial substitutes for the retailer. Pecking order of dual financing: the retailer first uses APD and then adopts POF.

In Chapter 4, we study a supply chain consisting of one retailer and two suppliers, where both the retailer and the offshore supplier may be capital-constrained. Our model establishes the following main findings. First, the unique equilibrium in single-financing mode is POF if the retailer’s internal asset level is below a certain threshold but is APD otherwise; in this case, the equilibrium region of purchase order finance is decreasing in demand variability and also in the retailer’s internal capital level. POF can alleviate the credit risk of an offshore

supplier by outsourcing capital from a creditor, and thereby offers triple benefits to supplier, buyer, and creditor. In contrast, APD may coordinate the channel by transferring financial flow from voluntary to binding positions within the supply chain. Second, the pecking order of pre-shipment finance under dual financing is that the retailer first uses internal capital for APD and then adopts POF to finance the offshore supplier—provided the channel coordination benefits of APD are dominated by the costs of financial distress; otherwise, she uses APD only. Third, pre-shipment finance (POF and/or APD) and backup production can be complements or partial substitutes for the retailer depending on demand variability. Backup production alone provides two benefits for the retailer: (i) hedging supply underage owing to the offshore supplier's financial constraint and (ii) hedging demand upside potential. Yet the first of these benefits is optimally provided by pre-shipment finance because dual financing releases the offshore supplier's capital constraint and thereby fully mitigates the effect of financial distress at a *lower* cost for the retailer. Hence the interaction effect between backup production and dual financing includes the profit increment from backup supply and the potential increase in distress cost. Overall, the integration of these strategies can create significant value because the expected profit from that approach is strictly greater than that from either pre-shipment finance or backup production alone. An overview of supply chain models in Chapters 3 and 4 is provided in Table 5.1.

This dissertation on operations and finance in global supply chains may suggest a number of research directions. First, new combinations of operational hedging and financial flexibility can be explored analytically. Second, empirical research on integrated risk management can be conducted to test its effectiveness in applications. Best practices of cross-functional, cross-supply chain risk management programs can be traced. Third, integrated risk management of operations and finance can be extended by incorporating the triple bottom line (3BL) of sustainability, which optimizes jointly the social, environmental, and economic performance. Fourth, our one-period, two-stage programs in Chapters 3 and 4 could be extended to accommodate multiperiod settings in which dynamic financial hedging or supply chain finance can be adopted concurrently with operational flexibility. Fifth, the firms' market pricing decisions can be incorporated into various competitive settings.

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**Affirmation – Statutory Declaration**  
**According to § 10 part 1 no. 6 of the Doctoral Studies’ Guide Lines**  
**(dated 5th March 2008 as amended on the 8th September 2009)**

I hereby declare, that the

**Dissertation**

submitted to the Wissenschaftliche Hochschule für Unternehmensführung (WHU)-Otto-Beisheim-Hochschule-was produced independently and without the aid of sources other than those which have been indicated. All ideas and thoughts coming both directly and indirectly from outside sources have been noted as such.

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The following persons helped me gratuitous/non-gratuitous in the indicated way in selecting and evaluating the used materials:

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Huchzermeier	Arnd	Doctoral supervision	gratuitous
Spinler	Stefan	Doctoral supervision	gratuitous
Darnell	Matt	copyedit	non-gratuitous

Further persons have not been involved in the preparation of the presented dissertation as regards contents or in substance. In particular, I have not drawn on the non-gratuitous help of placement or advisory services (doctoral counsels / PhD advisors or other persons). Nobody has received direct or indirect monetary benefits for services that are in connection with the contents of the presented dissertation.

The dissertation does not contain texts or (parts of) chapters that are subject of current or completed dissertation projects.

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